A STUDY OF DIGITAL SAMPLING IN GNATHOSONICS

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ABSTRACT

The purpose of this study has been to provide clinicians with a simple low cost system for gnathosonic investigation in the dental surgery, instead of referring patients to specialist centres. Hitherto the literature describing the sounds made by occlusion of the teeth has offered many conflicting hypotheses as to the relationship between the sounds produced and the condition of the gnathic system. Many techniques developed to investigate factors involved in tooth vibration or impact are cumbersome and time consuming. The simple system developed in this work is based on fast digital capture using an inexpensive microcomputer of a type commonly found in the home. Specific software has been developed to capture and manipulate the transient signals generated by tooth and other impacts. As part of the study the software has been rigorously verified for timings, frequency limits and program errors, and has been validated using both mathematically generated and other control signals such as those provided by a signal generator. The system has been used both *in vitro* and *in vivo* to investigate the manner in which shock waves from tooth impacts are received after transmission through the body structures. A meaningful interpretation of the data recorded has been established, although it has had to be accepted that scientific analysis of shock wave propagation through tissue requires further investigation and is beyond the scope of this work. In addition to sounds generated by occlusion of the teeth, sounds made by the percussion of implants set into the maxilla and mandible have also been recorded, on the assumption that serial recordings taken from the time of insertion could indicate integration or give early warning of failure. The technique of digital signal capture has been applied elsewhere in the body, for example sounds made by both natural and artificial joints. This limited study indicates that the developed system may have much wider application than gnathosonic measurement alone. It is suggested that the differing results of many researchers into gnathosonics may be due to lack of standardisation of the sensors and other equipment employed, and to misinterpretation of the sound recordings of the occlusion of the teeth. It is proposed that certain parameters should be established in the field of gnathosonics, particularly in regard to the sensors and recording apparatus. It is only then that the results from serial sessions, and the work of different investigators will stand comparison.

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LIST OF TERMS

Disk Diskette	Whenever the term "Disk" or "Diskette" appears in this thesis it refers to the normal floppy storage medium used with modern computers.
Model cement	The material generally marketed under the name of "Model Cement" is generally known in the dental field as "Sticky Wax".
us	Wherever the term "us" appears in the text it refers to a time measured in microseconds (10^{-6}seconds).

DECLARATION

This thesis is the sole work of the author with the exception of the help and guidance from the individuals acknowledged in the text.

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K.W.Tyson

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I am also indebted to the staff of the Department of Civil Engineering for their helpful advice concerning impacts.

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The justification for therapeutic intervention in the intact dentition has proponents whose criteria and priorities vary as widely as their techniques for occlusal adjustment. The very fact that patients' dentitions have survived with occlusions established via a variety of philosophies of jaw position, cuspal inclinations and interdigitations, is either a credit to the particular practitioner or a reflection of the amazing "adaptive capacity" of the human organism.

Brenman 1974[22]

CHAPTER 1

INTRODUCTION

INTRODUCTION

Gnathosonics is defined in the British Standards Glossary of Dental Terms (1983) as 'the study of the sounds produced by occlusion of the teeth during mastication, or by voluntary tapping of the teeth'. In principle it offers a non-invasive method of assessing the quality of the occlusion. Keeping sequential records allows the response to treatment to be monitored although interpretation of the recorded sounds has been the subject of much debate in the dental literature.

The sounds made by the teeth occluding can vary according to the harmony of the cuspal relations, the firmness with which the supporting tissues hold the teeth in the jaws and the balance of the musculature which controls the path and force of closure. The vibrations resulting from the impact of the teeth are registered by a sensor attached to the patient. Sensors may be affixed to the teeth, or more conveniently placed on the surface of the skin either one over each zygoma or a single sensor in the middle of the forehead.

The most commonly used sensor has been the microphone which has the disadvantage of readily picking up ambient noise, so ideally recordings should be made with the patient in an anechoic chamber.

If the sensor is placed on the skin then the sounds resulting from the occlusion of the teeth must be transmitted across the periodontal membrane, through the bones of the skull, pass through soft tissue and so cause the skin to vibrate. If the sensor is a microphone then the vibrations of the skin set up air waves which are in turn registered by the microphone. Accelerometers have the advantage of being attached directly to the skin surface and so vibrate with it, their disadvantage is their mass which will damp the vibration characteristics of the skin.

The sensors are pivotal to all sound recordings as it is only the data output of the sensor that can be analysed. Any data that the sensor cannot record is lost and any false data recorded by the sensor will be analysed as if it were true. The same conditions apply to the amplifiers and signal display instrumentation.

The sounds are of a transient nature and the practicalities of capture and making hard copy for reference are limited by the hardware available. Traditionally the sounds have been captured as analogue signals at high speed on magnetic tape, which is then replayed at low speed, to give chart recorders time to respond to the fine detail of the captured signals.

Chart recorders with high speed paper drive can further stretch the signal to separate the different oscillations. Such equipment is necessarily expensive. These constraints place the technique beyond the resources of the general practitioner, restricting it to specialist centres.

With the advent of modern microcomputers, the dentist is now presented with the possibility of low cost digital capture of occlusal sounds. Once captured in digital form, the signal can be manipulated on screen, expanding or enlarging it to display all of the features, even resolving it into its component frequencies without altering the original data. Further, recent studies have shown that miniature accelerometers which do not pick up ambient noise, can be used instead of microphones. Since most homes and modern dental practices already have microcomputers, the study of gnathosonics is now within easy reach of the general practitioner, as the additional equipment is low cost.

A fundamental objective of this thesis has been to demonstrate the validity of this proposition for one common make of microcomputer. A further step has been to use a domestic cassette recorder to capture occlusal sounds and act as a data store which can be scanned and analysed by the computer when time is available.

A second objective has been to apply the technique to other areas in the medical field where auscultation is employed.

A third objective has been to use the method in the physical field of materials.

The work reported in this thesis has been carried out in three stages according to the following protocol:

1. **Development of the hardware and software.** The software has been developed for the microcomputer to capture the full range of frequencies which make up the transient sounds produced by impact or percussion of the teeth. The suite of programs has been subjected to rigorous mathematical verification, and validation by control signals such as those produced by a signal generator and tuning forks which have themselves been standardised against an oscilloscope. The sensor, and the ability of the apparatus to capture, retain and display transient sounds accurately has been subjected to similar checks.

   Two cassette recorders of the type selected for the technique have been evaluated for frequency response and similarity of function by recording and replaying test signals of known frequency and amplitude as well as transient signals.

2. **Application of the technique**, firstly by *in vitro* modelling to establish the type of shock wave patterns generated when differing media are collided with variable force. Secondly, by comparison with similar experiments carried out on a dry skull before *in vivo* experiments were commenced.

The *in vivo* experiments have examined the transmission of the sounds of impact of the teeth and of other impacts to the skull to establish a protocol by which comparable observations might be made by different observers. The experiments examined the variability of the signals given by the sensors depending upon type, how and where they were attached to the head, their mass, area of contact and fixation pressure. All these factors have contributed towards the disparate results and consequent interpretation by different observers.

3. **Observations** on the use of the technique in the capture of sounds elsewhere in the body such as natural and artificial joints, prosthetic heart valve sounds as well as percussion for auscultation of other areas. Lastly applications outwith the medical

field.

As a result of this work, a number of sources of potential error have been identified which have received little or no mention in the literature. Considerable concern has been aroused over aliasing which results in false data being recorded when the sampling rate of a signal is too slow or the inertia of a writing instrument is too great. It is suggested that the many conflicting conjectures and conclusions which have been proposed in the field of gnathosonics have been caused by the apparatus and techniques used by different workers to collect and process data. It is very unusual for workers to publish the specifications of the equipment which has been used to collect data. The specifications which are published are normally restricted to the brand names of the amplifiers and recorders, whereas the sensors are merely stated to be of a certain type such as 'condenser' or 'dynamic' with no other data.

A number of parameters are therefore proposed, that if adopted, should allow researchers to be able to replicate others' work and experiments. Results could then be meaningfully explained when technique or apparatus differed from the standards.

CHAPTER 2

REVIEW OF THE LITERATURE

REVIEW OF THE LITERATURE

The sounds generated by the body have always been of medical interest and vary from the very low frequencies, such as those from heart valve closure, boriborigmi of various frequencies and the sharp sounds produced by joint cartilages and their capsular ligaments to the transient frequencies created by the impact of the teeth on sudden occlusion.

Auscultation, first defined in medicine in 1833, is the 'action of listening, with ear or stethoscope, in order to judge by sound the condition of heart, lungs, or other organs'.[1]

Listening to and interpreting sounds made by the body is an art which can only be learned by practice. The introduction of the stethoscope, the first of which was a wooden tube described by Laennec in 1819, greatly improved the conduction of sound from the chest wall to the ear of the practitioner and incidentally protected the sensibilities of both patient and physician.[2]

Williams, in 1829, was the first to develop the binaural stethoscope,[3] with two earpieces and two semi-rigid lead tubes joined to a single chestpiece for application to the patient's body. A more flexible instrument was developed by Dr Cammann (or Caman) in 1855, referred to by Alison who in 1856 described the Differential Stethophone where a three dimensional effect was achieved by using two chestpieces.[4] This development was the forerunner of the stereostethoscope described by Nicolai in 1936 for auscultation of sounds originating in the temporomandibular joints,[5] and later by Watt for spatial evaluation of sounds produced by occlusion of the teeth.[6]

The only other significant development in stethoscopy was that of using a shallow resonator (chestpiece) covered with either a flexible or a rigid diaphragm. A model designed by Bowles in 1901 with a rigid diaphragm, and referred to by Kerr in a paper on the stethoscope and symballophone in 1944,[7] is still in general use. However the rigid diaphragm was found to attenuate some of the faint aortic diastolic murmurs, and the open bell and rigid diaphragm chestpieces were therefore combined in order that the advantages of both types might be obtained by switching a valve to either chestpiece.

Records from dental stethoscopy were first reported in 1952 by Ekensten who made 'phonograms' of the sounds made by the temporomandibular joints.[8] The phonograms were made by photographing oscilloscope traces of sounds from the joints. The sounds were picked up by a crystal microphone and amplified before display. Ekensten claimed to be able to distinguish the traces demonstrating lip opening, movement of the meniscus and subluxation.

Brenman and Millsap in 1959 using similar apparatus first examined the wave patterns made by the teeth on occlusion,[9] although interestingly much earlier in 1948 von Békésy had used the sounds made by tapping the incisors together while investigating bone conduction of sound vibrations in the skull and the effects on hearing.[10] This work will be referred to again.

Brenman and Millsap called the wave patterns 'occlusograms' and concluded that while the pattern of one individual could not be superimposed upon that of another, there were basic similarities. Firstly there was an obvious difference between those with a 'solid' centric occlusion and those with a 'slip' or eccentricity. Secondly the occlusograms did not significantly vary between those patients with a natural dentition and those with prosthetic replacements such as crowns and bridges, and thirdly there was a difference in the occlusograms between those patients able to repeatedly tap their incisors together and those who could not. A most significant finding was that there was a marked change in the occlusogram if the body position was altered, so a positioner was developed to keep the head/thorax relation the same each time a recording was made.

Brenman[11] and Watt[12] published separately in 1963, both suggesting that the sounds generated by the gnathic system could provide information on the condition of the joints and state of the occlusion of the teeth.

Brenman used a dynamic type microphone strapped to the forehead whereas Watt used a hearing aid earpiece infraorbitally. Their conclusions were basically the same, in that short sharp sounds indicated a stable occlusion whereas a prolonged sound indicated disruption. Both Brenman and Watt recorded the sounds onto magnetic tape to be displayed on an oscilloscope for analysis and photographed for permanent record.

Brenman however indicated that a patient with no occlusal discrepancies should produce a waveform similar to that of a pure tone, the amplitude falling off with time as the sound would not be sustained. On the other hand occlusal discrepancies would lead to an irregular wave form such as that produced by the clash of cymbals.

This led to the conclusion that a closure beginning with a premature contact and followed by a slide into full occlusion would show a waveform starting with a high frequency irregular pattern merging into a lower frequency regular pattern at the point of actual closure. Later an instrument was commercially marketed for the recording of occlusograms.

These observations became the baseline for many other investigators in the field, although no data were presented to show that a pure sine wave would be produced from an ideal closure sound. In fact impacts do not generate pure tones, but generate transient signals which are high frequency and complex.

Brenman also prophetically quoted Rodriquez and Oester (1956) 'No method can be better than its practitioner. The basic information which electromyography provides cannot be wrong because it records the electric currents generated by biologic activity. The recognition and interpretation of the record is another matter, a matter of information, experience and good judgement.'[13] This statement is only true if the sensors, amplifiers and other hardware which supply the basic information are capable of giving a true picture of the activity under examination.

No researcher had set standards or validated any hardware, in particular the sensors which had been used, which would have allowed an informed judgement on the data offered.

By the mid sixties Watt and Brenman had defined their positions on the interpretation of tooth contact and temporomandibular joint sounds.[14,15,16] Watt had derived the term 'Gnathosonics' to cover the study of the sounds made by the masticatory apparatus and had classified the sounds of dental occlusion into three categories. Class A: sounds of less than 30 milliseconds duration; Class C: sounds exceeding 30 milliseconds in duration and Class B: sounds which include a mixture of class A and class C sounds. Watt later subdivided class A into two subgroups consisting of balanced and unbalanced muscle activity. The term 'separation noise' was also added to describe the sounds sometimes produced by the sliding contacts of the teeth as they disarticulate on jaw opening.

Thirty milliseconds seems to be a very long time for an occlusal sound generated by the teeth closing cleanly into centric occlusion. A result more to be expected would be in the order of ten milliseconds, as will be shown by work in this thesis. Thirty milliseconds could contain two impacts, each of ten milliseconds separated by a pause of ten milliseconds.

Brenman had concluded that there were two components to the types of waves generated when the teeth came into occlusion.[16] These were called the alpha and beta components, the alpha being high frequency and the beta of low frequency. The sum of both the components was assumed to represent the total duration of the occlusal event.

Both Brenman and Watt had demonstrated that the sounds made by an individual were reasonably reproducible on repeated closures at the same session and would stay essentially the same when taken at various time intervals. Further, records had been shown to change through alteration of the head position or adjustments to the occlusion. Chart writers had by now replaced the photography of oscilloscope traces as a means of keeping hard copy records.

Watt, utilising the graphic appearance of the occlusal sounds as a measure of the stability of the occlusion, used successive records to monitor the progress of adjustments by grinding to stabilise the occlusion.[15] There was no indication during recording and replay of standard parameters having been set on the instrumentation. Watt's work is therefore open to criticism. For example, in order to produce satisfactory traces a quiet sound made by a patient in pain may have been recorded and reproduced at a higher gain, giving rise to what appeared to be an extended sound because sound which would have died down to background level would have been amplified to a significant level. On the other hand a pain free patient generating a high amplitude signal by snapping the teeth together may have had the signal level reduced so giving rise to what appeared to be a short sound by record and replay amplitudes being reduced, leading to the last part of the signal being reduced to background level and so not included in the measurements. It is not possible to resolve this problem from the published reports alone.

In 1967 Watt drew attention to the work of other research in relation to effects of forced and natural vibrations of a system subjected to impact and to the resonances of the skull, mandible, soft tissue and transducer.[17,18] Watt concluded that these were likely to be constant for any one patient, but that care should be exercised in the comparison of records from different patients. Having drawn attention to some of the problems which might be considered, Watt did not consider them further.

Watt also compared high speed cinephotography with simultaneous sound records and found the high frequency sound on the traces to be synchronous with the visual image of the teeth sliding over each other and the duration of the visual and sound images to be in reasonable accord. Watt also refined the classification of occlusion.[19,20,21]

Brenman had concluded in 1974 that occlusal analysis by sound was accurate and reliable.[22] The frequency spectrum of occlusal sounds ranging from 50Hz to 3KHz. It is of interest to note that in this paper the head was not in the anatomical position as might have been expected if the jaws were to close in the patients centric position.

The lack of standards and reliance on unproved hardware is a feature of the dental literature on gnathosonics. Another feature is that which had been initiated by Brenman in 1963, of a beginning, a mid point and an end point in relation to movements caused by muscles. Later in the same paper reference was made to the movement of the mandible as having a definite end point, i.e. the occlusion of the teeth. Others took up the three points as referring to occlusion of the teeth, beginning with an early contact, followed by a slide and eventual full closure.

For instance Stallard in 1976 stated that the time of closure sounds varied from 10 to 50 milliseconds, dependent on the degree of slipping and sliding.[23] Sounds were recorded using a contact microphone applied to the forehead and replayed through a strip chart recorder, but as with so much of the gnathosonic literature no specifications were given. Stallard took the beginning to be the beginning of tooth contact, the interim relationship as the mandible being guided to the end point by the inclinations of the cusps of the teeth.

Frequency, duration and amplitude were defined as three important parameters, and the alpha and beta components of occlusal sounds identified. Diagrams in the paper appear to be examples of what might be expected in theory as alpha and beta waveforms rather than actual *in vivo* occlusal tracings. Stallard concluded that tracings from occlusal sounds were an extremely accurate diagnostic aid.

Watt in 1978 claimed to have validated the classification of occlusion by four studies.[24] Firstly by superimposition of traces, when those in class A showed a high degree of coincidence and those in class C showed none. Secondly by a subject's ability or inability to tap the teeth together and produce signals of similar length, which was again held to support the hypothesis that those with a well co-ordinated musculature show a more consistent pattern than those with poor co-ordination. Thirdly the intervals between signal starts was measured with the subjects tapping the teeth together at their own rate showed no significant differences between the three classes of occlusion. Fourthly silent periods were found to be absent on nearly twice as many occasions in class C cases than class A, and unilateral absences four times more common in class C than class B occlusions. Validation was based on the studies revealing significant differences between the classes in coordination and in muscle activity.

An investigation into the bone conduction of occlusal sounds was carried out by Takamiya in 1979.[25] By placing sensors in the external auditory meati and timing the interval between sounds generated at the point of artificially created premature contacts and the sensors, Takamiya concluded that it was possible to locate premature contacts. For example the time difference between the sound from the premolar region arriving at the sensors was in the order of 100 usec. The wave velocity calculated on the propagation times was 702.7 m/sec on the working side and 453.7 m/sec the balancing side. There was however no difference in the time duration of the occlusal sounds, the length of normal tapping being 7.85 msec. This is less than one third of the time allowed for a Class A occlusion according to Watt.

In the frequency domain the power spectrum of the normal occlusion showed a maximum at 901.9Hz followed by 316.9Hz and 3670.9Hz, but the frequencies detected in the auditory meati varied from DC to 1500 Hz. There was no comment on the possible recognition of a second premature contact occurring in close relation to other occlusal contact sounds which might have confused the picture.

In general, premature contacts do not appear to have been well defined. There seems to be an assumption of an early ectopic contact on closure, but the question has not been raised as to whether a series of cusps closing into correct centric occlusion one after the other at very short intervals would be considered as prematurities. There is no work on the coincidence of cuspal contacts in a stable occlusion, and indeed it would be remarkable if every cusp struck at precisely the same instant.

In the book 'Gnathosonics and Occlusal Dynamics' (1981).[26] Watt noted the work by von Gierke and others on the mechanical impedance of the human tissues, concluding that the resonances of the mandible, skull, teeth and tissues would not be likely to vary for an individual but that care should be taken in the comparison of traces derived from different patients.

Watt carried out *in vitro* experiments using a pendulum type impact tester to show that if three hammers struck three anvils simultaneously, a single impact would be observed. If two of the hammers were altered in height then two or more impacts would be demonstrated. The next step was to show the effect of an early contact followed by a slide into full contact. Conical hammers were used to engage matching recessed anvils which could be offset so that sloping surfaces would strike first followed by a slide into full engagement. This attempt was abandoned due to lack of success as it was assumed that the slide could not be demonstrated because of the rigidity of the apparatus and that the rubber bushing of the anvils was not comparable to the periodontal membrane and teeth.

Experiments using metal studs mounted on blocks on resilient bases in an articulator were used to show the size of premature contacts which might be detected by gnathosonic techniques. It was shown that 0.02 mm was well within the capabilities of the technique.

Watt also concluded that the normal rate of jaw closure was in the order of 148 mm/sec. Problems arise concerning premature contacts, as it was shown that the moment a premature contact takes place the rate of closure of the mandible is altered. It would seem therefore, that the rate of closure until such a first contact is achieved is academic, it being the final rate of closure between first and full contact which is of interest.

Although Watt again defined postulates on gnathosonics, there were two fundamental questions which still remained open. Firstly, the time apportioned to a stable impact, defined as clear and of short duration, is up to 30ms which appears to be excessive, most other reports being of a shorter time, in the order of 10 ms. Secondly, no standards were applied to the sensors, microphones were used in an anechoic chamber, or a variable reluctance microphone (to avoid ambient noise when a chamber was not available) during screening of large numbers of subjects. The output of the sensor is a function of the vibrating mass, frequency response, area of contact and pressure against the skin. Watt was aware of the importance of keeping the pressure of the sensors against the skin constant and devised a harness to hold the microphones in the infraorbital position when recordings were made in the anechoic chamber.

Watt also measured the time difference taken for the sound to reach bilateral sensors from a unilateral contact, for the purpose of spatial location by a stereostethoscope, but did not investigate the effects of crosstalk between the channels on full occlusion of the teeth and the effects this would have had on the tracings. Tracings were judged by measurement or by eye, quite different from aural discrimination.

Watt in 1980 and 1983 related temporomandibular joint sounds to mandibular movement and occlusal sounds,[27,28] classifying the joint sounds as clicks and crepitus, both of which could be sub-classified as hard or soft and by their position in the opening/closing cycle. This was followed by an analysis of the temporomandibular joint sounds of 110 patients. From this analysis Watt called into question the then current hypothesis of clicks being caused by the relation of joint to miniscus.

The development of the Dental Sound Checker otherwise called the Occlusal Sound-wave Detector or Dental Health Checker was reported by Tanaka in 1984.[29] Hard copy traces by this instrument were made by a pen recorder which was later superseded by a printer. The types of sound discussed were similar to those described by Watt. Condenser microphones were used as sensors and the points favoured for sound pickup were the body of the zygoma and anterior to the tragus for occlusal and TMJ sounds respectively. The auditory canal was used for the microphones when other data gathering equipment, such as mandibular movement transducers or EMG electrodes were in use. Correspondence between the smoothness of the opening and closing of the jaw and the sharpness of the occlusal sound was demonstrated.

It was recommended that records be used for general diagnosis and monitoring the progress of treatment together with other adjuncts such as X-ray, EMG, mandibular movement analyser and articulated models. Tanaka intended to move next into examining sounds in the frequency domain (spectral analysis).

The application of gnathosonic monitoring to complete and partial dentures before and after occlusal correction was investigated by Watt in 1985.[30] Five groups were examined. Group A: complete dentures made by students. Group B: complete dentures recalled for further records 1.5 to 3 years after fitting. Group C: complete dentures which had been made by general practitioners between 4 and 35 years previously. Group D: partial dentures made by students and Group E: partially edentulous patients having tooth supported partial upper dentures and bilateral free-end saddle lower dentures. Using the duration of the occlusal sounds as a yardstick the indications were that the patient adapts to complete dentures, the average duration of occlusal sounds falling from 42 ms on fitting to 16 ms after 1.5 to 3 years. Prolonged wearing showed an increase in instability in some patients so that it might be possible to have an indication of the optimum time to replace the dentures. Adjusted tooth supported partial dentures made little difference to the duration of the sounds, whereas tissue supported partial dentures, designed to load the more compressible tissues before the natural teeth met, registered a double sound as the dentures contacted before the natural teeth. It was concluded that most patients adapt to their complete or partial dentures and that the amount of adaptation required can be reduced by occlusal adjustment.

An extraordinary attempt to examine the impact forces applied to teeth on occlusion in three dimensions was made by Nakazawa in 1986.[31] A miniature triaxial accelerometer was attached to each of the upper teeth in turn starting with the canine and working back to the second molar, to determine shock, acceleration, duration of vibration and power spectrum. Differences caused by premature contacts were examined by overlaying various cuspal slopes. The recordings were examined to show the decrease in axial force and increase in lateral forces in such conditions.

One finding showed that there was no significant difference between the vibration duration of the control group and that group in which cuspal interference occurred. This could be in accord with the fact that if a prematurity is sufficiently large it will only be recorded as a single contact.

The control subjects' power spectra peaked between 690 and 840 Hz whereas teeth driven buccally by early contact peaked between 390 and 550 Hz and teeth driven lingually between 1880 and 1940 Hz. The paper concluded that the method was useful in the examination and diagnosis of occlusal contacts, but offered no explanation as to the cause of the differences in power spectra between buccally and palatally driven teeth.

Fuller (1987) carried out a detailed investigation into the sound wave patterns generated by the occlusion of the teeth,[32] the aims being to: 'Investigate the interrelationships of the components of the wave patterns of the tooth contact sound, to investigate the relationship between the tooth contact sound and its wave pattern, and to test the hypothesis that gnathosonic data can be used as an analogue of the quality of occlusion.'

The sensor employed was a microphone connected by a thin tube to a stethoscope bell which was placed centrally on the patient's forehead. The occlusal sounds were recorded for detailed analysis. Three components of the wave patterns were defined and measured: the total duration of the wave pattern from the point of commencement to the point where it was no longer detectable, the duration of the alpha waves from the point of commencement of the wave pattern to the point at which the pattern changed from high frequency to low frequency, and the maximum amplitude of the low frequency section of the wave pattern (beta waves). These parameters were analysed and account was taken of the slide of the teeth from the retruded contact position into the position of maximum intercuspation which had been measured with a leaf gauge. As the two sets of measurements were separate it is difficult to see how they can be related unless the assumption is made that the measured slide is identical in all closures.

The analysis of the data led to the conclusions that: 1. The duration of the alpha wave pattern and the total pattern is significantly related to the amplitude (loudness) of the sound. Therefore allowance should be made for amplitude when comparing traces. 2. The duration of the alpha waves may be used for comparison of data. 3. The duration of the alpha pattern bears the strongest relation to the categories of contact sound (Watt). 4. The tooth contact category, the duration of the alpha sound and the amplitude might be considered to be analogues of the occlusion. However, clinical assessment was thought to be more exact and simple. 5. If the study was to be pursued the duration of the alpha waves might be linked to occurrences between initial tooth contact and final closure in the position of maximum intercuspation.

The alpha and beta waves demonstrated appear, by inspection of the figures, to contain frequencies in the order of approximately 0.5 to 1KHz and 50 to 100Hz respectively. There was no investigation of the possibility of spurious wave forms being introduced by the use of an open bell stethoscope applied to the tissues and the sounds being sensed remotely through a narrow tube. Nor was there an investigation of coincidence of the components of the waveform with the actual moment of occlusion.

This paper could be considered to be the culmination of assumptions made throughout the dental literature, regarding the following as facts:

1) The sensors and other hardware give a true reproduction of the vibrations generated by the occlusion of the teeth.

2) The traces produced represent the first contacts of the teeth followed by a slide into terminal closure.

3) High frequency waves are generated by slides and low frequency by terminal closure or clean closure without sliding.

4) Ideal closure without any early contact or slide should show a low frequency wave form which decays rapidly.

In fact the situation is that:

1) No standards have been set for work to be compared.

2) There appears to have been no verification of the hardware, in particular the sensors.

3) Force and speed of closure have received little attention.

4) Tracings of the sound of closure taken at different times have not necessarily been recorded and replayed under the same conditions.

5) Little *in vitro* modelling has been carried out for the purpose of associating the components of the sound picture with the actual impact of the teeth.

6) Very little attention has been paid to the transmission and consequent modification of the

vibrations generated by the teeth as they pass through the bones and soft tissues of the head to be converted into electrical impulses by the sensor. Microphones require vibration of the tissue interface with air at the skin surface to form air waves before detection.

Tyson in 1987[33] suggested that the frequencies shown on the traces were not of great significance being largely a function of the physical properties of the tissues and transducer. Taking the view that it was the overall shape of the envelope produced by the trace that indicated the quality of the occlusal contact. A second paper[34] described an inexpensive method of taking gnathosonics into the surgery of the general practitioner by the use of a specially developed computer programme which could be run on a computer of a type commonly found in the home.

In contrast Teodorescu in the following year reported a simple and inexpensive electronic method of measuring the duration of occlusal sounds,[35] separating them into durations greater or less than a predecided length, such as 30 ms, to distinguish between Watt class A and C occlusions. The major drawback with this technique was the rejection of all frequencies higher than 500 Hz, for no better reason than that the band of 10 to 500 Hz was found to be suitable for the purpose. The sensors were microphones for hand held telephonic transmitters which might even have been carbon microphones, judging by the illustration, with a very low frequency response.

Freer in 1989[36] investigated the reproducibility of gnathosonic recordings at intervals of time. It was suggested that in the ideal stable occlusal contact, the first contact is the last contact, producing a single clear impact sound whereas unstable contacts would lead to sliding and muffled sounds. The point was made that up to that time little had been published on the reproducibility of gnathosonic recordings made at intervals of time. Freer noted that operators normally controlled both the X axis and the Y axis of the recordings (time and amplitude) and in addition the force and speed of closure could alter the length and amplitude of the signal. It was further noted that there was no accepted standard scale in the X axis and that inaccuracies could arise in choosing the beginning and end points of a trace, and that no satisfactory method of comparison had evolved.

The method employed was to mount a transducer below each orbit. The controls of oscilloscope and recorder were set and noted after tracings of similar amplitude had been obtained. Playback settings were similarly controlled. Reproducibility was considered acceptable if three out of five from a single series of sounds could be superimposed. This was considered to be the minimum degree of agreement acceptable.

The reproducibility within each group was relatively high, 65 to 70 per cent, but much lower across the same groups recorded one week apart, 25 to 30 per cent.

This study was unable to confirm adequate reproducibility of gnathosonic recordings across different series. Both duration and amplitude were considered to be key elements of the shape or pattern of a gnathosonic tracing, with amplitude being the most difficult to control. It was felt that much work was required before the system could be a reliable comparator of occlusal events over time, although the method might usefully be used as a quick non-invasive technique for group comparison and epidemiological studies.

For all the care taken to point out the shortcomings of previous workers, this paper only referred to the transducers as variable reluctance microphones and the reproductions of the traces gave no indication of the measurements in the X and Y axes.

Muramoto in 1989[37] investigated the effects of plaque control, scaling and root planing on occlusal sounds. Nine periodontally affected subjects and eight control subjects were examined. Thereafter the periodontally affected patients underwent treatment and were re-examined at one and three months post-operatively.

The results obtained showed firstly that the normal duration of an occlusal sound generated by a healthy dentition was less than 10 ms. and secondly that occlusal sounds from periodontally affected patients were of longer duration than those with a healthy dentition, but decreased and approached the normal value after treatment.

The occlusal sounds were monitored with a Dental Sound Checker, a commercially available instrument by the Yoshida Company Tokyo. This differs from the previously described Dental Health Checker (Tanaka 1984[29]) in that an accelerometer is used as a sensor, and prior to amplification and recording, the signal was processed by an attenuator/enhancer to ensure that all signals examined would not show a variation in input levels.

It was assumed that the three main components of occlusal sounds were: 1. The vibration of the teeth themselves due to their collision; 2. The vibration of the system composed of the teeth as a mass and the periodontal tissue as a viscoelastic body; 3. The resonance of the cranium and accessory sinuses induced by 2. It was concluded that changes in 1. and 3. were barely conceivable during the time under examination, therefore the changes must have taken place in 2. and those changes being in the viscoelastic nature of the periodontium.

The results are not unexpected but the information on data gathering is almost nonexistent. The sensors are referred to as microphones whereas a diagram shows them to be accelerometers of the beam type. Further the accelerometer is oil filled which causes a degree of damping and high frequency loss. Added to this the accelerometer casing is covered with a layer of rubber which leads to further high frequency attenuation. It is also stated that all signals are conditioned to an equal amplitude. So although there can be little doubt that the overall picture observed by the researchers will be in accord with the facts, which would be clinically demonstrable, the only way of reproducing the work would be to use the Dental Sound Checker.

Following the work of Muramoto, Taguchi in 1990[38] examined two similar groups to assess the duration of percussion sounds with the purpose of 1. establishing to what extent the duration of percussion sounds could be determined by an occlusal sounds analyser, 2. comparing the duration of percussion sounds in different types of healthy teeth and 3. determining the differences in the duration of percussion sounds in periodontally diseased and healthy teeth.

The teeth were percussed with an 8 mm metal ball of 6.5 g weight, using a percussive force of between 70 and 90 g. Readings above and below certain amplitudes were rejected as being unreliable. The teeth were also examined with a 'Periotest', an instrument manufactured to assess the periodontal health of a tooth by the amount of mobility.[39,40,41]

The findings were 1. The normal duration of percussion sounds ranged from 4.40 to 5.33 ms. 2. Percussion sound values of periodontally affected patients were of longer duration than those of healthy subjects. 3. A close correlation between duration and other individual parameters (probing depth, loss of attachment and bone loss) was found in all upper teeth, with the exception of the molars.

Again the results are to be expected. The instruments used for measurement appear to give arbitrary readings and there is very little information for other workers in the field to understand and draw informed conclusions unless the commercial instruments are available. The specifications of these instruments are not given.

Tooth mobility and the state of the periodontium have been monitored by other means, most notably by applying a force at right angles to the axis of a tooth and measuring the degree of displacement under a given force. Recovery time after a timed displacement is suggested as another significant factor. Other researchers have examined the effect of vibrating the teeth at various frequencies. These observations are not directly related to the theme of this thesis and are noted for completeness of the overall picture as are the reports on spectral analysis of the sounds made by occlusion of the teeth.

Muhlemann (1960) reviewed a ten year period of periodontal mobility measurements,[42] having developed the 'Periodontometer' (macro- and micro-) to measure tooth displacement under a given force between 100 and 500 grams for a given time (usually one to two seconds) and creating a TM (tooth mobility) score.

Kato (1968) reported a new method of periodontal examination by investigating the resonant frequencies of teeth with normal, and teeth with pathology of the periodontal membranes.[43] The apparatus analysed a range of frequencies applied to a tooth to find the particular frequency at which the tooth would resonate. The resonant frequency of the tooth alters as the periodontal condition deteriorates.

In the same year Noyes measured the mechanical input impedance of human teeth *in vivo*,[44] using a frequency range of 60 to 5000Hz and concluded that an incisor and the supporting membrane acted as a damped mass spring system. The intention was to develop a clinical instrument for the objective measurement of tooth mobility. In 1973 Noyes published another paper on the mechanical mobility of human incisors creating a new damped mass spring system and concluded that the different results recorded from upper and lower incisors were due to their difference in mass,[45] the supporting structures and also the supportive characteristics of the mandible and maxilla.

Korber in 1971[46] examined twelve factors affecting tooth mobility including tooth impacts, rate of loading and recovery, oscillations during recovery and tooth oscillations caused by bone conduction. The transducers were of an inductive noncontact design. These are useful in the anterior region of the mouth or on the skin surface. Records were shown of the twelve events so that such data could be recorded and evaluated.

The Periotest reported by Schulte (1983) and further expanded in 1988 and 1990,[39,40,41] was designed so that a rod could deliver four impacts to a tooth during one second. The application of force was set at right angles to the long axis of the tooth under test. An accelerometer measured the rate of deceleration of the percussing rod. Twenty identical impacts are applied and the rate of deceleration scored from 1 to 100 indicating a braking time of between 0.3 and 2.3 ms. It was concluded that the Periotest measures the degree of periodontal damping and indicates the degree of tooth mobility and in general the condition of the periodontium of each tooth examined. The paper in 1990 specifically related the Periotest values to that of bone loss and concluded that the method provided accurate information about the degree of bone atrophy.

In a review of methods for measuring tooth mobility Yankell 1988[47] in an interesting echo of the studies of gnathosonics stated 'that there continues to be controversy over the accuracy and reproducibility of clinical indices.' Further 'that tooth mobility values alone have little meaning and must be related to other diagnostic data.'.

Researchers have also investigated the power spectra of the sounds made by the masticatory apparatus. These have been mostly used in the investigations of the sounds made by the temporomandibular joints. Watt (1966b) shows a sonograph of an occlusal creak.[15] Oullette (1974) categorised the sonograms made from TMJ sounds into four identifiable groups and stated that specific frequencies were reproducible from one session to the next.[48]

Shi (1991) investigated the power spectra of fifteen subjects with complete natural dentitions.[49] Shi concluded that, using the Watt classification of occlusal sounds, short duration sounds showed a decrease in low frequency content whereas the high frequency may remain the same particularly under Class B conditions. Class C sounds may show a decrease in the high frequency component and an increase in the low frequencies. In practice the most useful data to represent the low, medium and high frequency bands are at F10, F50 and F80 bands. Shi suggests that with present day computer technology, occlusal sounds might be classified by frequency changes.

Outwith the dental field, other researchers have investigated the sounds made by joints, particular interest being concentrated on the hip and knee. Between 1982 and 1991 Kernohan and colleagues published seven papers recording the development of the technique of 'Vibrational Arthrometry'.[50-56]

The sounds made by congenital dislocation of the hip have been identified as different from the normal joint and a method of large scale screening of infants proposed. The vibration patterns derived from the patella can vary giving the investigator insight into the damage which might have occurred to the cartilages within the joint. The hardware is well documented as is the development of the technique. The only important data missing is the frequency range, the mass, surface area and force of application of the transducer. However the first three are available from the manufacturer. The frequency range is more than adequate for the sounds recorded and the mass of three grams for the most commonly used sensor is not enough to limit the higher frequencies generated by the joints. The cost of the sensor employed was not cheap, being in the order of several hundred pounds.

Reference books on shock and vibration such as Harris and Crede,[57] show that the vibrations generated by the impact of solid bodies are complex. The sounds are of a transient nature, starting with a forced vibration of the body struck and ending with the natural vibration of that body. The vibrations begin with a high amplitude and decay rapidly and much depends on the substance of which the hammer and the anvil are made.

Three articles which could have been of considerable value to workers in the field of sounds made by the occlusion of the teeth are those of Békésy (1948)[10] and von Gierke (1952 and 1960).[18,58] The first is concerned with hearing and of sound carried by bone conduction in the head, while the other two deal with vibrations transmitted through human tissues.

Békésy[10] was primarily concerned to find a way to reduce cross hearing (hearing with one ear the tone that is delivered to the other). Part of the problem of measuring the vibrations of the bones of the skull was that of the pick-up or sensor, as 'since soft skin is an inefficient transducer of the vibrations of the bony wall to a pick-up', also noted was that the thickness of the skin changed from one place on the head to another.

A vibration pick-up with a 30 mm diameter surface was used, pressed against the forehead with a pressure of 3 Kg. When the incisors were clicked together, the impulsive movement given to the bones of the head set the pickup into momentary oscillation. These were displayed on an oscilloscope and photographed as oscillograms.

Békésy noted that if the mass of the pick-up was multiplied by four, the frequency of the damped oscillations was halved. This rule did not hold for further increases in mass as the pick-up mass was no longer small in comparison to the mass of the head. Further, a layer of rubber between the skin and the pick-up diminished the frequency of oscillations of the system. The oscillograms showed a frequency of approximately 250 Hz recorded by a sensor weighing 230 g. The sensor used was a vibration transducer based on a miniature pendulum, which remained still while the housing which contained an electric coil vibrated. Electrical changes induced in the coil were displayed on the oscilloscope. This is, in essence, the same principle of using inertia as the modern accelerometer.

The 3 Kg pressure of the sensor on the forehead was maintained by a soft spring and the compliance of the patch of skin for the area and mass of the sensor calculated. It was also taken into account that the compliance of the skin varied with the pressure. The vibrations induced in the skull were monitored and frequencies under examination checked with sensors with different resonances. It was noted that among other resonances the oral cavity showed some resonances in the region of 1200 Hz and that opening the mouth could change the amplitude of vibration. The incisor teeth showed resonances in the region of 2400 Hz and the amplitudes varied between different teeth.

The vibration patterns throughout the skull were investigated as well as consideration of the paths taken by the vibrations. Altogether this paper held enough information so that basic standards could have been laid down for the study of occlusal sounds which would have allowed workers to compare their investigations, and if necessary, repeat the claims of other investigators.

The two papers by von Gierke[18,58] dealt with the transmission of vibration through the body tissues, both soft and hard, entering into the complex mathematics involving the theory of wave propagation in viscoelastic media. The points of dental interest were: 1) The sensor favoured was of the condenser type (not a microphone) which was very close to, but did not touch the skin, relying on the skin vibration to modulate a carrier wave by altering the capacitance between the probe and the skin surface. 2) The resonant frequency of the jaw to the rest of the skull was in the region of 100 to 200 Hz. 3) The skull has a fundamental frequency of 300 to 400 Hz with higher resonances in the order of 600 to 900 Hz. (Békésy also found an anteroposterior resonance of the skull itself at about 1800 Hz).

COMMENT

Throughout the dental literature on auscultation of the masticatory mechanism, great emphasis has been laid on the interpretation the traces representing the sounds made by the occlusion of the teeth. The only point of agreement appears to be that the teeth do make sounds on occlusion, but beyond this there is little agreement amongst authors as to what the traces really show and to the interpretation of the visual imprints of the sounds.

On the other hand no author has raised doubts as to the sounds which can be heard through the stethoscope, be it mono or stereo, and assessed by the ear of the operator. It is only too easy to hear a short sharp closure in contrast to a muffled double hit separated by a sliding sound. These are unique sounds which are directly experienced by the ear and are not open to assessment or repetition by another individual. If such sounds are to be examined by others, or kept as records, then the recording and reproduction of the sounds must either be absolute or made to certain set standards so that the work of one operator can be reproduced by another.

Some of the major assumptions have been:

1) That whatever hardware has been used, the recordings eventually demonstrated will be an accurate reproduction of the sounds generated by the tissues.

2) That unless contacts are truly simultaneous the sound will be complex beginning with an impact, followed by a slide into terminal closure. The sliding part of the sound may contain more impacts on the way to terminal closure.

3) High frequency sounds can be attributed to cusps sliding over each other whereas low frequencies are generated by terminal impact or a clean impact where there is no sliding component.

4) An ideal closure produces a low frequency with a sudden attack followed by a rapid decay.

Some of the major omissions have been:

1) There have been no standards laid down so that one worker can make a comparison between his work and that of others in the field. Sometimes the names of amplifiers, recorders and writers are given but not the sensor and it's specification. As the sensor is the

first link in the chain it should be essential that full details be given, including the frequency response, the manner in which the vibrations are detected and how they might have been modified during transmission through the tissues before detection. This is of particular importance when microphones of a type which detect sounds transmitted by the air are used, in that vibrations transmitted through the tissues to the skin are translated into air pressure waves before detection. Here much is dependent upon the area and flexibility of the skin selected for detection of the vibrations, the size and shape of the collecting bell and the pressures within it and how the air waves are delivered to the microphone. As far as the accelerometer type of sensor is concerned the specifications must include the mass, the area in contact with the tissues, the frequency response and the pressure used to hold the sensor in place.

2) There appears to be no verification of the equipment that has been used, particularly the sensors.

3) The force and speed of closure have received little attention, apparently the amplitude of the signals to be recorded being arbitrarily set to give a reasonable looking trace. In this way a low amplitude signal from a patient in pain might be enlarged so that residual signal which would have merged with background noise becomes counted in the signal length. Conversely a high

amplitude signal from a pain free patient might be reduced so that signal which might have been counted in the overall length would be depressed into background level.

4) Recordings made at different times, whether from the same patient or not, have not necessarily been made or replayed under the same conditions, so it is difficult to see how records can be compared with any degree of accuracy.

5) There has been little or no *in vitro* modelling, and the statement in the frequently cited paper of Bremner that a clear impact of the teeth should generate a pure wave form, like that of a piano has not been challenged from the standpoint of either the impact or the piano. Neither impact generates a pure tone, and transient frequencies are produced.

6) There has been little attention paid to the modifications which the signals might undergo during transmission from the teeth to the sensor, the assumption being that there is some high frequency loss which may or may not be of great consequence. What has not received attention is the possibility that the signal might have been added to by the effects of transmission through the tissues. The possibility that the so called beta wave, the low frequency generated by the terminal occlusion, might be an artifact has not been considered. Such an artifact might be caused by the

skin surface acting like the skin of a drum, leaving residual waves after the effect of an impact had passed. This would be most noticeable with microphones registering air waves.

CHAPTER 3

ALIASING

ALIASING - A PROBLEM IN SIGNAL CAPTURE

There are many practical problems in signal capture, the majority of which are not limited to gnathosonic studies but are relevant to all aspects of signal monitoring. For example, a hypothetically perfect sensor should respond equally to all frequencies, but in reality a sensor such as a microphone will have a characteristic frequency response which may only be uniform over a limited frequency range. This range should include all possible components of the studied signal, and a poorly chosen sensor may therefore alter a captured signal and give a false result.

Practical difficulties of this sort are well recognised, but one problem in particular is not obvious and does not appear to have received a mention in dentistry. It is however well known in other fields of signal capture, and can lead to a totally false sound picture being captured, the analysis of which would be meaningless. That problem is called aliasing.

Aliasing is a problem in both analogue and digital signal, and occurs when the recording rate is too slow for the frequency involved. In analogue systems such as chart recorders for example, the pen response may be too slow so that the recorder cannot possibly follow rapidly changing frequencies. The apparent 'signal' recorded bears little resemblance to the true signal.

Aliasing in digital capture occurs when the sampling rate is too slow, so that more than one wave passes between readings. The resulting apparent frequency is then low, and the slower the sample rate the worse this becomes. However, unlike analogue capture the problem can be readily analysed mathematically. For example figure 1 shows a hypothetical pure sine wave or tone of frequency f Hz sampled at approximately 1.1f. The resulting captured 'signal' appears to be a slow sinusoidal wave of only about 0.1f. The problem is that at least two samples per cycle are required to record the true frequency, and this sets a lower limit of 2f for the sampling frequency. For example, in order to capture a 1KHz signal the sampling rate must be at least 2KHz if aliasing is to be avoided. For complex real waveforms such as gnathosonic signals with overlapping tones of various frequencies the sampling rate should be at least twice the highest frequency present, otherwise the captured signal will contain spurious low frequencies. One routine way of ensuring this in general signal capture is an electronic filter to limit the upper signal frequency, but important information may then be lost. The alternative is to sample at such a high rate that all possible frequencies of interest are captured properly without aliasing. For example, in the experiments in this thesis the fastest sampling rate is 64KHz, implying reliable sample signal frequencies up to 32 KHz, well outside the range for gnathosonic measurements.

The problems caused by aliasing are highlighted in figure 2, where a computer-generated simple sine wave has been sampled at various frequencies, resulting in a range of apparent signals all derived from the one original. Only in the last case in figure 2, where there are more than two samples per cycle, is the true frequency recorded. For completeness, a computer-simulated 'pure' gnathosonic-type tone is shown in figure 3, where the wrong sampling rate has resulted in an apparent low frequency signal.

The phenomenon is well known in research involving signal capture and analysis. A complex real signal is usually analysed by a mathematical process called a Fourier Transform, which separates the signal into its contributing pure wave forms, producing what is often called a 'power spectrum' of the signal. Since analysis of the signal for frequencies greater than half the sampling rate will produce spurious results, the transform has to be set up with a built-in upper limit at this value. Frequencies higher than this are then ignored. An anti-aliasing filter in the original recording system should ensure their absence in any case. The limiting frequency (ie half the sample rate) is often called the 'Nyquist' or folding frequency.

It is clear from this that gnathosonic hardware cannot sensibly record frequencies greater than half the sampling rate, and indeed will introduce spurious low frequency components if such frequencies are present. Therefore if sounds up to 1KHz are studied, and are reported in the literature, the signal sampling frequency should have been at least 2KHz, and filtering or some other means of limitation should have been used to prevent aliasing. However, such precautions do not appear to have been reported in the gnathosonics literature.

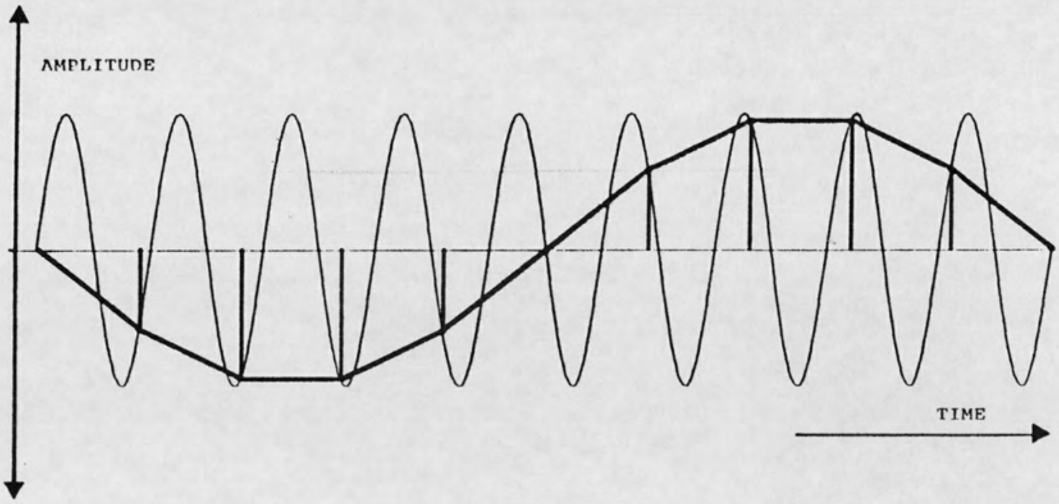


Fig.3.1. Aliasing - the effect of too low a sample rate. Nine cycles of the true signal frequency f Hz of a simple sine wave are sampled at approx. 1.1f, individual samples being shown by vertical lines. The resulting apparent 'frequency' is only about 0.1f, as shown by the heavy line.

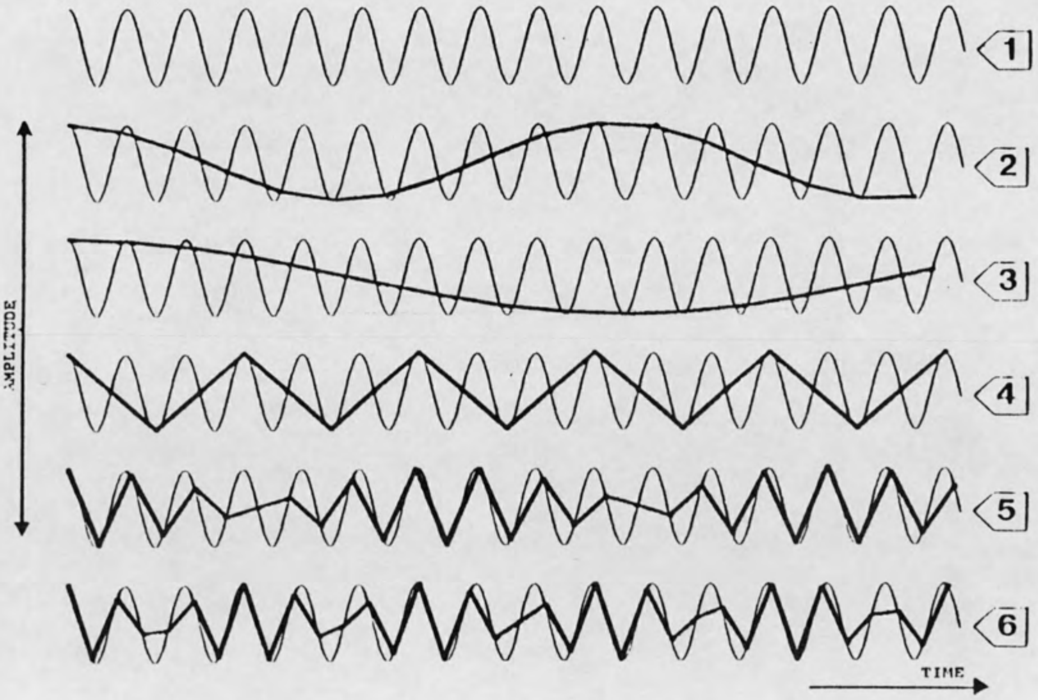


Fig.3.2. Aliasing of a sine wave at various sample rates. (1) the true signal frequency f Hz, sampled at 73 samples per cycle (spc). Figures given are samples-per-cycle and approx. relative frequency: (2) 1.11 spc, 0.11f (3) 0.95 spc, 0.05f (4) 1.33 spc, 0.33f (5) 1.85 spc, 0.85f (6) 2.32 spc, 1.0f. Only in (6) are samples taken at >2 spc to reproduce the correct frequency.

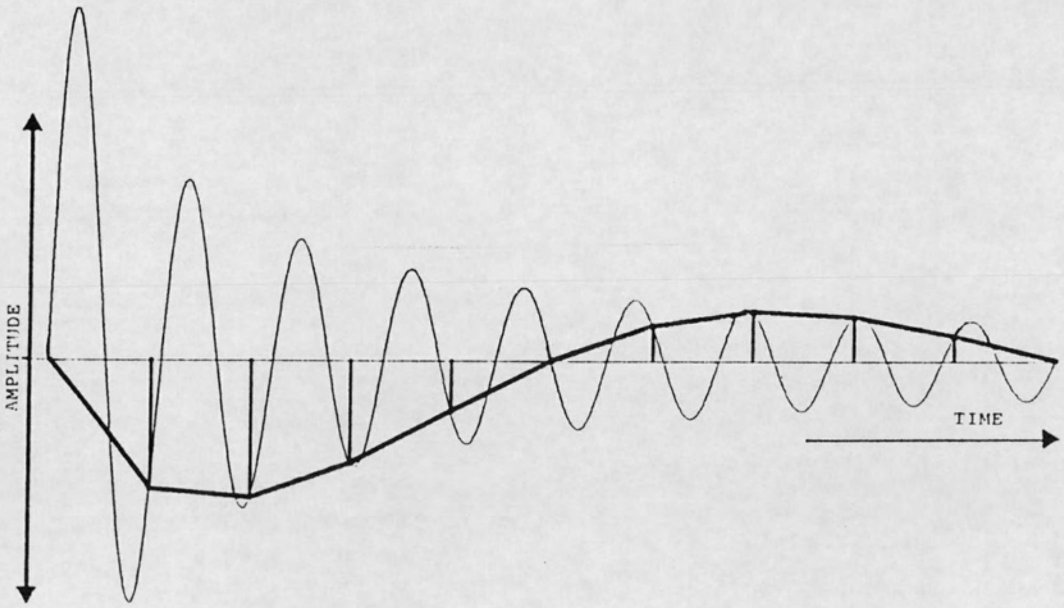


Fig.3.3. Similar to figure 3.1. Aliasing of a simulated gnathosonic signal to produce an apparent low frequency sound shown by the heavy line.

CHAPTER 4

A LABORATORY STUDY OF SIMPLE IMPACT SOUNDS

A LABORATORY STUDY OF SIMPLE IMPACT SOUNDS

> An impact is a single collision of one mass which is in motion with a second mass which may either be in motion or at rest.[57]

INTRODUCTION

An impact collision causes a shock wave to propagate through a material, producing surface vibrations which are often detected directly as sound. After the impact the material continues to vibrate at its own natural frequency, the vibrations decaying exponentially until they can no longer be discerned. The vibration envelope is therefore normally expected to have two components or spectra, a primary shock spectrum caused by the collision proper followed by a residual shock spectrum consisting of the decaying natural vibration of the struck object.[57]

Transient vibrations such as this are sometimes simple, as when a bell of single pure tone is struck, but are more often complicated by having numerous residual frequencies, each of which must have been present in the initial pulse. Indeed, since a bell may be made with any arbitrary tone, and since a bell will resonate when struck, it follows that the initial impulse must contain all possible vibration frequencies. Just as two simple sine waves may be combined by a process of reinforcement or cancellation to produce a composite waveform, so it may be shown that a single pulse containing all possible vibration frequencies takes the form of a square wave.[59] For an ideal collision of infinitely short duration between incompressible materials, it can also be shown that the initial pulse would be infinitely narrow with infinitely high amplitude.[59] In practice of course, the pulse will be modified by the mechanical properties of the materials and will deviate from the ideal square waveform.[59]

For such an ideal collision, it follows also that the initial pulse will contain any resonant frequency of the sensor used to detect the vibrations. Since the sensors are normally themselves vibrating systems such as microphones or vibration transducers (accelerometers), they would therefore be expected to have such a resonant frequency which would appear as part of the detected envelope. A difficulty for vibration studies is to distinguish this from the vibration proper, the generally accepted method being to ensure that the resonant frequency of the sensor is well outside the range of frequencies under study. In that case, it is then a relatively simple matter to eliminate it from the captured sound envelope using an electronic filter. In favourable cases, and particularly where the vibration of the struck object is damped in some manner, the resonant frequency may be lost in the material and may not even reach the sensor, obviating the need for electronic filtering. For example the vibration of teeth is damped by the surrounding tissues,[10,18] so that careful choice of sensor might well avoid the problem of spurious frequencies arising from the sensor itself. It is clear from this that an important aspect of any vibration study must be the establishing of the range of frequencies involved, combined with knowledge of the resonant frequency of possible sensors.

This is however not the only reason for determining the range of frequencies under study, particularly where vibration studies employ digital signal capture. The advantage of this method over classical analogue capture is that the captured envelope is easily stored and reproduced, for example by a microcomputer, but the method suffers from a potentially serious error known as signal aliasing, which occurs when the sampling rate is too slow for the frequencies under study (chapter 3). For any given frequency at least two samples per cycle are required to record the signal faithfully, and if the sample rate drops below this the apparent 'frequency' can be several orders of magnitude less than the true value. It follows, for example, that to detect a signal of 1KHz the sample rate must be at least 2KHz, and it follows further that the detecting system must be capable of such a sample rate.

These are serious problems, and the study of tooth sounds is further complicated because the sensors are not normally placed directly on the teeth but are attached to the skin and therefore detect sounds after they have been damped by the periodontal membrane and have passed through the bone of the alveolus and skull.[10] The extent to which this modifies the true sound envelope does not appear to have been documented in the literature, and the problem of aliasing does not appear to have been addressed in spite of the numerous reports of studies of these sounds. Further, the range of frequencies produced by the teeth in collision does not appear to have been definitively established by previous workers, and there appears to have been little attempt to develop laboratory models to separate the various aspects of this complex problem.

It is clear from the foregoing arguments that an essential first step must be the determination of this frequency range, not least because without this knowledge it is not possible to select equipment capable of reliably capturing the transient signals involved. It is also clear that the complex *in vivo* problem should be separated into a series of simple laboratory models as a first stage in developing a proper understanding of the processes involved.

A series of such *in vitro* model collisions was therefore undertaken, initially with hard simple substrates but ultimately using extracted teeth, beginning with either freely suspended or rigidly mounted materials and then attempting to model the periodontal membrane, with the intention of not only determining the frequency range produced by the teeth in collision but also demonstrating that standard microcomputers are capable of reliably capturing all frequencies within this range.

EXPERIMENT 4.1.

A SIMPLE COLLISION BETWEEN FREELY SUSPENDED LABORATORY MATERIALS

There are many factors to be considered in the development of a satisfactory laboratory model of *in vivo* dental sounds. Among the most important of these are not only a proper simulation of the moment of tooth contact, but also the correct mounting of the teeth that are in collision. For example, in simpler models the teeth may be regarded as rigidly mounted in bone, whereas a more complex model would take account of the fact that between tooth and bone there is a resilient periodontal membrane. Since laboratory models have not been reported in the dental literature to any extent, much of the significance of tooth collisions and mounting is unexplained. For instance Watt only examined the gross results of metal to metal collisions.[26] It was therefore considered essential in these studies to begin with the simplest possible model where the objects in collision were freely suspended rather than mounted. On the assumption that complex bodies such as teeth might produce correspondingly complex collision signals, it was further considered necessary that initial studies should involve simple relatively homogeneous non-biological materials.

METHOD

Materials selected for these studies are shown in table 4.1, and all experiments were carried out at ambient temperature. A vibration transducer was attached to one object (the anvil) by Model Cement at a point diametrically opposite the intended point of collision, and also by a fine cable to a storage oscilloscope for signal capture, as shown in Plate 4.1. The anvil was freely suspended by 30cm of this cable,

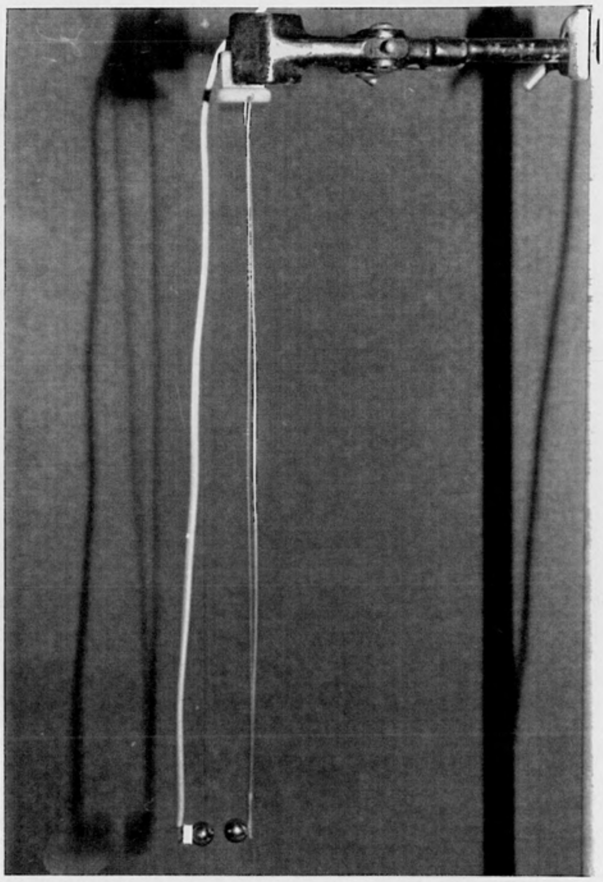


Plate 4.1 Freely suspended steel spheres, one with accelerometer attached.

and was struck by the second object, (the hammer) attached by Model Cement to a 30cm pendulum tapper swinging through an arbitrary small arc chosen not to cause sensor overload. Collision signals were captured at a timebase of 1ms, equivalent to a sampling rate of 100 per millisecond, and satisfactory signals were dumped directly to a dot matrix printer.

TABLE 4.1

Materials in free collision.

EXPERIMENT	ANVIL	HAMMER	DIAMETER
4.1.a	glass	glass	15mm
4.1.b	steel	steel	10mm
4.1.c	plastic	plastic	25mm
4.1.d	glass	plastic	15/25mm
4.1.e	plastic	glass	25/15mm
4.1.f	plastic	plastic	35/35mm

RESULTS

The results of experiment 4.1 are shown in figs 4.1.a-f as oscilloscope screen dumps corresponding to experiments 4.1.a-f.

DISCUSSION

All experiments showed a similar signal pattern consisting of a single pulse followed by a decaying frequency of 12.5KHz, consistent with the expectation of an initial forced pulse followed by a residual vibration of the anvil. In view of the range of materials used, a common frequency of 12.5KHz might seem surprising. However according to the sensor's specification this is its natural resonant frequency, suggesting strongly that the decaying frequency observed in all cases is that of the sensor and not the material proper.

It is of course possible that the 12.5KHz signal is the result of a much higher frequency being aliased by the oscilloscope. The chosen oscilloscope sampling rate of 100 per millisecond can reliably capture frequencies up to 50KHz, but any higher frequencies would inevitably be aliased. As previously discussed (chapter 3), the effect of aliasing is sample-rate dependent so that a change in sample rate produces a change in aliasing. However, when faster oscilloscope sample rates up to 1000 per millisecond were used the captured signal did not change, confirming the 12.5KHz frequency as a true component of the captured signals. In view of its appearance in all experiments, regardless of materials used, it was therefore assumed to be the natural resonant frequency of the sensor.

It also appears that in all cases the freely suspended objects have minimal natural vibrations and only show the forced pulse as the anvil is momentarily deformed by the impact. It is no surprise therefore that in a collision between different materials (figs 4.1.d and 4.1.e) it does not appear to matter which material is the anvil. Similarly it is not surprising that object size appears to be unimportant in determining signal characteristics (figs 4.1.c and 4.1.f).

Any differences between the various collisions in figs 4.1.a-f appear to involve only the duration of the initial pulse. For example, a glass/glass collision in fig 4.1.a produces a short initial pulse whereas a plastic/plastic collision in fig 4.1.c shows an initial pulse approximately four times longer. Presumably this reflects a difference in mechanical properties such as hardness or elastic modulus, although other effects such as surface texture may also be involved. Interestingly, collisions between dissimilar materials appear to show an initial pulse with the characteristics of one of the materials rather than some intermediate value. For example the glass/plastic collisions in figs 4.1.d and 4.1.e show an initial pulse similar to the plastic/plastic collisions in figs 4.1.c and 4.1.f. This may be important in gnathosonic studies where teeth collide with restorative materials, but the generality of the observation and its rationale require further study.

In any event, the captured signals are unlike reported gnathosonic traces in the literature.[16,17,19,20] In particular they are too simple, and do not display the complexity of true *in vivo* signals, suggesting that either a model with freely suspended objects is too simplistic or that simple laboratory materials are not representative of biological structures such as teeth.

In order to address these latter points it was considered necessary to extend the study to include freely suspended extracted teeth. Before doing so however, it was noted that in cases where the arbitrary pendulum arc before collision was too large, the sensor went into overload, the effect being to 'clip' the signal amplitude at a value fixed by the sensor characteristics. Since this might occur in all future studies it was considered appropriate to carry out a limited investigation of the effect of sensor overload on the captured signal, prior to a study with extracted teeth.

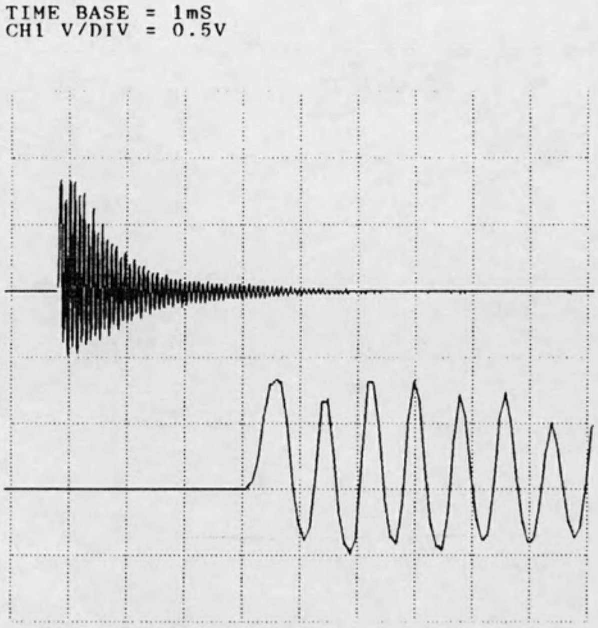


Fig.4.1.a. Screen dump of free glass/glass collision.
Upper trace: Forced and natural resonance.
Lower trace: Upper trace with 10x expanded timescale.

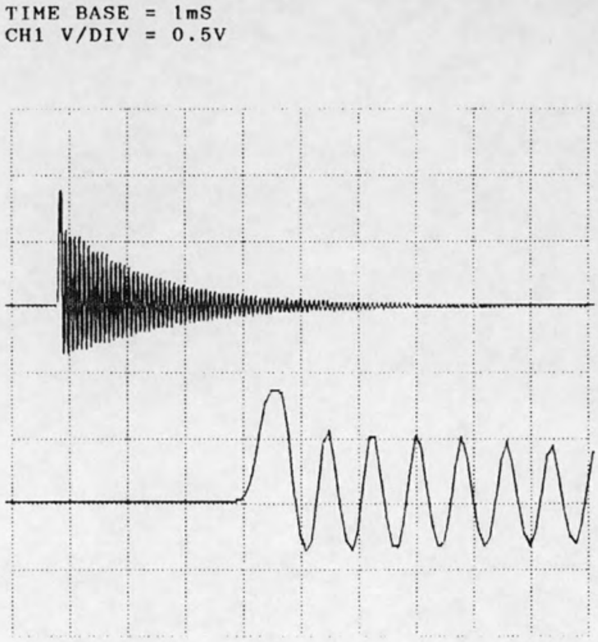


Fig.4.1.b. Screen dump of free steel/steel collision.
Upper trace: Forced and natural resonance.
Lower trace: Upper trace with 10x expanded timescale.

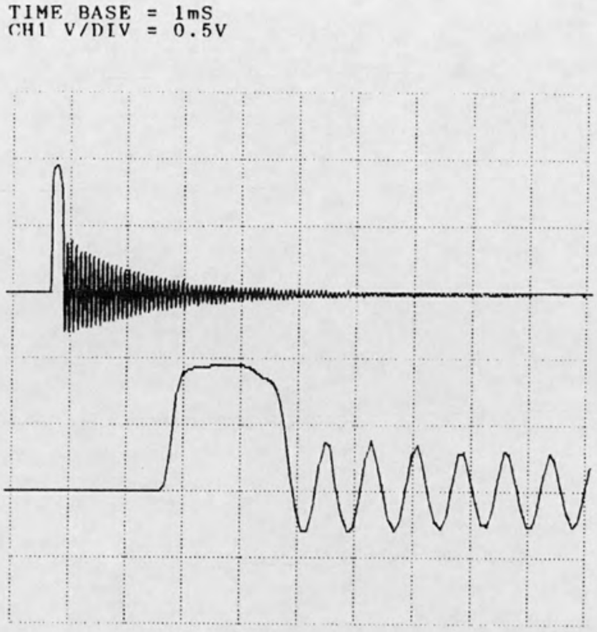


Fig.4.1.c. Screen dump of free plastic/plastic collision.
Upper trace: Forced and natural resonance.
Lower trace: Upper trace with 10x expanded timescale.

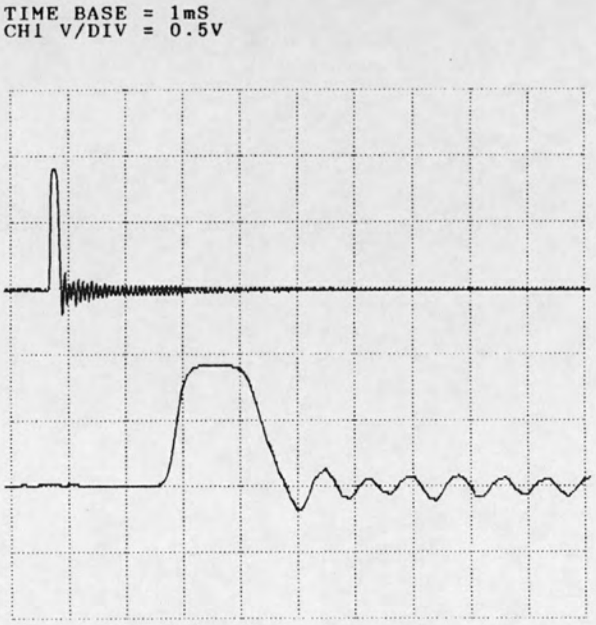


Fig.4.1.d. Screen dump of free glass/plastic collision.
Upper trace: Forced and natural resonance.
Lower trace: Upper trace with 10x expanded timescale.

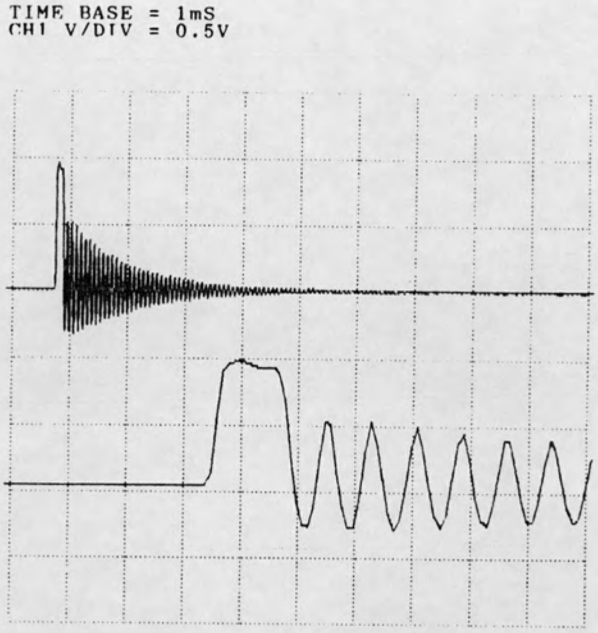


Fig.4.1.e. Screen dump of plastic/glass collision.
Upper trace: Forced and natural resonance.
Lower trace: Upper trace with 10x expanded timescale.

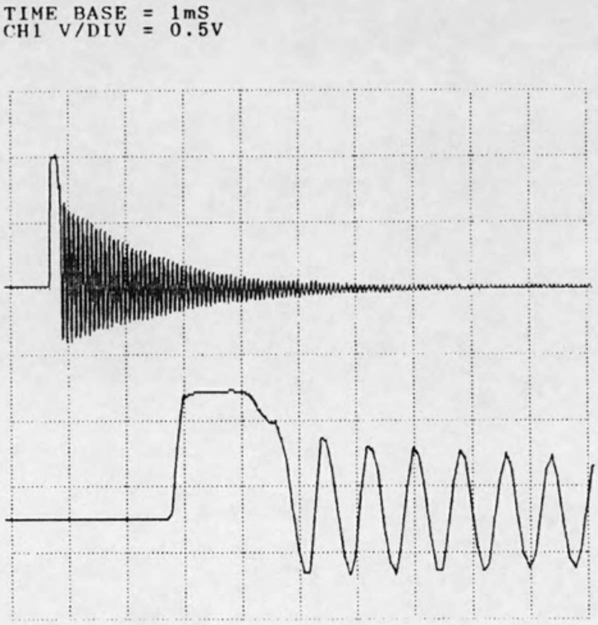


Fig.4.1.f. Screen dump of plastic/plastic collision.
Upper trace: Forced and natural resonance.
Lower trace: Upper trace with 10x expanded timescale.

EXPERIMENT 4.2.

THE EFFECT OF SENSOR OVERLOAD ON THE CAPTURED SIGNAL

METHOD

Experiments 4.1.a-c were repeated until the captured signal exhibited overload with an increasing pendulum arc according to table 4.2.

TABLE 4.2

Materials in free collision.

EXPERIMENT	ANVIL	HAMMER	DIAMETER
4.2.a	glass	glass	15mm
4.2.b	steel	steel	10mm
4.2.c	plastic	plastic	25mm

RESULTS

The results of experiment 4.2 are shown in figs 4.2.a-c as oscilloscope screen dumps corresponding to experiments 4.2.a-c.

DISCUSSION

Overload conditions are problems which affect electrical circuitry and can occur when input signals exceed the working range of the electronic components.

To protect the circuits and subsequent processing of the signals against overload manufacturers frequently incorporate protection circuitry to limit the amplitude of the input frequency. For example, one method is an automatic gain control where the whole signal is attenuated to avoid overload, and another is to electronically 'clip' the signal at a predetermined amplitude. The latter method has been adopted by the manufacturer of the accelerometer used in this study. The 'clipping' effect can be clearly seen in figs 4.2.a-c where the peak of the first wave has been truncated and information lost. Additionally the specification of the sensor shows that the limiting amplitude is not symmetrical, the cut-off points being 1.0V positive and 0.3V negative. The asymmetry is evident in figures 4.2.a-c, complicating any interpretation of overloaded signals. It is further evident that after overload the sensor does not recover in time to properly display the natural 12.5KHz resonant frequency of its active mass. It might be considered that this recovery time could be a method of filtering out the resonant frequency of the accelerometer, but as the whole picture is altered and the initial pulses of the signals do not compare well with those obtained in experiment 4.1, it was concluded that captured signals which overload the sensor should be discarded.

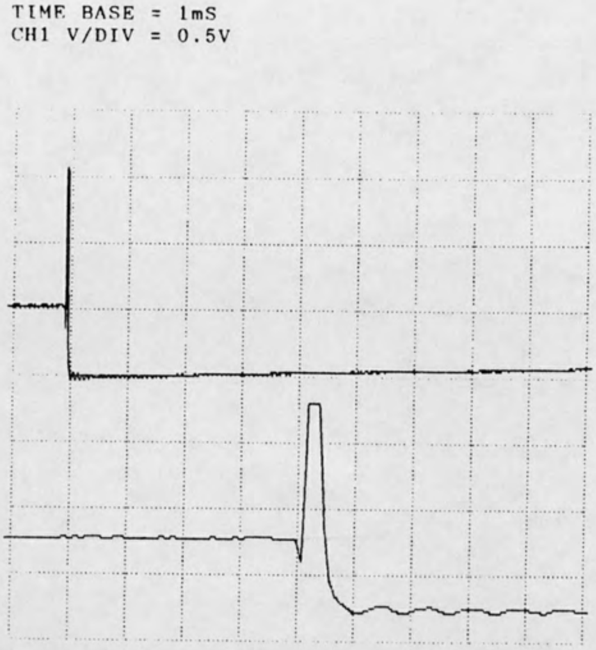


Fig.4.2.a. Screen dump of free glass/glass collision.
Upper trace: Overloaded sensor.
Lower trace: Upper trace with 10x expanded timescale.

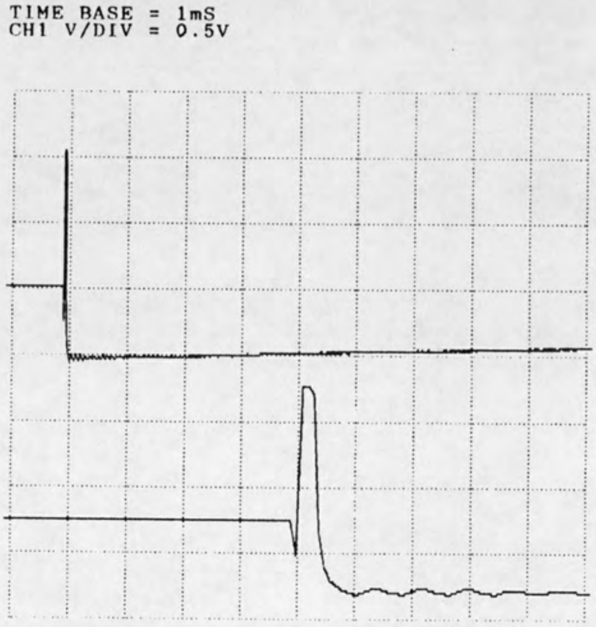


Fig.4.2.b. Screen dump of free steel/steel collision.
Upper trace: Overloaded sensor.
Lower trace: Upper trace with 10x expanded timescale.

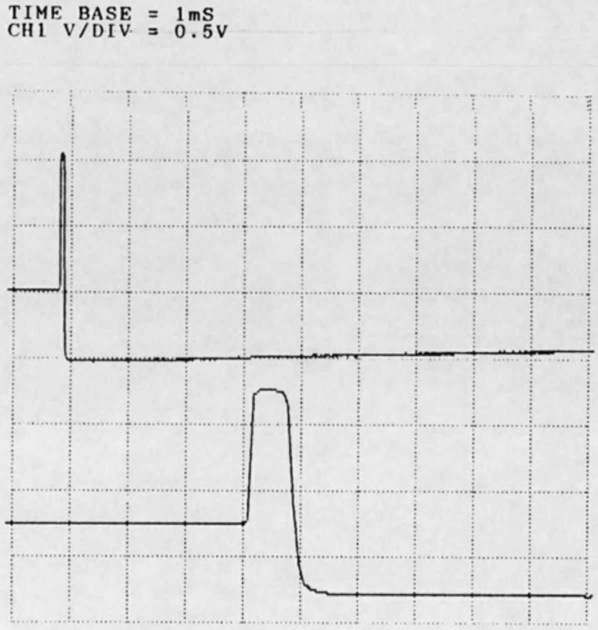


Fig.4.2.c. Screen dump of free plastic/plastic collision.
Upper trace: Overloaded sensor.
Lower trace: Upper trace with 10x expanded timescale.

EXPERIMENT 4.3

A SIMPLE COLLISION BETWEEN FREELY SUSPENDED EXTRACTED TEETH

As the signals captured in experiment 4.1 were dissimilar to *in vivo* gnathosonic traces it was concluded that either a model involving freely suspended objects is too simplistic or simple laboratory materials are not representative of complex biological structures such as teeth. In order to address these points, the study was extended to examine collisions between freely suspended extracted teeth.

METHOD

Crowns of extracted posterior teeth were sectioned at the neck with a water-cooled abrasive disc. A hammer crown was prepared by attaching one of the sectioned crowns to the arm of a 30cm pendulum tapper with Model Cement as described in experiment 4.1. An anvil crown was prepared by truncating one cusp of a sectioned crown with a water-cooled carborundum wheel and fine dental stones. The prepared anvil was then attached to an accelerometer (BU1771 Knowles Laboratories, UK) and suspended in the manner described in experiment 4.1, as shown in Plate 4.2. The hammer and anvil were then brought into collision either cusp-to-cusp (experiment 4.3.a), or cusp-to-flat enamel (experiment 4.3.b) as described in experiment 4.1.

RESULTS

The results of experiment 4.3 are shown in figures 4.3.a and 4.3.b, as oscilloscope screen dumps corresponding to experiments 4.3.a and 4.3.b.

DISCUSSION

A possible complication of *in vitro* modelling of tooth collisions is that no two enamel surfaces are identical, and there might therefore be significant differences between enamel-enamel collisions *in vivo*. Experiment 4.3 was therefore carried out in two parts to provide examples of differing enamel surfaces in collision. It was considered that if differing enamel surfaces showed similar collision traces, it would be reasonable to assume that tooth contacts in general could be compared. Indeed, if this were not the case gnathosonics would fail as a potential clinical technique.

It can be seen from figures 4.3.a and 4.3.b that

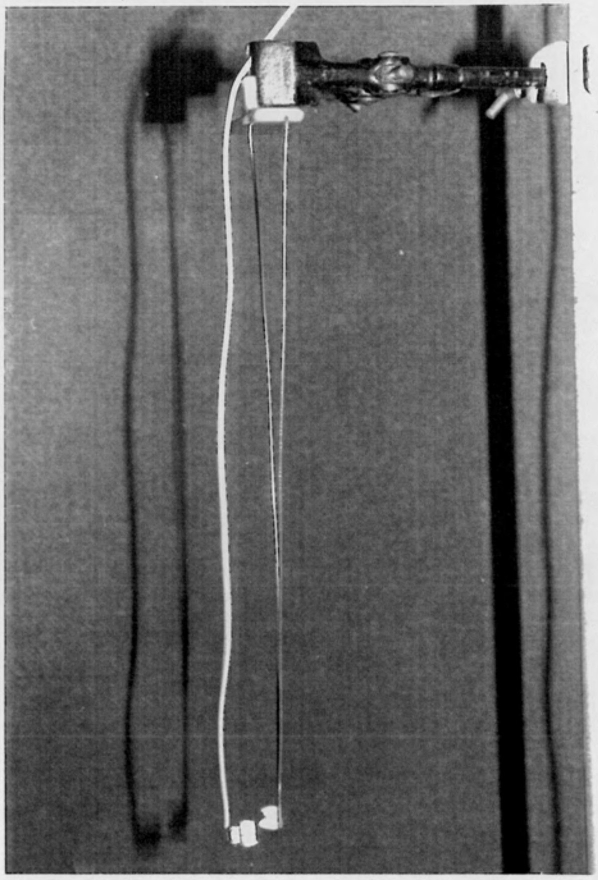


Plate 4.2 Freely suspended crowns, one with accelerometer attached.

the traces from differing enamel-enamel collisions do have a similar pattern, and therefore it can be assumed that the same should apply to enamel-enamel collisions *in vivo*. Furthermore the traces are similar to those of the non-biological materials in experiment 4.1. It would appear reasonable to assume therefore that simple laboratory materials may indeed be a satisfactory model of complex structures such as teeth, at least in freely suspended collisions. Since the traces are unlike published gnathosonic records, this implies that the model is too simplistic and requires modification.

As with experiment 4.1 the signals in figures 4.3.a and 4.3.b appear to consist of an initial pulse followed by a decaying 12.5KHz frequency due to the accelerometer. The appearance of such a 12.5KHz frequency in gnathosonic traces would be inconvenient and might make an accelerometer unacceptable as a transducer. However previous studies in the dental literature indicate that sensors do not show this *in vivo*,[16,17,19,20] suggesting again that the model is too simple. If this frequency is indeed lost *in vivo*, these results suggest that the important frequency may be the initial pulse, which from the first half cycle appears to be in the order of 7KHz. Any hardware designed to capture such signals would be required to resolve this frequency at minimum.

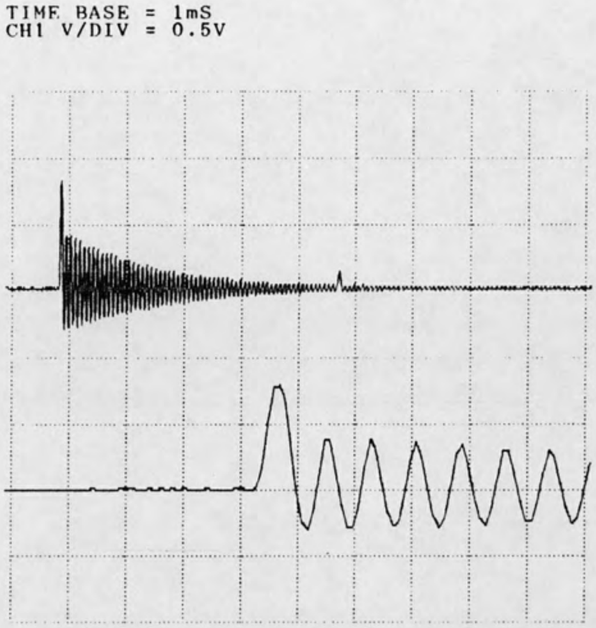


Fig.4.3.a. Screen dump of free enamel/enamel collision.
Upper trace: Cusp anvil and cusp hammer.
Lower trace: Upper trace with 10x expanded timescale.

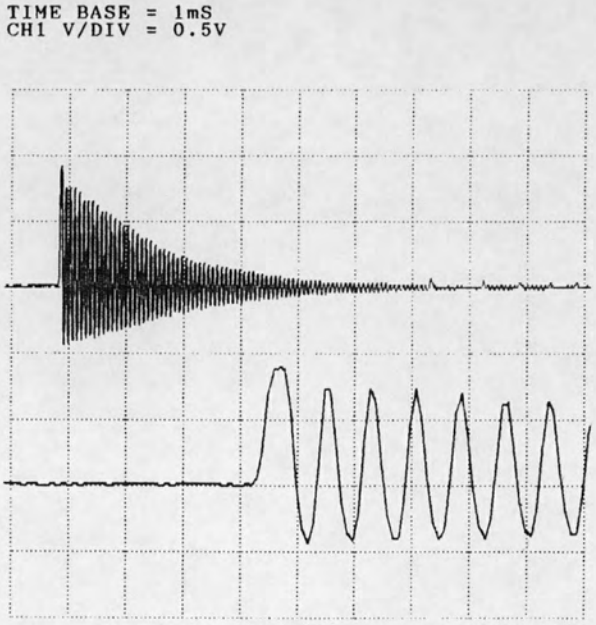


Fig.4.3.b. Screen dump of free enamel/enamel collision.
Upper trace: Flat enamel anvil and cusp hammer.
Lower trace: Upper trace with 10x expanded timescale.

CONCLUSIONS FROM EXPERIMENTS 4.1 AND 4.3.

It would appear from experiments 4.1 and 4.3 that collisions between freely suspended objects exhibit an initial pulse followed by the residual frequency of the sensor, and that any natural resonance of the struck material is too small to be detected. In addition, the variation in the duration of the first pulse suggested that it might be a useful clinical parameter in the assessment of collisions. However, according to the model the resonant frequency of accelerometers might cause problems *in vivo*.

The traces obtained are however unlike published gnathosonic signals, suggesting that the model is too simple. The most obvious difference between this model and the situation *in vivo* is that teeth are not normally freely suspended but are mounted in bone. It was necessary therefore to extend the model to study the effect of fixed anvil mountings.

EXPERIMENT 4.4.

SIMPLE COLLISIONS INVOLVING A FIXED ANVIL

Teeth *in vivo* are anchored in bone, but the anchorage is complex since the teeth are suspended by the periodontal membrane. The simplest condition to model is that of an ankylosed tooth, where the tooth is rigidly fixed in the bone. Therefore as a first and simple model, a series of experiments was carried out where various materials were brought into collision using a rigidly mounted anvil.

METHOD

A series of collisions, 4.4.a-h, was carried out with non-biological materials using the general procedure described in experiment 4.1 according to tables 4.4.a and 4.4.b, except that the anvil was rigidly mounted in a 20Kg bench clamp, as shown in Plate 4.3. Two experiments, 4.4.b and 4.4.f, were repeated five times and the results of each series averaged to determine the reproducibility of signal generation. Experiments 4.4.g and 4.4.h were carried out to compare the effect of light and heavy collisions.

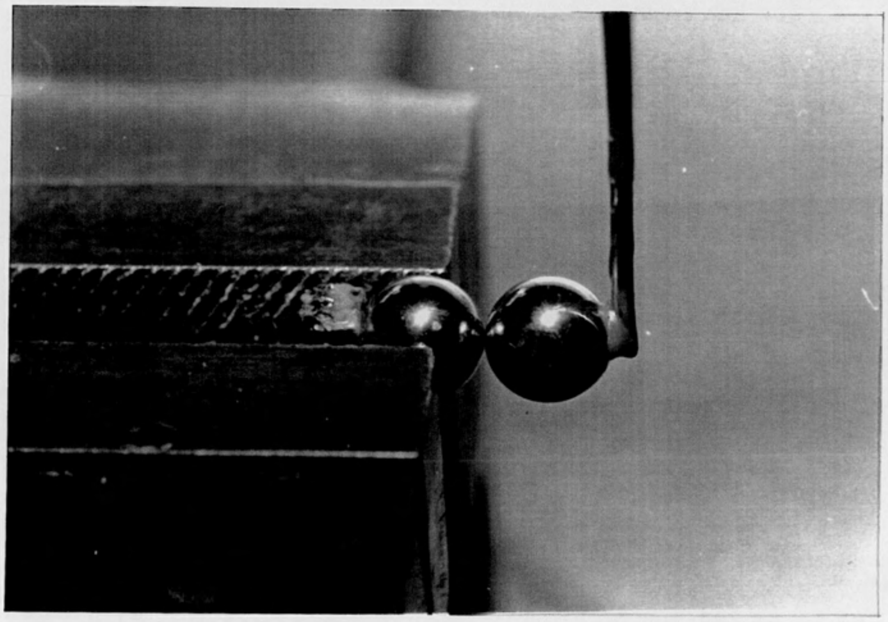


Plate 4.3 One steel sphere with accelerometer attached held in clamp.

TABLE 4.4.a - MATERIALS

Differing materials in collision - fixed anvil.

MATERIAL		DIMENSIONS		MASS
brass	anvil	cylinder	10mm diam.x20mm	12g
plastic	anvil	cylinder	10mm diam.x20mm	1.5g
steel	hammer	sphere	10mm diam.	4g
plastic	hammer	sphere	25mm diam.	9g

TABLE 4.4.b - EXPERIMENTS

EXPERIMENT	ANVIL	HAMMER
4.4.a	brass	steel
4.4.b	as 4.4.a but average of 5	
4.4.c	brass	plastic
4.4.d	plastic	steel
4.4.e	plastic	plastic
4.4.f	as 4.4.e but average of 5	
4.4.g	brass	steel
4.4.h	4.4.g traces overlaid	

RESULTS

The results of experiment 4.4 are shown in figs 4.4.a-h as oscilloscope screen dumps corresponding to experiments 4.4.a-h.

DISCUSSION

The mass of the bench clamp used to mount the anvils was in the order of 20Kg so that the anvil, as part of that mass, became rigidly fixed in comparison to the hammer. It is apparent from figs 4.4.a-f that where one object is fixed, collisions between different materials produce similar signals to those observed in experiment 4.1 for freely suspended spheres, i.e. an initial pulse followed by a decaying 12.5KHz frequency. There are however major differences in the amplitude and duration of the initial pulses, both parameters being reduced. To ensure that experimental errors did not contribute significantly to these differences from experiment 4.1, experiments 4.4.a and 4.4.e were each repeated five times to produce average signals of consecutive collisions, shown in figs 4.4.b and 4.4.f respectively. Single and averaged traces are comparable, suggesting that experimental error is unlikely to have made a significant contribution to the observed differences. However, as with experiment 4.1 these results do not resemble gnathosonic records *in vivo*, suggesting that the model is still too simple to represent the true *in vivo* situation.

It can be seen that the 12.5KHz resonant frequency of the accelerometer is still present in all traces, and the initial pulses have become of this order. This implies that an accelerometer would be of little value if such frequencies were present *in vivo*. However *in vivo* gnathosonic traces do not normally show such frequencies, further suggesting that the model is not a good approximation to the *in vivo* condition.

In experiment 4.1 it was suggested that differences in the initial pulse of collisions between various materials might reflect differences in mechanical properties. It is also possible that differing rates of collision could affect the initial pulse, as presumably the harder the collision the longer the objects would remain in contact. This can be seen in fig 4.4.g where the upper trace shows a light collision and the lower trace a heavier collision. There is an obvious difference in amplitude between the early part of the initial pulses but the accompanying difference in duration, particularly for the first half wave is more clearly shown in fig 4.4.h where the traces have been overlaid. It is also possible that this reduction in amplitude and duration could be due to part of the energy of collision being absorbed by the bench clamp. Both of these factors could occur *in vivo*, suggesting that the duration of the initial pulse is unlikely to be a reliable factor as a parameter in modelling tooth collision. Interestingly however, the estimated frequency of the initial pulse, based on the first quarter wave only, is 6±1KHz in both cases, consistent with the figure for freely suspended objects in experiments 4.1 and 4.3, and again suggesting that the frequency range is approximately 0-7KHz (apart from the 12.5KHz sensor resonance).

It would appear at this stage that the first half of the initial pulse from a collision can vary with differing materials, the force of impact, and the method of mounting. However the residual resonant frequency of the accelerometer can still be seen in the signal, suggesting strongly that the model is still not a good representation of *in vivo* conditions.

However as with experiment 4.1 the results may not represent complex structures such as teeth. Therefore the study was again extended to extracted teeth to determine whether non-biological materials were a good model for the signals generated by tooth collisions.

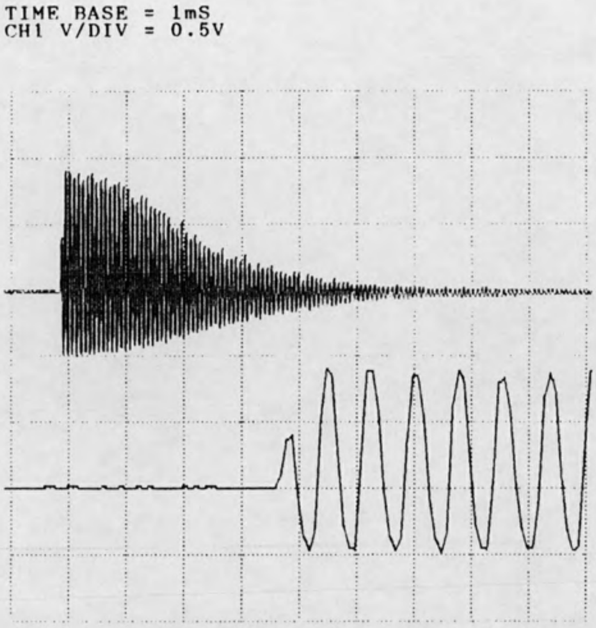


Fig.4.4.a. Screen dump of brass/steel collision.
Upper trace: Brass anvil and steel hammer.
Lower trace: Upper trace with 10x expanded timescale.

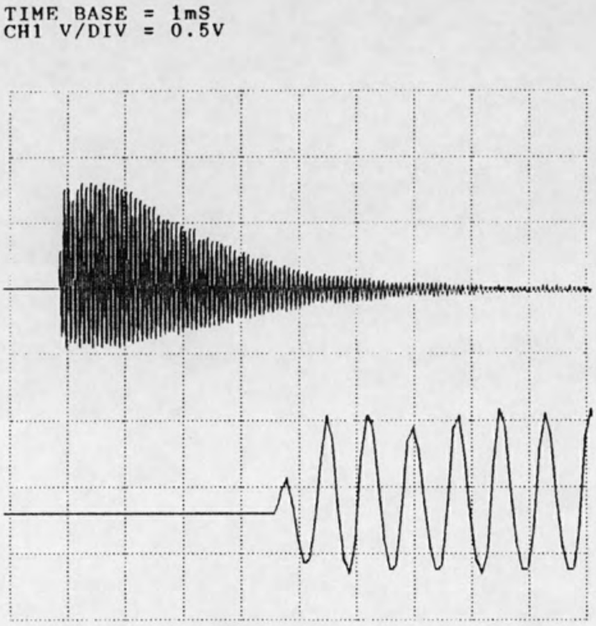


Fig.4.4.b. Screen dump of brass/steel collision.
Upper trace: Average of 5 collisions.
Lower trace: Upper trace with 10x exanded timescale.

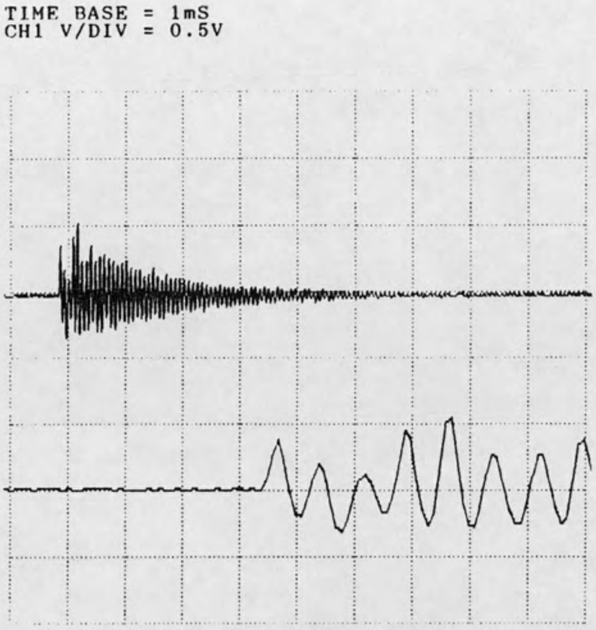


Fig.4.4.c. Screen dump of brass/plastic collision.
Upper trace: Brass anvil and plastic hammer.
Lower trace: Upper trace with 10x expanded timescale.

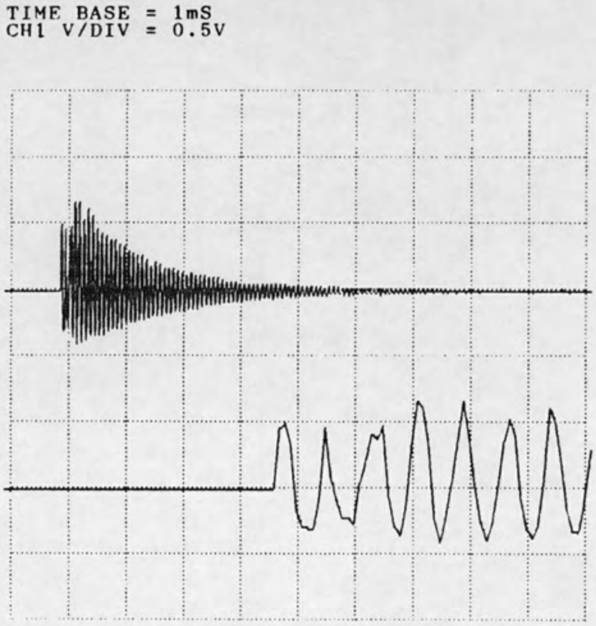


Fig.4.4.d. Screen dump of plastic/steel collision.
Upper trace: Plastic anvil steel hammer.
Lower trace: Upper trace with 10x expanded timescale.

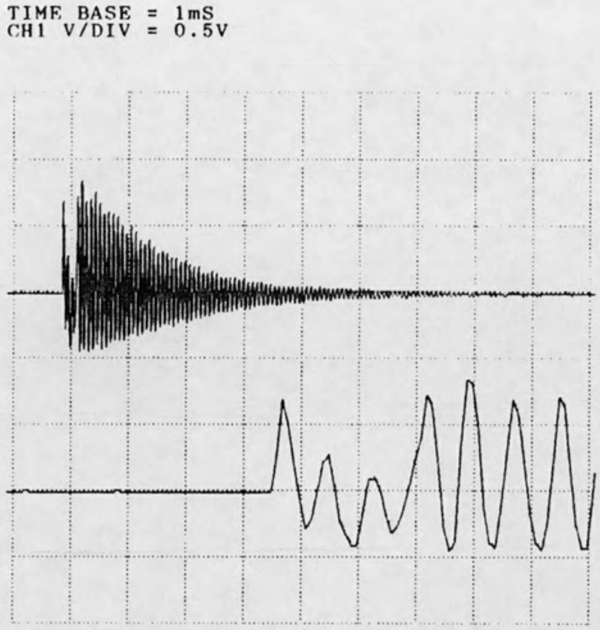


Fig.4.4.e. Screen dump of plastic/plastic collision.
Upper trace: Plastic anvil plastic hammer.
Lower trace: Upper trace with 10x expanded timescale.

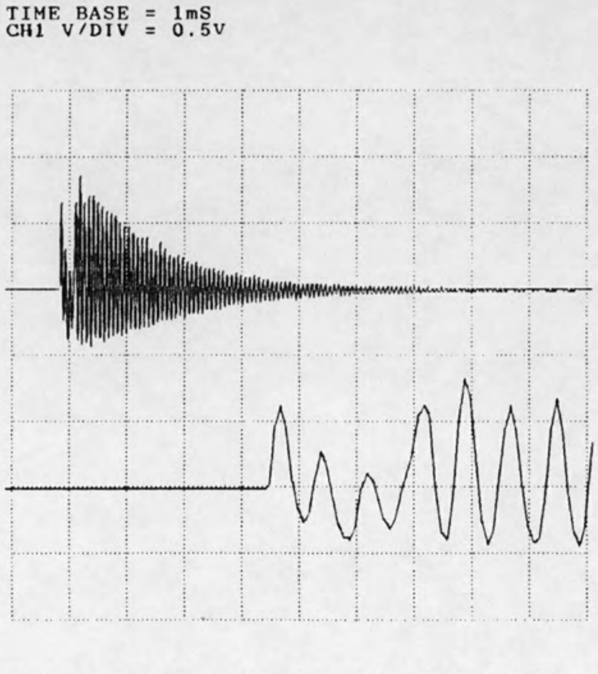


Fig.4.4.f. Screen dump of plastic/plastic collision.
Upper trace: Average of 5 collisions.
Lower trace: Upper trace with 10x expanded timescale.

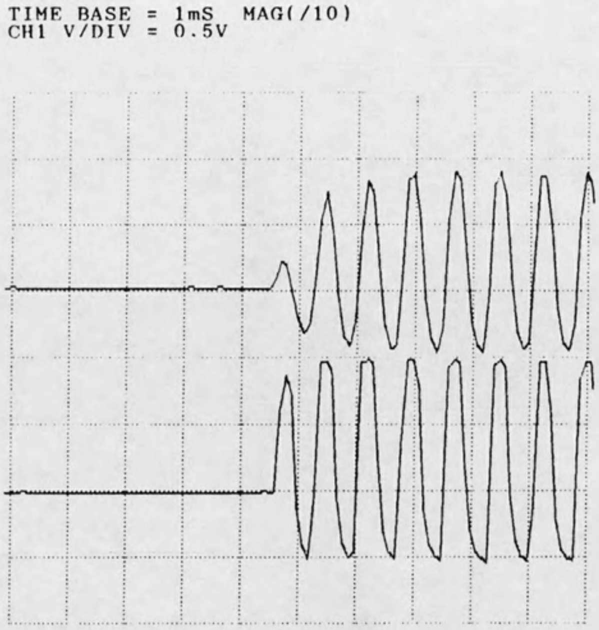


Fig.4.4.g. Screen dump of brass/steel collision.
Upper trace: Hammer with a 0.5cm swing.
Lower trace: Hammer with a 8cm swing.

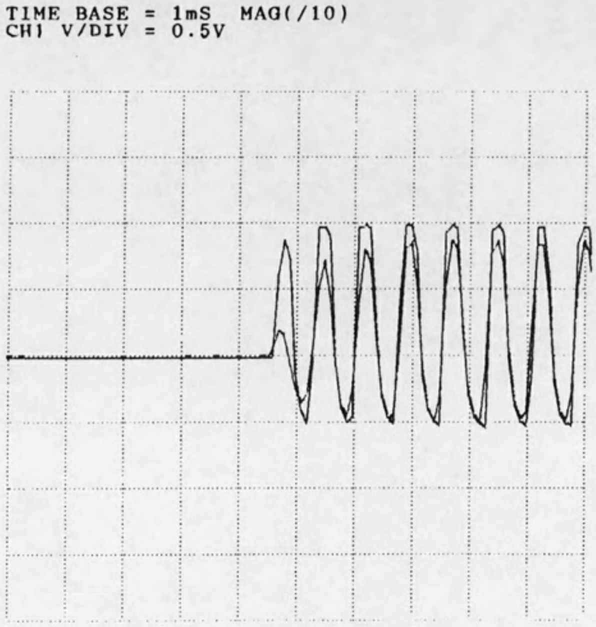


Fig.4.4.h. Screen dump of brass/steel collision.
Traces shown in 4.4.g overlaid for comparison.

EXPERIMENT 4.5.

A SIMPLE COLLISION BETWEEN EXTRACTED TEETH WHERE THE ANVIL TOOTH IS FIXED

METHOD

Collisions were carried out between the crowns of extracted teeth, both cusp-to-cusp (experiment 4.5.a) and cusp-to-flat enamel (experiment 4.5.b), according to the procedure in experiment 4.4, using crowns of teeth prepared as in experiment 4.3.

RESULTS

The results of experiment 4.5 are shown in fig 4.5 as an oscilloscope screen dump. The upper trace shows a cusp-to-cusp collision, and the lower trace a cusp-to-flat enamel collision.

DISCUSSION

It can be seen from figure 4.5 that the traces are similar to those of the non-biological materials in experiment 4.4, reinforcing the earlier suggestion that non-biological materials may be a good model for teeth in such studies. As in experiment 4.4, an initial pulse

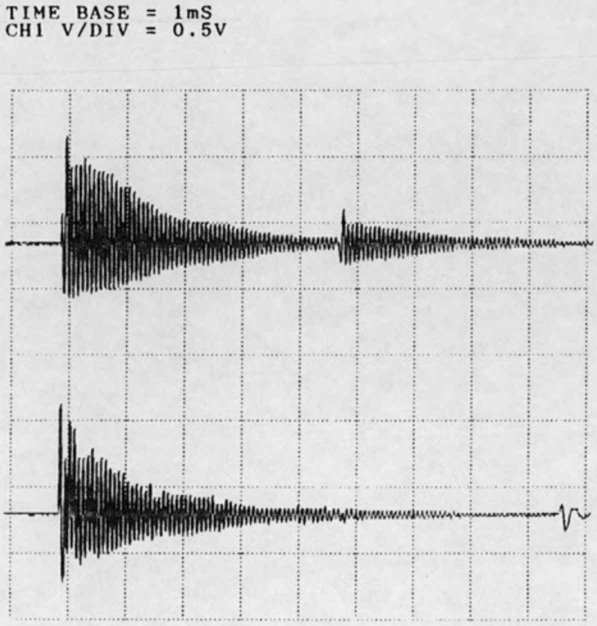


Fig.4.5. Screen dump of enamel/enamel collision.
a) Upper trace: Cusp anvil and cusp hammer.
b) Lower trace: Flat enamel anvil and cusp hammer.

is still followed by a 12.5KHz resonance of the sensor which is not a desirable feature, and the signal does not resemble known *in vivo* records.[16,17,19,20]

GENERAL DISCUSSION OF EXPERIMENTS 4.4 AND 4.5

It would seem that at least two major factors may be operating in the collisions investigated thus far, i.e. the mechanical properties of the materials and the force of collision or impact. It could of course be argued that the signals observed with a fixed anvil might include a spurious contribution from the bench clamp itself. For example, a bell, no matter how heavy, has a particular frequency at which it will resonate and will ring upon being struck, as the pulse generated by the impact of the hammer contains all possible frequencies and must therefore contain the resonant frequency of the bell.

In contrast a large metal clamp, of the order of 20Kg, usually has no resonant frequency particularly when fixed to a bench. Such an anvil could therefore only transmit the shock waves produced by the striking hammer, as the forced or natural vibrations of the anvil would be eliminated by its mass. It is reasonable to assume therefore that the shock waves pass through the anvil and cause the active mass of the accelerometer to vibrate, this being the only part of the whole system which is capable of free movement. Thus after the initial pulse forced by the shock wave, the active mass continues to vibrate at the expected frequency of approximately 12.5KHz. This would not be desirable in the clinical situation because the vibrations are generated by the sensor, not the teeth.

Experiments 4.4 and 4.5 suggest that the initial pulse, which appears to be in the order of 6±1KHz, may be the significant part of the trace. However, the results still do not accord with published gnathosonic records,[16,17,19,20] the most likely reason being that the model is not sufficiently analogous to the teeth in their sockets, as no movement of the anvil was permitted and therefore no account taken of the soft tissue of the periodontium. The model was therefore altered to investigate the changes which might be brought about by allowing the anvil a degree of movement.

EXPERIMENT 4.6.

COLLISIONS WITH THE ANVIL SET IN A RESILIENT MOUNTING

INTRODUCTION

To improve the *in vitro* model and provide a system more closely resembling a tooth fixed in the bone by the periodontal membrane, a further series of experiments was undertaken in which a resilient material was placed between the anvil and its mounting to simulate the periodontium.

METHOD

A series of collisions, 4.6.a-d was carried out in a similar manner to experiment 4.4, except that a natural rubber sleeve 13mm wide by 1mm thick was interposed between the anvil and its fixed mounting as shown in Plate 4.4. The experiments were carried out according to tables 4.6.a and 4.6.b, using specimens from experiment 4.4.

TABLE 4.6.a - MATERIALS

Materials in collision - resilient mounting.

MATERIAL		DIMENSIONS		MASS
brass	anvil	cylinder	10mm diam.x20mm	12g
plastic	anvil	cylinder	10mm diam.x20mm	1.5g
steel	hammer	sphere	10mm diam.	4g
plastic	hammer	sphere	25mm diam.	9g

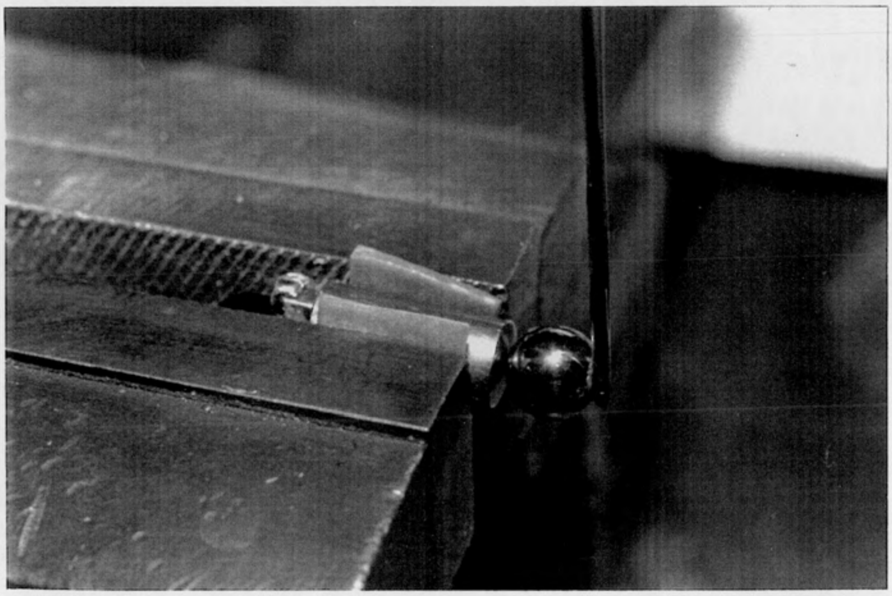


Plate 4.4 Anvil mounted resiliently in the clamp.

TABLE 4.6.b - EXPERIMENTS

EXPERIMENT	ANVIL	HAMMER
4.6.a	brass	steel
4.6.b	brass	plastic
4.6.c	plastic	steel
4.6.d	plastic	plastic

RESULTS

The results of experiment 4.6 are shown in figs 4.6.a-d as oscilloscope screen dumps corresponding to experiments 4.6.a-d.

DISCUSSION

The periodontal membrane suspends a tooth in its socket so that axial occlusal forces are transmitted to the lamina dura as tensile stresses. The membrane contains fibrous and cellular tissue, vessels and fluid which results in a visco-elastic behaviour.[18,58] To modify the laboratory model to simulate the presence of the periodontium in the simplest manner, a layer of natural rubber was interposed between the anvil and its mounting. Natural rubber is not a visco-elastic material but being resilient allows a degree of independent movement of the anvil, which will then act as a damped mass spring system, where the object is the mass, the rubber mounting sleeve a damped spring and the bench clamp the solid foundation upon which the system is mounted. The rubber mounting also introduces into the experiments the factor of natural vibration of the object as a whole, independently of the mounting. The first pulse is assumed to result from a forced movement of the anvil, followed by a much lower natural vibration of both the anvil and resilient sleeve. Experiments 4.6.b-d show what appear to be a number of 'initial' pulses presumably caused by 'chattering' or multiple strikes between the hammer and the vibrating anvil before final separation after the collision. These multiple collisions might be analogous to the clinical situation where there can be a rapid succession of tooth contacts as a disrupted occlusion engages on closure of the jaws.

The overall signal envelope thereafter is of low amplitude, most probably due to the inertia of the mass and the presumed damping of the elastic collar. The waves are of much lower frequency compared to those of the natural frequency of the sensor and are in the order of 1KHz or less. They can be seen in all the upper traces in figures 4.6.a-d.

The resonant frequency of the accelerometer is in the order of 12.5KHz, and complicates the whole signal, appearing like a carrier wave for the much lower frequency vibrations. This is particularly noticeable for the metal-to-metal collision in fig.4.6.a, where the shock wave is sufficient to cause considerable excitation of the active mass of the sensor, but the effect is less marked in figures 4.6.b-d where plastic is involved in collisions. However the 12.5KHz component is well removed from the lower frequencies, suggesting that it could be readily filtered electronically.

One interesting feature of these traces is that the initial pulse appears to be more similar to those produced by freely suspended anvils than rigidly fixed anvils. This may at first appear to be a retrograde step after experiments 4.4 and 4.5, but in the latter experiments the anvil was immovable. Now that the anvil is allowed a degree of movement, the reappearance of variations in the initial pulse similar to those in experiment 4.1 is welcome as it might contain information which could be used as a clinical parameter.

Apart from metal-to-metal collisions the traces are now more recognisable as having the form of a gnathosonic record *in vivo*.[16,17,19,20] The traces appear extended or stretched in comparison to a normal trace, but this is a characteristic of the oscilloscope

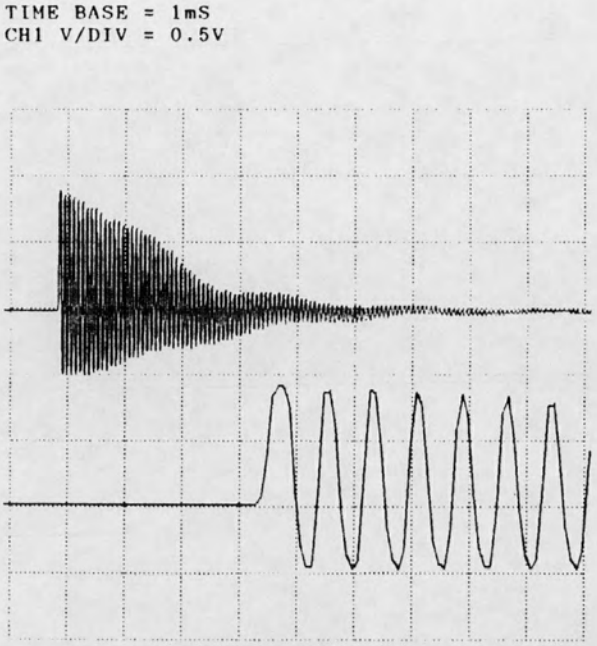


Fig.4.6.a. Screen dump of brass/steel collision.
Upper trace: Resiliently mounted anvil/steel hammer.
Lower trace: Upper trace with 10x expanded timescale.

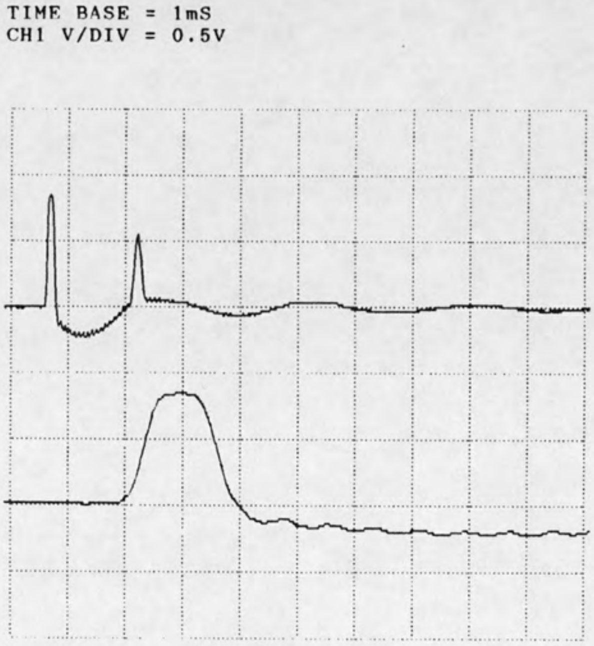


Fig.4.6.b. Screen dump of brass/plastic collision.
Upper trace: Resiliently mounted anvil/plastic hammer.
Lower trace: Upper trace with 10x expanded timescale.

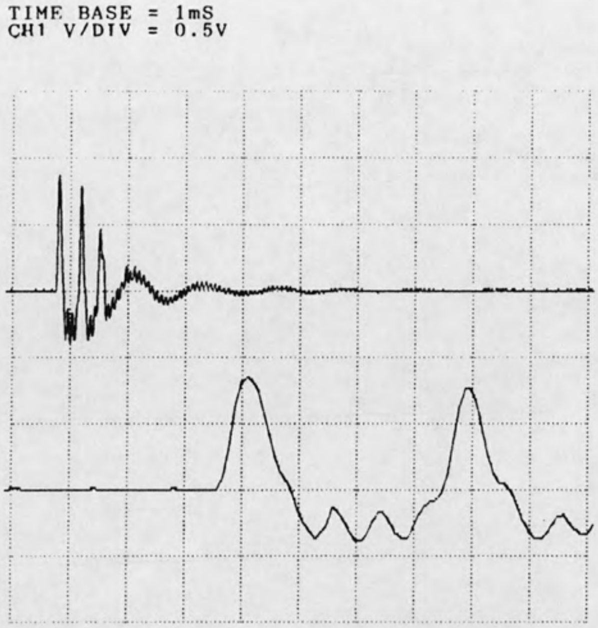


Fig.4.6.c. Screen dump of plastic/steel collision.
Upper trace: Resiliently mounted anvil/steel hammer.
Lower trace: Upper trace with 10x expanded timescale.

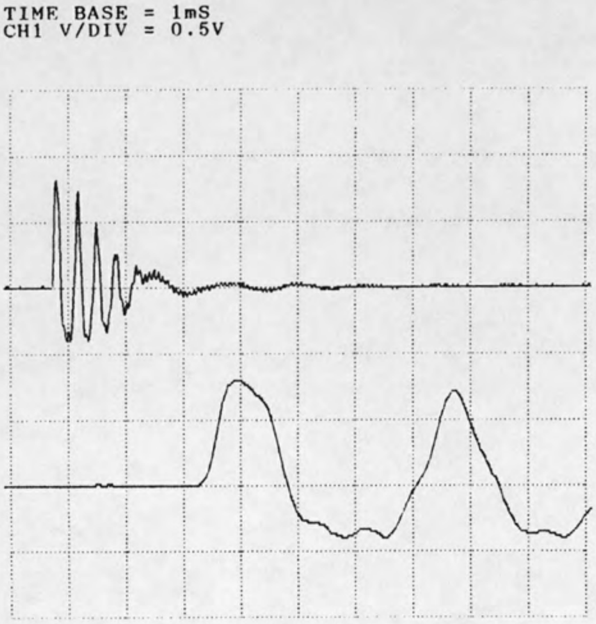


Fig.4.6.d. Screen dump of plastic/plastic collision.
Upper trace: Resiliently mounted anvil/plastic hammer.
Lower trace: Upper trace with 10x expanded timescale.

display and has no physical significance. The observed frequencies in figures 4.6.a-d appear to be in the range 0-12.5KHz. If the 12.5KHz resonance of the accelerometer is excluded, the range reduces to 0-6±1KHz as in all previous experiments, suggesting that hardware developed to capture such signals must be capable of resolving at least this frequency range. As the resonance of the accelerometer is largely suppressed by mounting the anvil in a resilient material, an accelerometer would appear to be a reasonable sensor to employ for the frequencies produced by the collisions under study, provided always that these observations are repeated *in vivo*.

As with previous experiments involving collisions between non-biological materials, this study was then extended to include damped collisions between extracted teeth.

EXPERIMENT 4.7.

COLLISIONS WITH EXTRACTED TEETH IN A RESILIENT MOUNTING

METHOD

Collisions were carried out between the crowns of extracted teeth, both cusp-to-cusp (experiment 4.7.a) and cusp-to-flat enamel (experiment 4.7.b) following the same procedure as experiment 4.5 except that a natural rubber sleeve 1mm thick was interposed between the anvil and its fixed mounting as described in experiment 4.6.

RESULTS

The results of experiment 4.7 are shown in figures 4.7.a and 4.7.b as oscilloscope screen dumps corresponding to experiments 4.7.a and 4.7.b.

DISCUSSION

It can be seen from figures 4.7.a and 4.7.b that the traces are similar to those of the non-biological materials in experiment 4.6. This is in agreement with all previous observations, and again suggests strongly that simple non-biological materials may be used as a substitute for teeth for *in vitro* gnathosonic studies. In addition, Figures 4.7.a and 4.7.b resemble extended or stretched traces of a clinical tooth contact, suggesting that the introduction of a resilient layer provides a better simulation of the *in vivo* situation.

Most importantly, the traces produced by cusp-to-cusp and cusp-to-flat enamel collisions are indistinguishable (figures 4.7.a and 4.7.b respectively), suggesting that collisions between enamel surfaces *in vivo* may similarly be indistinguishable. Indeed, without this factor the whole concept of gnathosonics as a method of assessing the quality of the occlusion would fail.

It can be seen from figures 4.7.a and 4.7.b that a 12.5KHz frequency is still present, although of such a low amplitude that the signal is no longer confused, and the signal proper can be readily discerned.

Experiments 4.1-4.5 have considered the possibility of using the initial pulse as a clinical parameter. In experiments 4.1-4.3 it was suggested that the initial pulse might contain useful information, but in experiments 4.4 and 4.5, using a refined *in vitro* model it was apparent that the initial pulse might in fact be unreliable as such a parameter. It can be seen in figures 4.7.a and 4.7.b that the introduction of a resilient mounting has not only further modified the initial pulse but distorted its symmetry. The initial pulse would therefore appear to be dependent on a number of factors, the natures of which are unclear at this time. Further experimentation would be required to assess the usefulness or otherwise of the initial pulse as a clinical parameter.

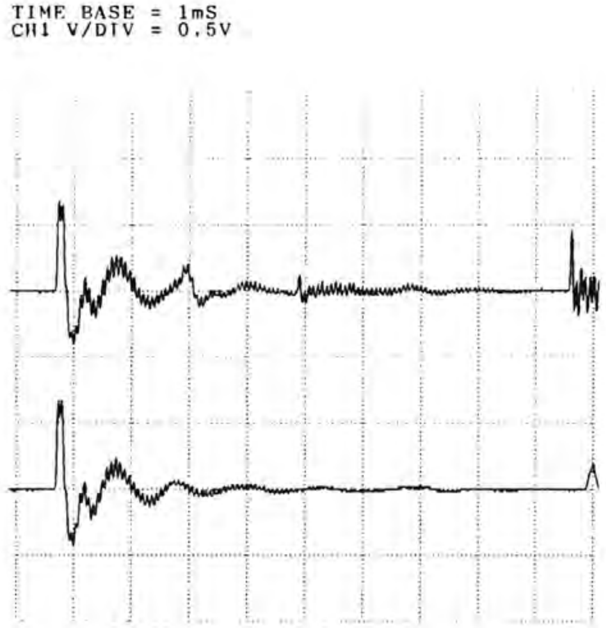


Fig.4.7.a.Screen dump, resiliently mounted anvil.
Upper trace: Cusp to cusp with a slide after collision.
Lower trace: A second collision compared.

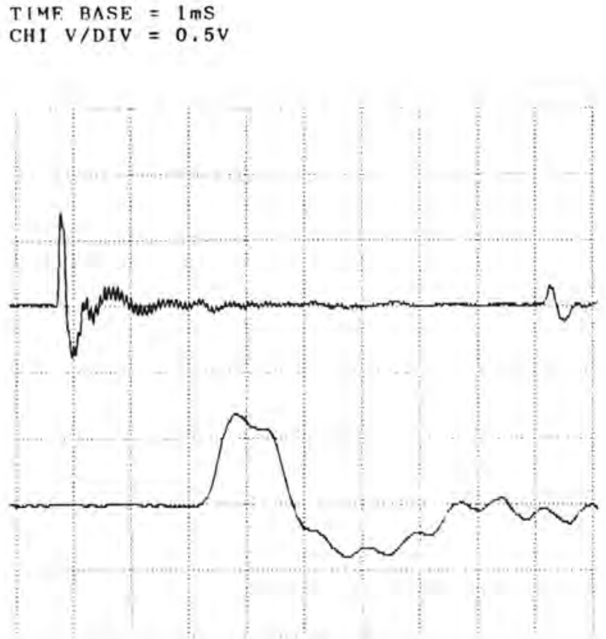


Fig.4.7.b. Screen dump, resiliently mounted anvil.
Upper trace: Flat enamel anvil and cusp hammer.
Lower trace: Upper trace with 10x expanded timescale.

The initial pulse however, is important in determining the frequency range of the collision signal, but its asymmetry in figures 4.7.a and 4.7.b implies that its frequency cannot be reliably determined from the first half cycle as was carried out in earlier experiments. Instead, a closer approximation may be made using the first quarter cycle or rise time of the initial pulse, from which the frequency of the initial pulse again appears to be in the order of 6±1KHz, in agreement with previous observations in this series. As observed in experiment 4.6 for non-biological materials, the remainder of the signal in figures 4.7.a and 4.7.b has a frequency in the order of 1KHz or less, providing yet further evidence that non-biological materials are a good model for teeth. The critical range for any hardware selected to capture the sound of tooth collisions should therefore be at least from 0-7KHz, implying a minimum sample rate of at least 14KHz.

GENERAL DISCUSSION OF EXPERIMENTS 4.6 AND 4.7.

These damped models are an attempt to provide a closer simulation of one tooth being struck by another on closure of the jaws, or being percussed by an instrument. It could however still be argued that the collisions between simple substances in experiment 4.6 may not be a good model for the teeth which have a complex internal microstructure. Surprisingly the experiments do show an overall similarity suggesting that non-biological models may be used to assist in the understanding of collisions between the much more complex materials of which teeth are composed.

Experiments 4.6 and 4.7 show initial pulses similar to those obtained using freely suspended materials (experiments 4.1-4.3). The 12.5KHz resonant frequency of the accelerometer observed in experiments 4.1-4.5 is considerably reduced in amplitude and appears like a low amplitude carrier wave for the lower residual frequency of the anvil (figures 4.7.a and 4.7.b). The range of frequencies, excluding the 12.5KHz, remains in the order of 0-6±1KHz, further suggesting that non-biological materials may be a good model for teeth.

Unlike experiments 4.1-4.5, it now appears that an accelerometer might be an acceptable sensor for tooth collisions *in vivo*, but it would be preferable if the residual resonance could be further reduced. Published gnathosonics with accelerometers in fact show no such resonance, suggesting that the model requires further refinement.

A possible criticism of the model is that the elastic mounting which damps the vibrations of the anvil was chosen arbitrarily and is unlikely therefore to exactly model the periodontal membrane. An investigation of alternative materials is outside the scope of this initial study, but would form a suitable basis for any future work, which should include direct measurement of the mechanical properties of the periodontal membrane.

There is, however, a more obvious limitation to the current model in that the sensor is mounted directly on the surface of the anvil. However in clinical work the sensor is most frequently mounted on the forehead, or in some other convenient position where tissues overlaying bone are thin.[11,12] In terms of the model, this would imply that there should also be a resilient layer between the anvil and the sensor, whereas in experiments 4.1-4.7 the sensor has always been directly attached to the anvil. It was therefore considered necessary to modify the model in this way in order to provide a closer approximation to *in vivo* conditions, in the expectation that the residual 12.5KHz sensor resonance might become insignificant, as already observed in published gnathosonic traces.[16,17,19,20]

EXPERIMENT 4.8.

COLLISIONS BETWEEN CROWNS OF TEETH WHERE THE ANVIL IS RESILIENTLY MOUNTED AND THE SENSOR RESILIENTLY MOUNTED ON THE ANVIL

INTRODUCTION

The model in experiment 4.7 represented a tooth mounted in bone with a resilient medium to simulate the periodontal membrane. However, although the model provided collision signals resembling those observed *in vivo*, a residual 12.5KHz frequency due to sensor resonance was still evident. This is not observed *in vivo*, a possible reason being that in clinical gnathosonic procedures a sensor is normally mounted on the forehead or zygomatic area and not directly onto a tooth. The model was therefore further modified to accommodate this by adding a resilient layer between the sensor and anvil to simulate the effect of tissues interposed between the teeth and the sensor.

METHOD

Collisions were carried out between the crowns of extracted teeth, both cusp-to-cusp (experiment 4.8.a) and cusp-to-flat enamel (experiment 4.8.b), following the same procedure as experiment 4.7 except that a 1mm layer of natural rubber was interposed between the sensor and the anvil, affixed to each by Model Cement, as shown in Plate 4.5.

RESULTS

The results of experiment 4.8 are shown in figures 4.8.a and 4.8.b as oscilloscope screen dumps corresponding to experiments 4.8.a and 4.8.b, and are overlaid for comparison in figure 4.8.c.

DISCUSSION

It is clear from figures 4.8.a and 4.8.b that introducing a resilient layer between the crown of the anvil tooth and the sensor appears to produce a further reduction in excitation of the resonant frequency of the sensor. The traces now resemble stretched *in vivo* signals and, as has been observed in all previous experiments with teeth, there is no apparent difference between cusp-to-cusp and cusp-to-flat enamel collisions. This can be clearly seen in figure 4.8.c where 10x expanded traces of experiments 4.8.a and 4.8.b have been overlaid for comparison. The implication is that enamel collisions *in vivo* can be compared with each other. These observations are remarkable considering the

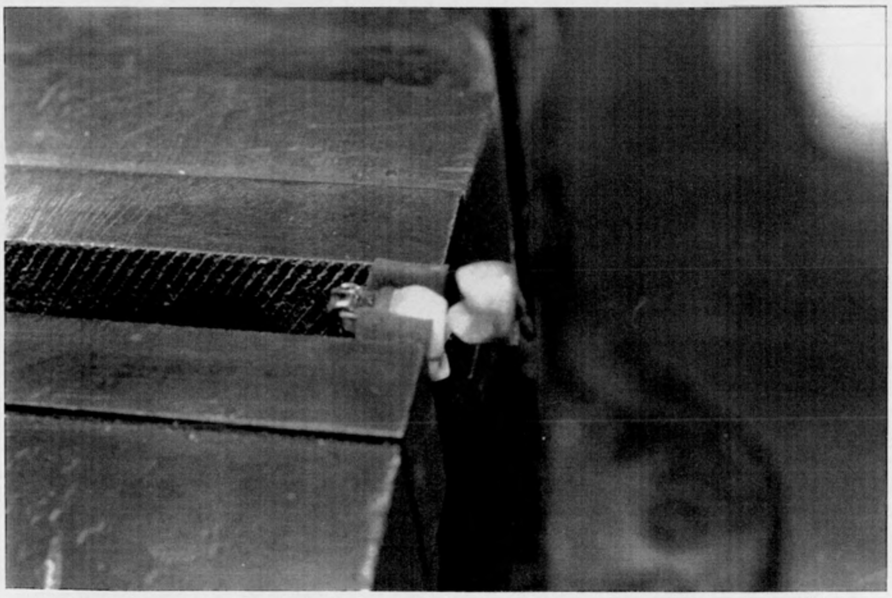


Plate 4.5 Natural rubber between crown and sensor, the crown is resiliently mounted in the clamp.

simplicity of the model in comparison to the physiological and anatomical complexities of the situation *in vivo*.

The similarity with known gnathosonic signals suggests strongly that the model is a good representation of *in vivo* conditions, although undoubtedly further refinements are still possible. It follows from this that an accelerometer should be an acceptable sensor for *in vivo* studies, and indeed such a sensor has already given excellent results when used on patients.[33,34]

Interestingly, unlike experiment 4.7 the first half of the initial pulse in figures 4.8.a and 4.8.b has become symmetrical again, but the reason for this is unclear. The maximum frequency present, according to the rise time of the pulse, is again in the order of 6±1KHz, supporting the suggestion already made in several experiments in this series that if the model is indeed a good representation of *in vivo* conditions, then the frequency range involved is of the order 0-7KHz. The further implication of course is that to avoid the problem of aliasing, digital sampling should be carried out with a sample rate of at least 14KHz, and that any hardware should be capable of such a rate.

These observations have all been carried out at an oscilloscope sample rate of 50KHz to avoid the problem of aliasing. The corollary, of course, is that if the actual frequency range is 0-7KHz, a sample rate as low as 14KHz would have been sufficient to reliably capture all frequency components. In contrast, if any of the observed low frequencies is the result of an aliased higher frequency, lowering the sample rate would alter the aliasing pattern and hence the profile of the captured signal.

A critical test of the apparent frequency range would then be to determine the effect of a reduction in sample rate on the signal envelope. A final experiment in this series was therefore carried out to test this corollary, with the added advantage that lower sampling rates would allow longer signals to be recorded, approaching the duration of *in vivo* observations. For example, in experiment 4.8.a the total signal duration (full screen width) was 10 milliseconds whereas a normal *in vivo* recording is in the order of 100 or more milliseconds. Longer signals would also allow multiple strikes of the type observed *in vivo* to be recorded.

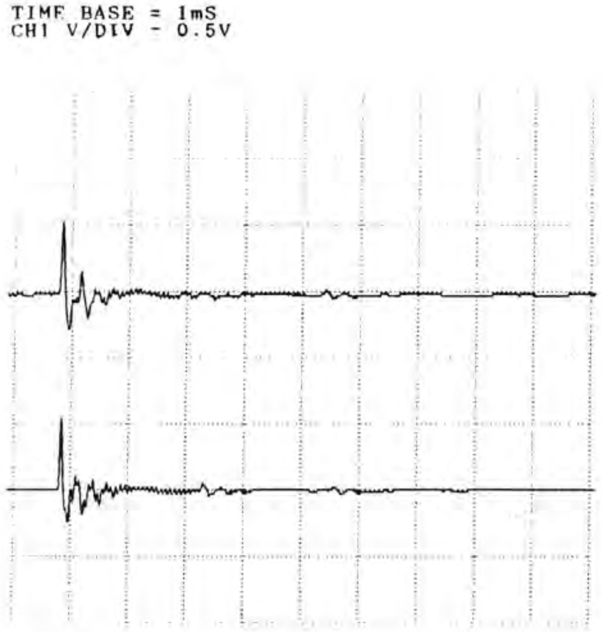


Fig.4.8. Screen dump, resiliently mounted sensor.
a) Upper trace: Cusp to cusp collision.
b) Lower trace: Flat enamel anvil and cusp collision.

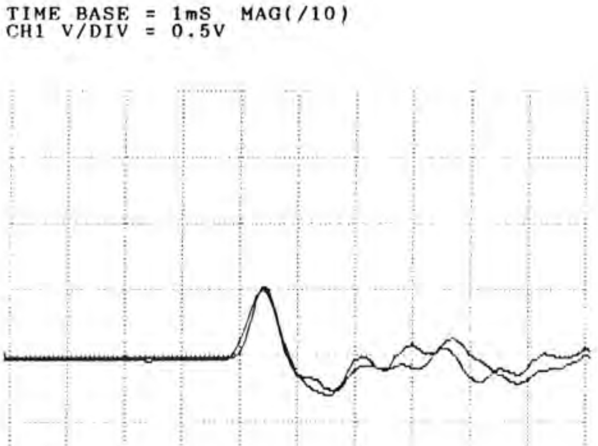


Fig.4.8.c. Screen dump, resiliently mounted sensor.
Traces 4.8.a and 4.8.b with 10x expanded timescale, superimposed for comparison.

EXPERIMENT 4.9.

THE EFFECT OF A REDUCED SAMPLE RATE (SLOWER TIMEBASE) ON COLLISIONS BETWEEN CROWNS OF TEETH.

METHOD

Experiment 4.8.a (cusp-to-cusp) was repeated as experiment 4.9.a and 4.9.b with timebases of 10ms and 5ms, equivalent to sample rates of 10KHz and 20KHz respectively.

RESULTS

The result of experiment 4.9 is shown in figures 4.9.a and 4.9.b as oscilloscope screen dumps corresponding to experiments 4.9.a and 4.9.b. Figures 4.9.c and 4.9.d are 10x expansions in the X axis of 4.9.a and 4.9.b respectively.

DISCUSSION

The problem of aliasing in signal capture has already been discussed in detail elsewhere in this thesis (chapter 3), the limitation being that to capture a signal with a maximum frequency component of fHz a sample rate of at least 2f is required. As the sample rate drops below this the first effect is that occasional peaks or troughs are missed, but if the sample rate decreases further whole groups of waves are lost and the apparent frequency can be several orders of magnitude lower than the real value.

Experiments 4.1-4.8 in this series have used an oscilloscope sample rate of 50KHz, implying that signal frequencies up to 25KHz can be reliably captured. Experiments 4.7 and 4.8 in particular have suggested a frequency range in the order of 0-7KHz for gnathosonic-type collisions, so that a sample rate of only 14KHz would have been sufficient. Since the oscilloscope captures a fixed number of samples (4096) the additional effect of a reduction in sample rate would be to extend the duration of the captured signal. This could be important in gnathosonic studies where, for example, multiple 'strikes' rather than a single clean collision are involved.

Reduction of the sample rate to 20KHz in figure 4.9.d provides a captured signal comparable with figure 4.8.a, consistent with the frequency range being less than the Nyquist or folding frequency of 10KHz and confirming that no frequency greater than 25KHz has been present in previous experiments. In addition the saw tooth shape of each wave suggests strongly that the upper frequency present is close to the 20KHz sample rate limit.

In contrast, a reduction in sample rate to 10KHz in figure 4.9.c produces a captured signal in which the first minor wave after the pulse is missing by comparison with figure 4.9.d. This suggests strongly that aliasing has begun, and that the true upper frequency must be greater than the folding frequency of 5KHz.

Taken together, these observations are then consistent with the true frequency for enamel/enamel collisions being of the observed order 0-7KHz, at least for the *in vitro* model studied here. If the model is a good representation of *in vivo* conditions, a similar frequency range should also be found *in vivo*.

It follows from this that any gnathosonic hardware selected on the basis of this model should be capable of a sample rate of at least 14KHz, and to allow for cases where the sensor resonance is unexpectedly large, the sample rate should be at least twice the 12.5KHz resonance frequency, ie. 25KHz.

The signal duration in figure 4.9.b approaches that recorded by others *in vivo*,[16,17,19,20] and it is

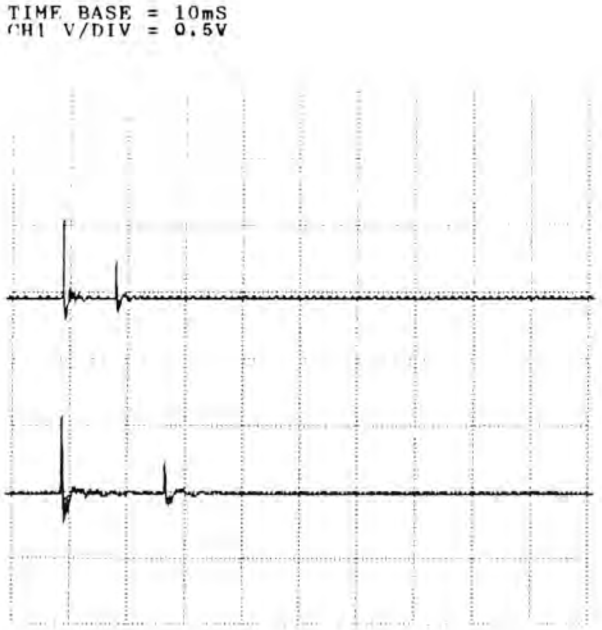


Fig.4.9. Screen dump: elastic between sensor and anvil.
a) Upper trace: 2x strike. Timebase 10ms.
b) Lower trace: 2x strike. Timebase 5ms.

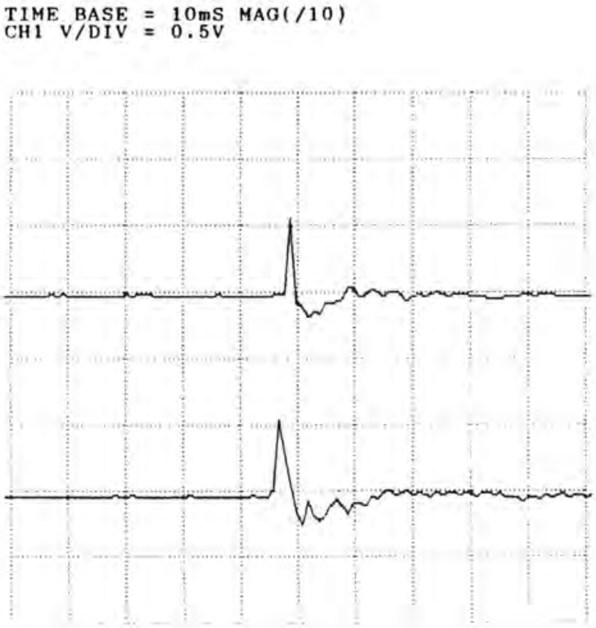


Fig.4.9. Screen dump: elastic between sensor and anvil.
c) Upper trace: Trace a) with 10x expanded timescale.
d) Lower trace: Trace b) with 10x expanded timescale.

interesting to note that figure 4.9.b strongly resembles these published traces, again suggesting the validity of the *in vitro* model. However the model may still be criticised, most importantly because the soft tissues are not truly elastic due to their fluid content and behave in a viscoelastic manner.[18,58] Investigation of alternative resilient mountings was outside the scope of the work reported here, but further modification of the model would form a suitable basis for any future work in this field, including not only healthy tissues but the effects of pathological processes.

CONCLUSIONS

1) The results from the collision of extracted teeth in these experiments appear to show a good correlation with the results obtained from the non-biological materials.

2) The duration of the first pulse in the collision appears to give some indication of the hardness of the materials.

3) Where there is free collision or the anvil is fixed in position, natural vibrations of the sensor are marked as there is no damping of the anvil involved, figs 4.3.a and 4.5.(a and b).

4) The presence of a resilient mounting (fig.4.7.a and b) causes a reduction in the upper frequency range. A further reduction in the natural vibration of the sensor is effected by the insertion of an elastic layer between the sensor and the tooth substance (fig.4.8.a). Under these conditions the waveform appears similar to that expected of *in vivo* recordings where there is tissue damping between the teeth and the sensor. The effect is particularly marked when the timebase is altered to a longer period such as 5 or 10ms (fig.4.9.).

GENERAL DISCUSSION

The purpose of experiments 4.1-4.9 has been to use simple laboratory models to determine the probable range of sound frequencies generated by tooth collisions, so that suitable digital sampling hardware can be selected without the inadvertent introduction of either signal aliasing or spurious sensor frequencies. These experiments have been largely successful, and the frequency range involved appears to be 0-6±1KHz. To avoid the problem of signal aliasing, any hardware should therefore be capable of sampling at twice this rate, ie 14KHz.

In addition, the experiments have shown that accelerometers may be suitable sensors for gnathosonic studies. The particular sensor in this study exhibited a resonant frequency at 12.5KHz, which is well removed from the collision signal proper and therefore amenable to electronic filtering. Fortuitously however, the experiments have also shown that in resiliently mounted models the resonant frequency is largely attenuated so that filtering is unnecessary. However, since even a small residual sensor frequency might be aliased and appear in a captured signal as a spurious low frequency, a more conservative requirement of any sampling hardware would be that it should be capable of capturing the 12.5KHz resonant frequency. To avoid aliasing, this in turn implies that the hardware should be capable of sampling at twice this frequency, ie 25KHz.

This is the minimal information required for reliable gnathosonic studies, yet it has never previously been reported in spite of the large volume of gnathosonic literature. It is also remarkable that there has been no detailed attempt to model the problem, not only to develop a better understanding but also to provide a control against which experiments may be compared. Rather, most literature reports appear to be based on the implicit assumption that gnathosonic traces are a good representation of tooth sounds, even though the sound wave may have passed through numerous hard and soft tissues to the skin surface where most sensors are placed, and may have been modified in the process. Indeed, the results presented here suggest that such modification should be expected, and the absence of control experiments in the gnathosonic literature may explain the difficulty in correlating the results from different research groups.

The data reported should be regarded as preliminary until confirmed by further work, but it appears reasonable to make certain initial generalisations which highlight the problem of interpreting existing literature. For example, impact force and/or rate of impact appears to affect the impact signal not only in amplitude but also duration (experiment 4.4.g and h). In a clinical context this implies that a patient in pain might produce a different signal to a normal patient, and indeed this is part of the rationale for gnathosonics as a clinical tool. However, some authorities have in the past adjusted the signal gains to render them of equal amplitude for 'comparison' purposes, thereby losing important diagnostic information.[36] At the same time, the studies reported here indicate that signal duration varies among collisions in a manner which is difficult to understand and interpret even with a simple model, yet this has not prevented others from using signal duration (or rather the duration of various parts of the signal envelope) as a clinical parameter.[32] Thirdly, an implicit assumption in most gnathosonic reports is that there is such a thing as an 'enamel-enamel' collision that does not vary in quality even though the enamel prisms may vary in orientation and the collision may vary from a direct 'hit' to a glancing blow. The work reported in experiments 4.7 and 4.8 is to the author's knowledge the first attempt to test this assumption, and rather fortuitously for gnathosonics these first results suggest that enamel-enamel collisions may indeed be comparable *in vivo*.

The models used in these studies appear simple, but were difficult to fully understand. For example, it was surprising to find that freely suspended bodies show no residual vibration when struck. It could be argued that such a vibration is indeed present but of such high frequency or low amplitude as to be undetectable by the sensor employed, and this possibility could be investigated in any future work. The only part of the signal envelope which could consistently be assigned to the collision was the initial pulse, but as the model was refined the change in the initial pulse was difficult to interpret except in broad terms such as 'mechanical properties'. The inability to fully understand simple models raises fundamental questions about clinical interpretation of the complex *in vivo* situation, and suggests strongly that further work on model systems could be of great benefit to the study of gnathosonics.

Such further work should include resilient mountings other than natural rubber, since it is not clear how closely the latter resembles the mechanical properties of the periodontal membrane. Indeed, it might be beneficial to measure the mechanical properties of all the various tissues through which the signal passes *in vivo*, so that they might all be incorporated properly in more complex laboratory models. At the same time it may also be possible to develop simple laboratory models for pathalogical states such as fremitus, ankylosis or diseases of the supporting structures of the teeth. The success or failure of osseointegrated implants may also be similarly studied.

Further pursuit of these possibilities was beyond the scope of the work reported here, which was designed specifically to provide a likely frequency range for gnathosonic data. The study of laboratory models remains an excellent basis for any future work however, and should be encouraged.

CONCLUSIONS

1. *in vitro* models appear to provide collision signals with characteristics similar to those *in vivo*.

2. A vibration transducer is suitable as a sensor for gnathosonic signals, particularly where soft tissue is interposed between the sensor and the signal source.

3. The range of signals generated by gnathosonic-type collisions appears to be 0-6±1KHz, but there may also be a higher frequency component due to sensor resonance.

4. Any hardware selected for digital signal capture should be capable of a sampling rate at least twice the highest frequency present to avoid aliasing. For the gnathosonic frequencies alone this implies a sampling rate of at least 14KHz, but the sensor used in this study had a resonant frequency of 12.5KHz, indicating a more critical minimum sampling rate of 25KHz.

CHAPTER 5

FURTHER *IN VITRO* MODELLING

FURTHER *IN VITRO* MODELLING

INTRODUCTION

A problem with signal capture in gnathosonics is the placement of the sensor. The sounds generated by collision or percussion of the teeth must be sensed at some stage if traces and/or recordings are required. It appears from the literature that workers have chosen both sensors and the place of sensing in an arbitrary manner or have followed without questioning the example of others. Readings have been taken directly from the teeth or indirectly from areas such as over the temporomandibular joint, zygomatic or malar region and the forehead, using a variety of sensors.

The literature is further confused by a lack of standardisation. For example, not only has a variety of sensors been employed but also there appears to have been no control over the choice of amplifiers, recorders (including oscilloscopes) and equipment to make hard copy. The specifications, which include the capabilities and limitations of all the instrumentation, are poorly documented. In addition little work has been done to investigate the transmission of vibrations from the teeth to the sensors. It is hardly surprising therefore that not only do the reported findings vary but there is also some confusion as to their interpretation.

The following annotated references illustrate the nature of these problems:

EKENSTEN,[8] used a crystal (larynx type) microphone placed in the area of the zygoma or temporomandibular joint as 'osseous parts conduct sound better than muscular ones'. A low frequency amplifier fed the signal to an oscilloscope. Hard copy was obtained by photography of the traces. No specifications, frequencies or timings were given, which leads to difficulties in gaining a critical understanding of the work.

BRENMAN variously used a 'particular type of microphone',[9] a dynamic contact microphone,[11] a crystal contact microphone and a contact microphone,[16,22] but no specifications were given. The forehead was used as an area to pick up signals,[9] but no reason was given. The frequency range was stated to be 50Hz to 3KHz. The gnathosonic signal was divided into alpha and beta waves to indicate a sliding component before the teeth came into full occlusion. This division was based upon what the traces were thought to represent, but without proofs, specifications or frequencies. The only timing noted was that the duration of the alpha wave might be expected to be in the range of 0-7.6ms.[16]

WATT variously used a hearing aid earpiece,[12] crystal microphone,[14] variable reluctance microphone and variable capacitance microphones,[26] but no specifications were given. Watt finally settled on sensors placed bilaterally in the infraorbital position, giving no well supported reasons. Early work was uncalibrated, and the later classification of occlusion used a duration of 30ms to separate good occlusion from poor occlusion, <30ms typifying good and >30ms poor.

STALLARD used a contact microphone mounted on the forehead.[23] No specifications or frequencies were given, the duration from first contact to full occlusion being 10-50ms. The alpha and beta waves described by Brenman were accepted. Because of the lack of control data it would not be possible to properly reproduce this work.

TAKAMIYA placed microphones in the external auditory meati.[25] The frequency range recorded was 0-1500Hz, and the time taken from first contact to full occlusion in a good dentition was approx. 8ms.

TANAKA used a Dental Sound Checker[29] which employed a condenser microphone placed over the zygoma because of thinness of the skin. No specifications or frequencies were given. A good centric occlusion was found to have a duration of less than 10ms. Without the experimental data the work could not be properly reproduced. Further, although the work is extensive it is intrusive and very time consuming.

NAKAZAWA used triaxial piezoelectric accelerometers which were cemented to the teeth.[31] Power spectra and frequency were analysed in three dimensions. The sound of a good occlusion was recorded as being less than 1ms in duration.

FULLER used a specified electric microphone connected by a tube to a stethoscope bell mounted on the forehead,[32] but no reason for the choice of position was given. Alpha and beta waves were analysed. No specifications or frequencies were given. Watt's classification was used but tables showed Class I occlusions to average 76.3ms and Class III to average 87.3ms. However measurement of traces in the figures showed the total duration of signals to be in the order of 30ms.

TEODORESCU used carbon type telephone microphones placed bilaterally on the cheeks.[35] No specifications or time durations were given. The frequency range reported was from 10 to 500Hz. Again the lack of data makes reproducibility and understanding of the work difficult.

FREER placed variable reluctance microphones bilaterally in the infraorbital position.[36] No specifications, frequencies or timings were given. The repeatability of gnathosonic recordings was claimed to be poor.

MURAMOTO claimed to use a microphone but an illustration showed this to be an oil damped beam-type accelerometer.[37] An analogue-to-digital converter was employed in signal processing but no specifications were provided. No data were given concerning the Dental Sound Checker used in the work. Normal closure sounds were reported as taking less than 10ms, the duration becoming prolonged with the progress of periodontal disease. Yet again the lack of data provided makes the proper understanding and reproducibility of the work difficult.

In view of the equivocal nature of much of the literature and the difficulty in comparing the various reports from different laboratories, or indeed repeating the described work, it was concluded that for the purpose of this thesis the literature should be disregarded and the work started afresh, taking into account the major factors involved in the behaviour of the teeth on impact and the modifications imposed on the vibrations by transmission through the tissues.

The purpose of this chapter is to explore the reliability of these pathways and to select the most advantageous sensor position.

BACKGROUND

The hard tissues of the teeth are surrounded by the soft tissue of the periodontal membrane. Other soft tissues are for the most part a mixture of connective tissue, muscle, fascia, fat, vascular tissue and skin and may be approximated to viscoelastic substances which will respond in different ways to excitation by a range of different frequencies. Transmissions of vibrations throughout the tissues is a major subject and work by authors such as von Gierke are extensive.[18,58]

Surprisingly, work published by Békésy in 1948 while investigating bone conduction in relation to hearing[10] gave more basic information on sensing tooth contacts than any paper of dental origin. Using a precursor of the modern accelerometer, Békésy recognised the significance not only of the placement and coupling of the sensor to the skin but also of the effect of its mass and the pressure holding it in place, and the manner in which these factors could influence the frequency of the sounds recorded. It was clear from the reports that Békésy was also aware of the resonances of the skull and sensor.

A tooth, periodontium and bony socket may be regarded as similar to a damped mass spring system, where the tooth is the mass, the periodontium the damped spring and the bone the foundation upon which the system is mounted. When a tooth is struck, vibrations are transmitted across the periodontal membrane and in the process suffer a degree of damping so that much of the high frequency spectrum generated by impact or percussion of a tooth is lost. The signal is further modified by transmission through bone and other tissues to the skin surface. The problems arising through these factors are modelled in this chapter.

THE PROBLEM OF SENSOR POSITIONING

Sensors to record tooth vibrations can be located in at least three areas:

1) On a tooth
2) Directly connected to the alveolar bone
3) On surface tissue

1) TOOTH MOUNTED SENSORS

Vibrations detected by mounting a sensor directly on the side of a tooth will register vibrations at right angles or parallel to the tooth axis depending upon the type and orientation of the sensors employed. It is well known that the teeth and their suspensory apparatus are designed to withstand axial forces. Even so, the vibrations generated by the impact of the teeth on occlusion may not always be axially directed, and tooth collisions within the arches may not always be simultaneous. For example a lower buccal cusp normally occludes with up to four upper cusps and frequently in a slope to slope relationship as the rounded apex of the cusp may not occlude with the full depth of the fissure or the embrasure between the marginal ridges of adjacent teeth. Dependent on the coincidence of the contacts of the teeth, lateral forces may be generated between the cusps. Even if all the contacts are simultaneous, forces would, in principle, be expected to be generated at right angles to all points of contact including those which are on the slopes of the cusps. In addition all the vibrations should be reinforced or interfere as they travel throughout the substance of the tooth. In that case the sensor therefore should record not only the bodily movement of the tooth but also other frequencies such as the shock waves generated by the impact.

2) BONE MOUNTED SENSORS

Vibrations may be registered by a sensor mounted upon a hypodermic needle which can penetrate the soft tissues and detect vibrations directly from the bone. This method does not appear to have been used by other workers in the field, but preliminary studies by the author have shown that although it is intrusive, the method is effective and gives good results. The preliminary study also indicated that high frequencies are damped by the soft tissues of the periodontal membrane, unless a tooth is ankylosed or an osseo-integrated dental implant is present, and the work is reported later in this chapter.

3) SKIN MOUNTED SENSORS

Sensors placed on the skin have been the most commonly used and least intrusive vibration detectors. They receive signals which have been transmitted through bone and layers of soft tissue to the skin surface, with further loss of high frequency detail.[18,58] It is the vibration of the skin which is measured either directly by the sensor (accelerometer) or indirectly through the vibrations of the air set in motion by the skin (microphone). Although there is considerable high frequency loss, work by the author in this thesis suggests that the overall duration of a sound is not altered appreciably. Both the short sounds of teeth hitting cleanly together and the more prolonged sounds caused by the teeth hitting and then sliding over each other into full occlusion can be properly registered.

EXAMINATION OF SENSOR PLACEMENT

A series of experiments was devised to examine the effect of the position of the sensor in relation to the form of the signal detected on percussion of the teeth, and to select an appropriate site for all future studies.

The experiments were divided into three sections.

PART I The modelling of teeth set in bone to determine the effect of the periodontal membrane.

PART II Experiments on a dry skull to locate a suitable site for sensor placement.

PART III Dry skull with simulated soft tissue to model the effect of skin on the signals received at the preferred sensor site.

PART I - THE MODELLING OF TEETH SET IN BONE

EXPERIMENT 5.1.

TRANSMISSION OF VIBRATIONS FROM A STEEL ROD PARTLY EMBEDDED IN AN ACRYLIC BLOCK

INTRODUCTION

A tooth set in alveolar bone was modelled by partially embedding a threaded steel rod in a block of acrylic, the thread approximating to an irregular root surface. A rod thus directly processed into the acrylic is analogous to an ankylosed tooth.

METHOD

A 25mm threaded steel rod was embedded to a depth of 17mm in a 20x20x20mm acrylic block, and the block held rigidly in a bench clamp in a similar manner to that described in experiment 4.4. An accelerometer was attached to the opposite face of the block, normal to the long axis of the rod. The head of the rod was struck with a plastic hammer attached to the arm of a pendulum tapper, both normal to and parallel to the long axis of the rod, with sufficient force to register a signal of good amplitude without overloading the accelerometer. The experiments were carried out according to table 5.1, and the signals recorded on a storage oscilloscope (Thurlby DSA 524, Thurlby Electronics Ltd, UK).

TABLE 5.1 - MATERIALS AND DIRECTION OF IMPACT

EXPERIMENT	HAMMER	FORCE	DIRECTION OF IMPACT
5.1.a	plastic	tapper	axial
5.1.b	plastic	tapper	transverse

RESULTS

The oscilloscope screen dump of the captured signals are shown in figure 5.1.a.

DISCUSSION

The results of the experiments show a similar signal pattern to those of Chapter 4 where the anvils were rigidly clamped. It can be seen from figure 5.1.a that there are differences in the form of the signal recorded from an axial or transverse blow. This would appear to indicate that further studies of the propagation of vibration through the tissues surrounding a tooth might be of value, particularly as the teeth in their natural mounts are designed to withstand axial forces yet the normal method of percussion by a clinician is in the transverse plane.

However, a possible criticism of these experiments is that no account has been taken of the periodontium. A further series of experiments was therefore carried out on models with simulated periodontal membranes surrounding the rod threads.

EXPERIMENT 5.2.

THE MODELLING OF TEETH WITH A PERIODONTIUM

METHOD

An oversize hole was prepared in an acrylic block, similar to that used in experiment 5.1 and a threaded steel rod embedded in it using a silicone rubber impression material (Extrude type 1, Kerr Mfg. Co. UK). Two such blocks were prepared with silicone wall thicknesses of 0.5mm and 1.5mm respectively, and the experiment carried out in a similar manner to experiment 5.1, according to table 5.2.

TABLE 5.2 - MATERIALS AND DIRECTION OF IMPACT

EXPERIMENT	HAMMER	PERIO.	DIRECTION OF IMPACT
5.2.a	plastic plastic	0.5mm 0.5mm	axial transverse
5.2.b	plastic plastic	1.5mm 1.5mm	axial transverse

RESULTS

The oscilloscope screen dumps of the signals are shown in figures 5.2.a and 5.2.b.

DISCUSSION

The traces in fig 5.2.a, from the rod with the 0.5mm lining, which were recorded at five times the sensitivity of the fixed rod in experiment 5.1 are attenuated by comparison. The traces in experiment 5.2.b where there was a 1.5mm resilient layer, were also recorded at five times the sensitivity of the fixed rod in experiment 5.1, and again show attenuation of the signal but to a lesser degree. In addition, signals show an apparent alteration in frequency. The thickness of the resilient lining appears to affect the degree of attenuation and alteration in frequency, the most likely reason being the damping/resonance characteristics involved. These effects require consideration in the interpretation of traces derived from patients with poor periodontal ligaments, or who are unable to occlude the teeth with a snap.

It would seem therefore that the introduction of an elastic medium into the system modifies the vibrations, as was shown in Chapter 4, leading to alteration of the signal in amplitude and wavelength. It is still evident however that there is a significant difference between the signals generated by axial and transverse percussion. This raises a problem in wave form which might be a critical factor in gnathosonic wave analysis, never previously mentioned in the literature, for example one possible implication is that gnathosonic wave forms may not be amenable to close analysis.

Because these differences were so marked and because of the possible importance of the results, it was considered necessary to repeat experiment 5.2 with the sensor mounted on a face of the acrylic block parallel to the long axis of the rod.

EXPERIMENT 5.3.

MODELLING TEETH WITH A PERIODONTIUM BUT WITH THE SENSOR MOUNTED PARALLEL TO A TOOTH AXIS

METHOD

The experiment was carried out as described in experiments 5.1 and 5.2, but with the sensor mounted on a face of the acrylic block parallel to the long axis of the rod, according to table 5.3.

TABLE 5.3 - MATERIALS AND DIRECTION OF IMPACT

EXPERIMENT	HAMMER	PERIO.	DIRECTION OF IMPACT
5.3.a	plastic plastic	none none	axial transverse
5.3.b	plastic plastic	0.5mm 0.5mm	axial transverse
5.3.c	plastic plastic	1.5mm 1.5mm	axial transverse

RESULTS

The oscilloscope screen dumps of the signals are shown in figures 5.3.a-c.

DISCUSSION

Comparisons with figures in experiments 5.1 and 5.2 show differences in the traces derived from mounting the sensor at right angles or parallel to the long axis of the rods. Signals from the resiliently mounted rods have been recorded at five times the sensitivity of the fixed rod used in experiments 5.1. The signals show some similarity but there are significant differences in detail. These factors should be considered in any further investigations into wave analysis which might be undertaken, but this is beyond the scope of this work.

GENERAL DISCUSSION OF EXPERIMENTS 5.1-3.

These experiments show that there is a difference in wave form when model teeth are struck either axially or transversely. It might be concluded therefore that differing waveforms are produced in differing directions depending on the angle at which the tooth is struck. These vibrations are transferred to and propagated throughout the surrounding media, and are sensed according to the position and orientation of the sensor. The only consistent feature is the shape of the wave envelope which shows the impact as a whole whereas the detail may be difficult to interpret clinically. This should be of major concern to workers in the field of

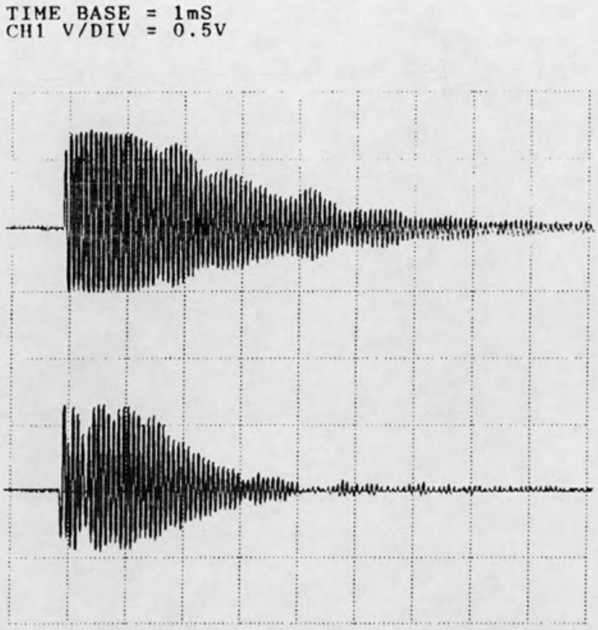


Fig.5.1.a. Steel rod mounted in an acrylic block.
Sensor mounted normal to axis.
Upper trace: Rod struck axially.
Lower trace: Rod struck transversely.

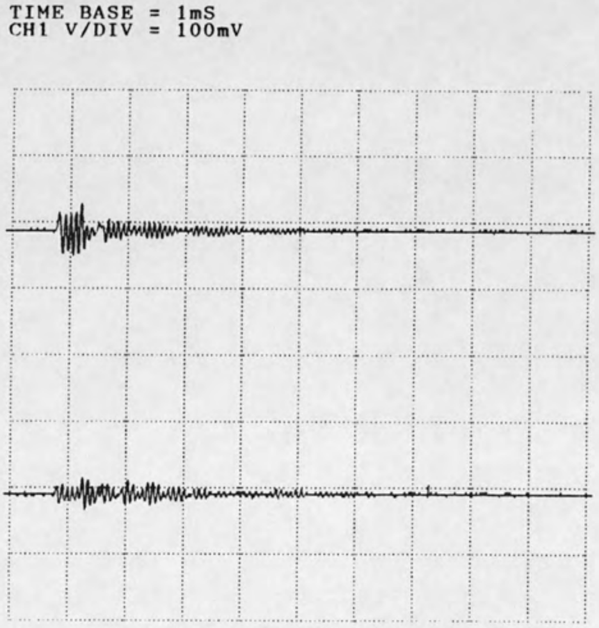


Fig.5.2.a Steel rod in an acrylic block with a 0.5mm resilient lining. Sensor normal to axis.
Upper trace: Rod struck axially.
Lower trace: Rod struck transversely.

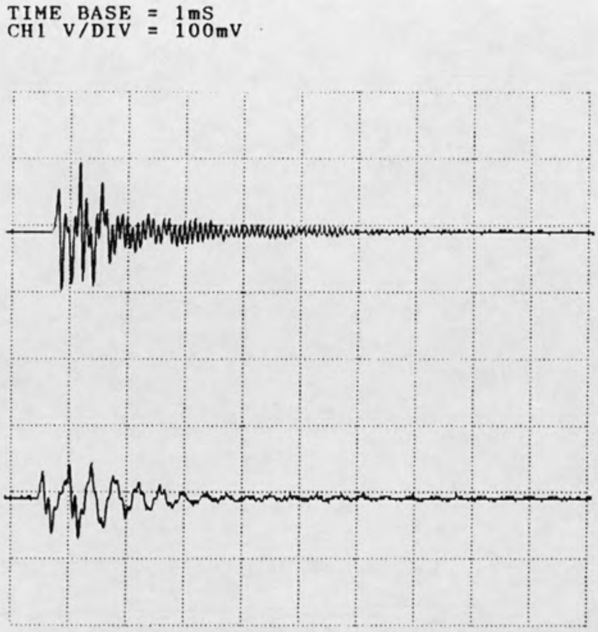


Fig.5.2.b. Steel rod in a acrylic block with a 1.5mm resilient lining. Sensor normal to axis.
Upper trace: Rod struck axially
Lower trace: Rod struck transversely.

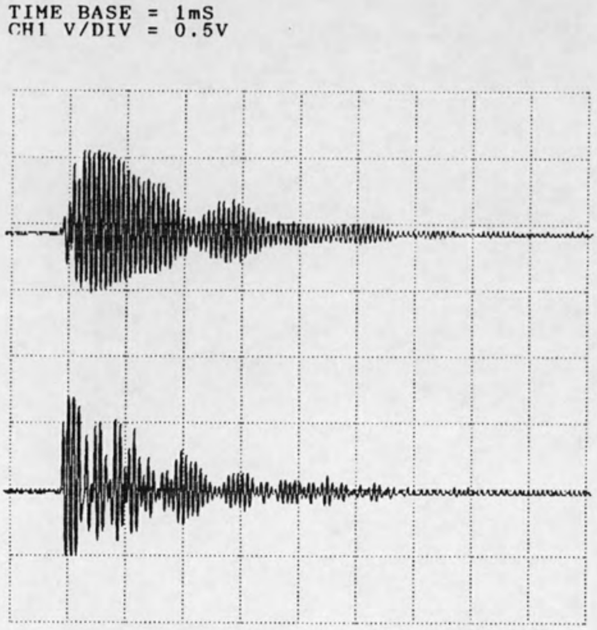


Fig.5.3.a. Steel rod mounted in an acrylic block.
Sensor mounted parallel to axis.
Upper trace: Rod struck axially.
Lower trace: Rod struck transversely.

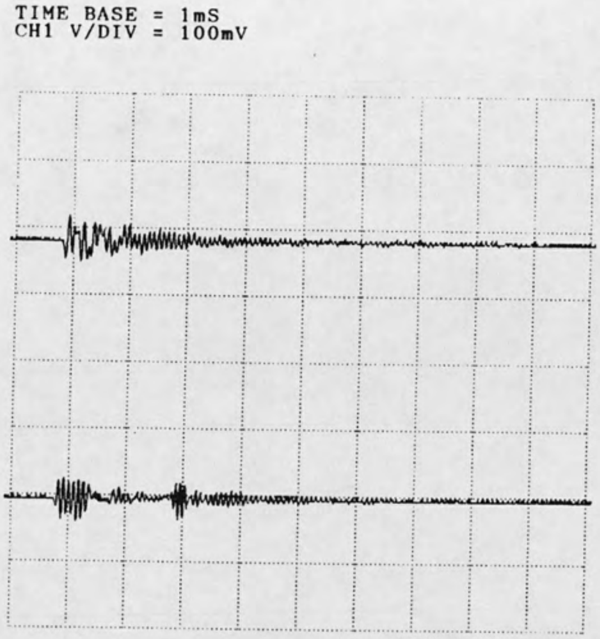


Fig.5.3.b. Steel rod in an acrylic block with a 0.5mm resilient lining. Sensor parallel to axis.
Upper trace: Rod struck axially.
Lower trace: Rod struch transversely.

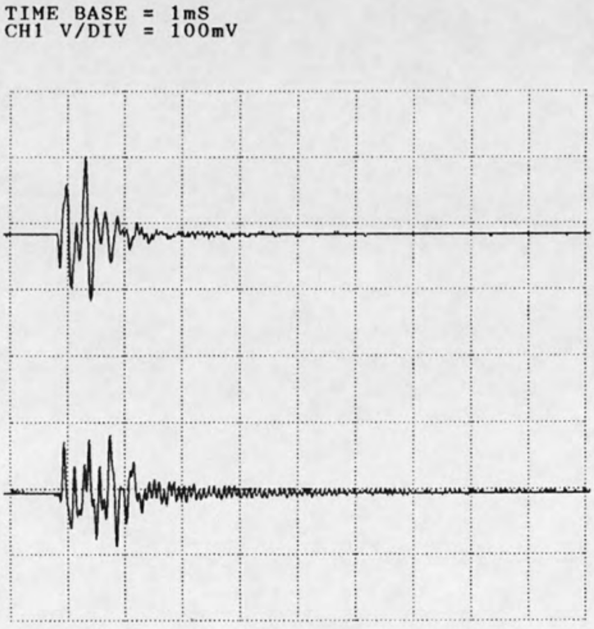


Fig.5.3.c. Steel rod in an acrylic block with a 1.5mm resilient lining. Sensor parallel to axis.
Upper trace: Rod struck axially.
Lower trace: Rod struck transversely.

wave analysis in gnathosonics.

However the models used in this chapter are still open to criticism on three important points. Firstly, the periodontal membrane does not behave in an elastic manner, but rather as a viscoelastic medium and so there will be some differences in the signal conditioning as it passes across the membrane. Secondly, bone is neither immovable nor solid, and thirdly there is soft tissue between the bone and the point of sensing the vibrations.

Before modelling the effect of a layer of soft tissue placed between the hard tissues and the sensor, it was considered necessary to first model the vibrations generated by impact using a dry skull.

PART II - EXPERIMENTS ON A DRY SKULL

INTRODUCTION

The spread of vibrations throughout the skull is complex, radiating from the point of impact, and passing through fused sutures to all parts of the bony mass. At the simplest the skull can be regarded as an irregular hollow sphere.[10] For example, vibrations can reach the glabella from the lambda by right and left circular routes via the temporal regions, over the calvarium by way of the sagittal suture and less directly by way of the occiput, around foramen magnum and forward through the sphenoid and ethmoid complex. The result at the glabella will be a complex wave form as all the waves converge.

An impact at the middle of the intermaxillary suture can travel to the glabella by way of the nasal septum, the frontomaxillary buttress, the zygomatic buttress and the pterygoid buttress. Absolute analyses of these waveforms would be a major work in itself. It is assumed in this study that the signals received at the transducer are the result of impacts at a given point on the skull which can only be evaluated relative to one another but not absolutely in terms of waveform.

The study of gnathosonics is dependent upon the recording and interpretation of sounds made by impacts on the teeth. It is therefore of the utmost importance that the site selected for sensing the vibrations generated in the skull should transmit as true a sound picture to the skin surface as possible.

A series of experiments was therefore carried out on a dry skull to examine sensing impacts in the maxillary area at different points on the skull and to select a position giving the most satisfactory results. It was hoped by this means to reduce the number of complicating factors such as the presence of soft tissue *in vivo* to a minimum.

EXPERIMENT 5.4.

MAXILLARY IMPACTS RECORDED AT THE LAMBDA

METHOD

A dry skull, without mandible or calvarium, was laid upside down on a thin polyurethane mat. An accelerometer (BU1771 Knowles Laboratories, UK) was attached to the lambda with a minimum of model cement, and the median suture of the maxillae was struck with a hand held plastic tapper (see Plate 5). For comparison the skull was afterwards struck on the right zygoma. The signals were recorded using a storage oscilloscope as in experiment 5.1.

RESULTS

The oscilloscope screen dump of the captured signals are shown in figure 5.4.a.

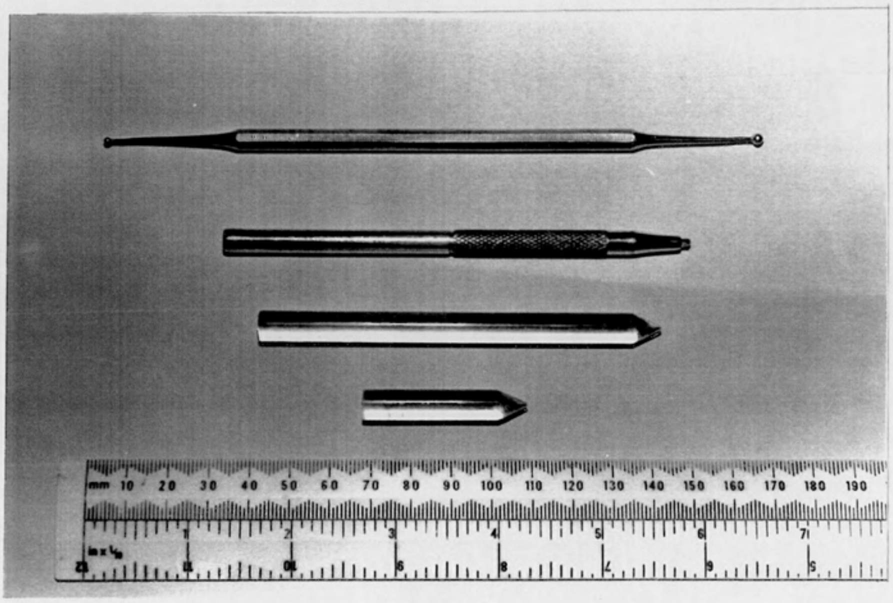


Plate 5 Plastic and metal hand tappers used clinically.

DISCUSSION

Striking the maxilla and zygoma, shown in figure 5.4.a produces remarkably similar traces. Apart from the resonant frequency of the sensor, lower frequencies are present due to vibrations in the dry skull. Bony resonances will normally be damped by the soft tissues *in vivo*, but are clearly not damped in the dry specimen. This type of resonance would complicate the signal derived from tooth impact. The same results might be expected from a sensor placed on the vertex, but the vertex could not be used in these experiments as the calvarium had been separated from the remainder of the skull. It was considered that it would be useful to repeat these experiments *in vivo*, with the possibility that the skull resonance might be damped by the presence of soft tissues to such an extent that a useful impact signal might be recorded.

EXPERIMENT 5.5.

MAXILLARY IMPACTS RECORDED FROM THE ZYGOMATIC AREA

METHOD

The dry skull was prepared as in experiment 5.4 but two accelerometers, calibrated against each other, were attached one on each zygomatic prominence. The maxilla was struck in successive experiments with a hand held plastic tapper in the midline, on the left side, on the right side and equally on both sides by striking a pair of dividers on the hinge while the points rested in the first molar region of each maxilla. The signals were recorded using a storage oscilloscope as in previous experiments.

RESULTS

The oscilloscope screen dumps of the captured signals are shown in figures 5.5.a-e.

DISCUSSION

It can be seen from figure 5.5.a that the signals recorded at each zygoma are similar but not identical. When these traces are overlaid in figure 5.5.b, the similarity in the signal shape or envelope is evident. There appears to be a degree of 'crosstalk' when the strikes are unilateral, as shown in figures 5.5.c and 5.5.d. Even when dividers are used to deliver a similar impact to each maxilla, as shown in figure 5.5.e, the results were comparable but not identical. It is not possible to tell from traces such as these the

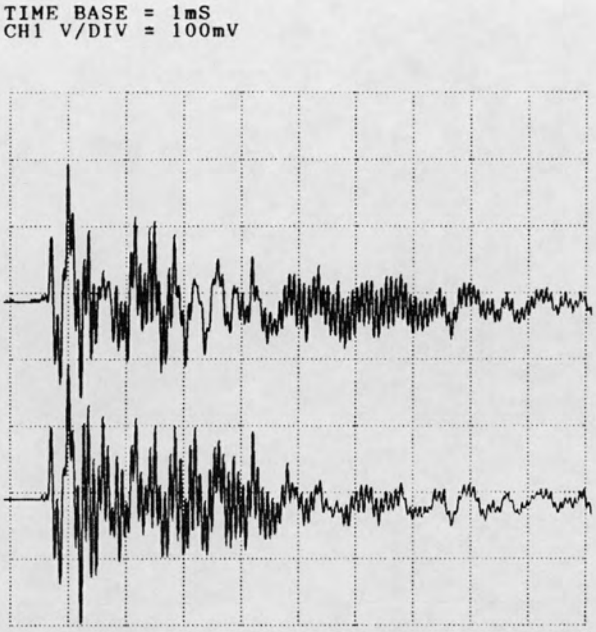


Fig.5.4.a. Dry skull, accelerometer attached at lambda.
Upper trace: Maxilla struck on median suture.
Lower trace: Right zygoma struck.

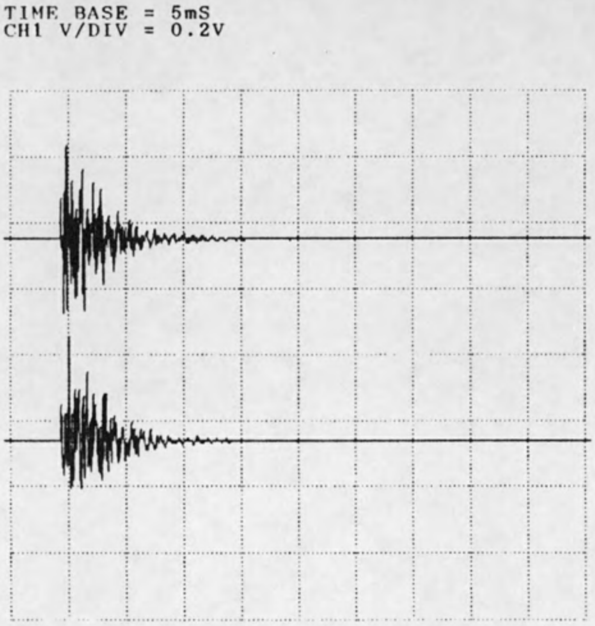


Fig.5.5.a. Dry skull, sensor attached to each zygoma.
Maxilla struck in the midline.
Upper trace: Signal received at right sensor.
Lower trace: Signal received at left sensor.

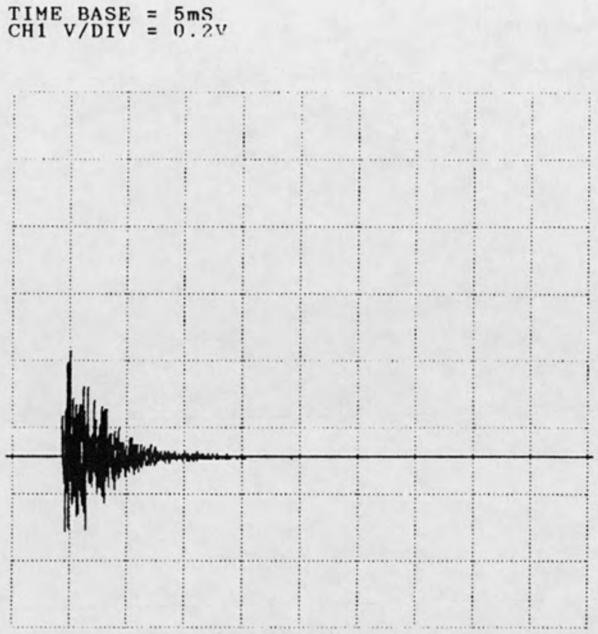


Fig.5.5.b. Traces in figure 5.5.a overlaid for comparison.

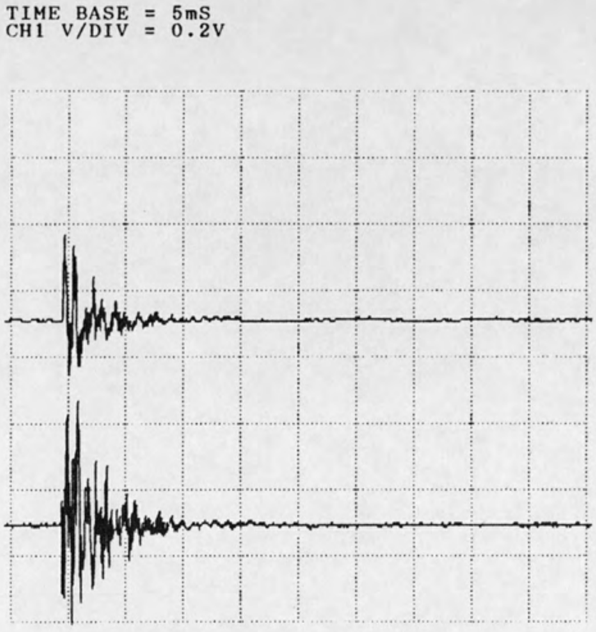


Fig.5.5.c. Dry skull, sensor attached to each zygoma.
Left maxilla struck, showing crosstalk.
Upper trace: Signal received at right sensor.
Lower trace: Signal received at left sensor.

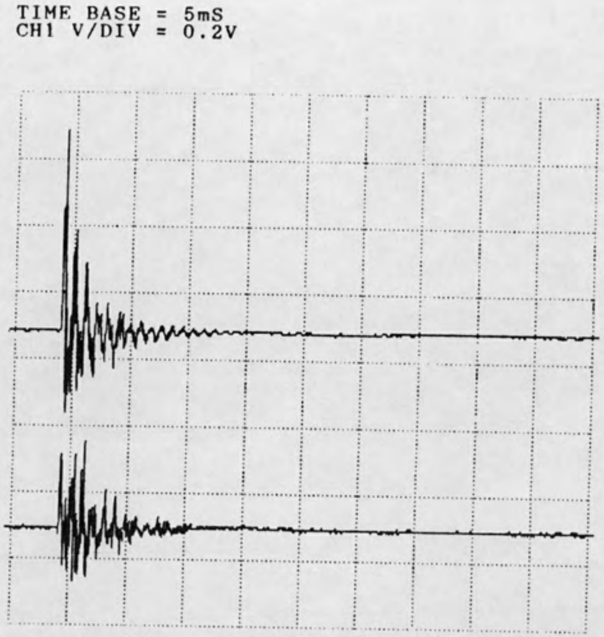


Fig.5.5.d. Dry skull, sensor attached to each zygoma.
Right maxilla struck, showing crosstalk.
Upper trace: Signal received at right zygoma.
Lower trace: Signal received at left zygoma.

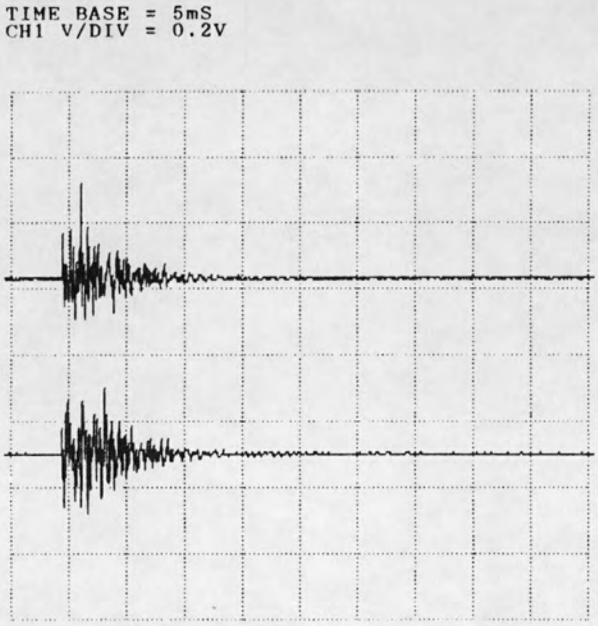


Fig.5.5.e. Dry skull, sensor attached to each zygoma.
Dividers struck to give similar impulses.
Upper trace: Signal received at right zygoma.
Lower trace: Signal received at left zygoma.

origin of a particular sound in the dental arch. The ears are capable of such discrimination if a stereostethoscope is used *in vivo* but very highly sophisticated instrumentation would be required to analyse the signals received from the two sensors. For the purpose of the work reported in this thesis bilateral recordings are considered to be an unnecessary complication. The same reasoning applies to recording occlusal sounds from sensors placed in the region of the temporomandibular joints.

EXPERIMENT 5.6.

MAXILLARY IMPACTS RECORDED FROM THE GLABELLA

METHOD

The dry skull was prepared as in experiment 5.4 but an accelerometer was attached to the area of the glabella, the smooth area of bone between the superciliary arches. An upper left premolar tooth was fixed in its socket with model cement. The maxilla was struck with a hand held plastic tapper in the midline, on the left and right sides and on the cusp of the cemented tooth. For the purpose of comparison the strike in the midline was repeated using a metal tapper. The signals were recorded using a storage oscilloscope as in experiment 5.1.

RESULTS

The oscilloscope screen dumps of the captured signals are shown in figures 5.6.a-c.

DISCUSSION

It can be seen from figures 5.6.a-c that the signals captured at the glabella appear to be uncomplicated by major skull resonances and sufficiently strong not to require excessive gain to be recorded. Hammers of differing materials produce differing characteristics as shown in figure 5.6.a, as could be expected from the experiments in chapter 4. Again these experiments indicate that signals are not identical but the overall signal envelope or shape appears similar for similar strikes, as can be seen in figures 5.6.b and 5.6.c showing strikes from the maxillary area. Anatomically the area of the glabella is part of the frontal bone situated above the maxillary butresses, and is only thinly covered so that a sensor is separated from the underlying bone by approximately 4mm of soft tissue. These factors indicate that it should be a preferred point to sense occlusal sounds externally.

Another factor to be considered is that the inner and outer tables of the skull deep to the glabella separate to form the frontal sinuses, which are variable in configuration. A further experiment was therefore carried out to establish how critical the placement of a sensor would have to be to obtain repeatable results.

EXPERIMENT 5.7.

POSITIONING OF A SENSOR TO OBTAIN REPEATABLE TRACINGS

METHOD

Two accelerometers which had been calibrated against each other were attached, with a minimum amount of model cement, side by side to the glabella of the dry skull, separated by approximately 1mm. The maxilla was struck in the midline with a plastic tapper. The positions of the sensors were exchanged, and the maxilla struck in the same place. The signals were recorded using a storage oscilloscope as in experiment 5.1.

RESULTS

The oscilloscope screen dumps of the captured signals are shown in figures 5.7.a-d. Figures 5.7.b and

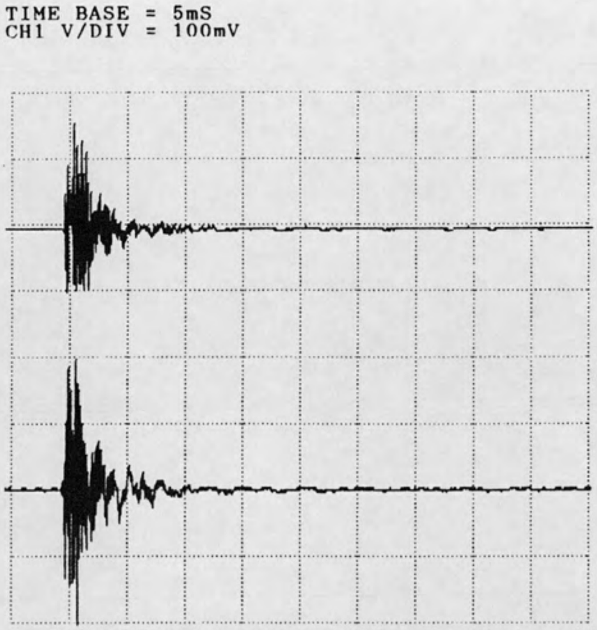


Fig.5.6.a. Dry skull, sensor attached to the glabella.
Maxilla struck in the midline.
Upper trace: Struck with plastic hand tapper.
Lower trace: Struck with steel hand tapper.

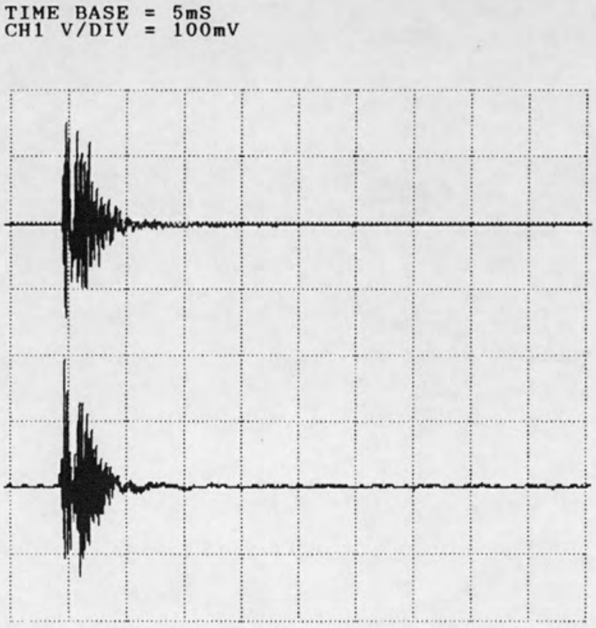


Fig.5.6.b. Dry skull, sensor attached to the glabella.
Upper trace: Right maxilla struck.
Lower trace: Left maxilla struck.

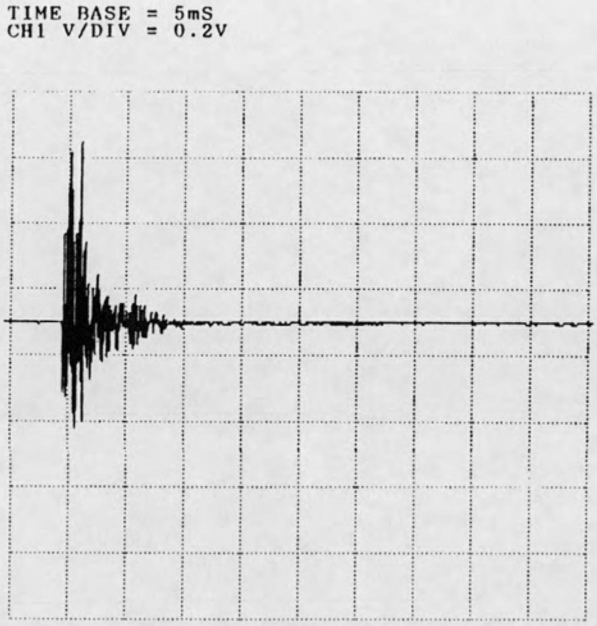


Fig.5.6.c. Dry skull, sensor attached at the glabella. Premolar fixed in socket struck.

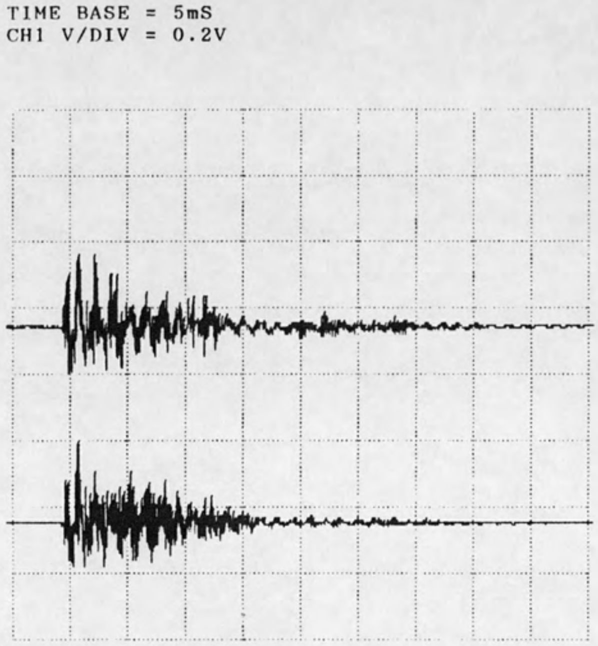


Fig.5.7.a. Dry skull, two sensors attached at the glabella.
Upper trace: Signal received at right sensor.
Lower trace: Signal received at left sensor.

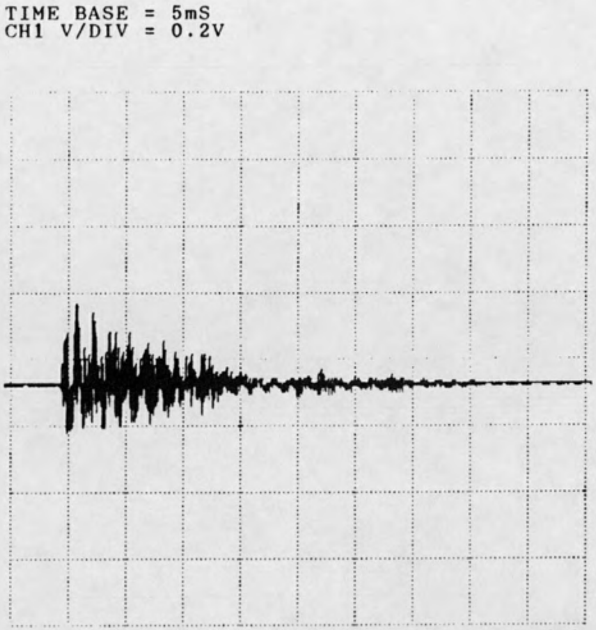


Fig.5.7.b. Traces in figure 5.7.a overlaid for comparison.

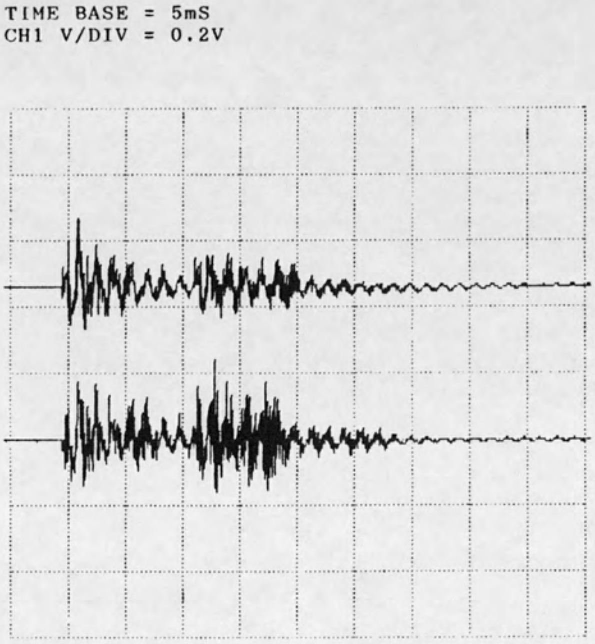


Fig.5.7.c. Dry skull, two sensors attached at the glabella, positions exchanged.
Upper trace: Signal received at right sensor.
Lower trace: Signal received at left sensor.

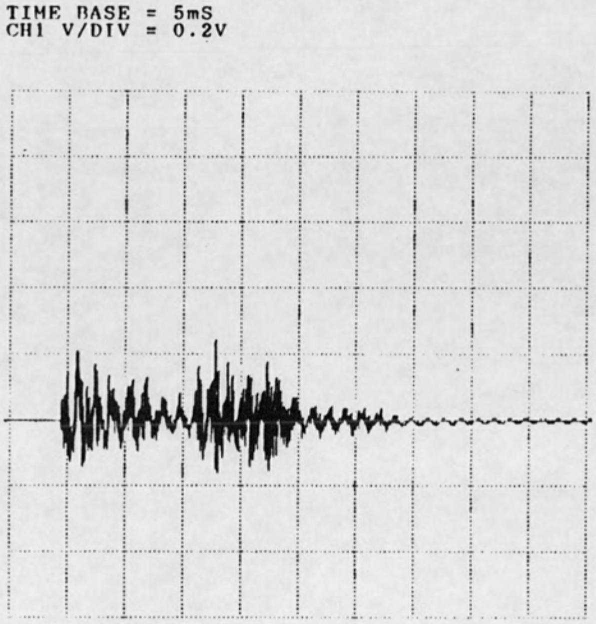


Fig.5.7.d. Traces in figure 5.7.e overlaid for comparison.

5.7.d overlaid the two traces in figures 5.7.a and 5.7.c respectively.

DISCUSSION

It can be seen from figure 5.7.a that although the traces produced by the two accelerometers are similar in overall shape, they are not identical. The same applies to figure 5.7.c. However traces derived from the same areas (upper 5.7.a and upper 5.7.c: lower 5.7.a and lower 5.7.c) appear to be more similar, indicating that attempts to reproduce waveforms will not only require identical strikes but identical positioning of the sensor. This indicates that studying gnathosonics by wave analysis would be difficult. However the overall similarity of the signal shapes or envelopes can be seen in the overlaid traces in figures 5.7.b and 5.7.d.

GENERAL DISCUSSION OF EXPERIMENTS 5.4-7.

This series of experiments indicates some of the factors which have to be considered in selecting the position to apply the sensor. Although the vibrations generated by impact of the teeth spread throughout the skull by numerous pathways, they can be monitored at any point on the bony surface. Signals so captured will be complex due to the multiple routes that the vibrations may follow, so for practical purposes the shape or signal envelope may be the only useful guide to the amplitude, composition and duration of the single or multiple impact sounds made by the teeth. Therefore for general use a single sensor appears to offer the least ambiguous data.

The areas examined were those where the tissue layers between the bone and the skin surface are thin and least diverse. In the dry skull the lambda was shown in experiment 5.4 to be strongly affected by resonances or other frequencies generated in the skull. It is reasonable to assume that the same effects would be present at the vertex if the skull were complete. A further disadvantage of both these areas *in vivo* is that in the majority of patients accessibility is a problem due to the presence of hair. It may be however that such resonances might be attenuated to an acceptable extent *in vivo* by the presence of the brain and other soft tissues.

The use of unilateral or bilateral sensors gives 'sided' traces, as shown in experiment 5.5 with no guarantee of accuracy because it is unlikely that hard and soft tissue transmission characteristics would be equal bilaterally.

The glabella as shown in experiment 5.6, appears to be the position of choice because the area is accessible, a sensor can be easily applied and the bone conduction to the area is good, passing directly up the fronto-maxillary buttress. Other paths which the vibrations can follow such as the zygomatic and pterygoid buttresses are tortuous and as a consequence could suffer attenuation. In a similar manner the effects of the frontal sinuses may well be complex, and are beyond the scope of this thesis. It has been shown however, in experiment 5.7 that there is a variability in the waveform of signals captured when sensors are placed even a short distance apart so that signals are unlikely to be reproducible. Overall signal shapes or envelopes are however, comparable.

A final series of experiments to simulate the presence of soft tissue was considered necessary to assess the degree of signal modification which might be expected if soft tissues were present.

PART III - DRY SKULL WITH SIMULATED SOFT TISSUES

INTRODUCTION

The presence of soft tissues between teeth and bone has been modelled earlier in this thesis by natural and silicone rubbers (Chapter 4). *In vivo* the periodontium is normally a relatively thin membrane, in the order of 0.1mm. However the thickness of soft tissues overlying the bone in the regions of the glabella or zygoma is in the order of 4mm. It was considered necessary to attempt to model the introduction of such soft tissues into experiments with the dry skull before *in vivo* trials because experimental models in this thesis have shown that the presence of resilient materials alter the structure of signals. It is reasonable to suppose that such experiments might give useful information on the *in vivo* situation. Experiments were therefore carried out to simulate soft tissues, firstly using a threaded steel rod partially embedded in acrylic as a simple model, then with a dry skull.

EXPERIMENT 5.8.

SIMULATED PRESENCE OF SOFT TISSUES - ACRYLIC BLOCK

METHOD

The experiment was carried out in a similar manner to that described in experiment 5.1.a, except that a layer of animal soft tissue, approximately 4mm thick and contained in polyethene film, was interposed between the sensor and the point of application to the acrylic block. The sensor and tissue were held in place with elastic bands. The experiment was then repeated without the layer of animal tissue. Signals were recorded in a similar manner to that described in experiment 5.1.a.

RESULTS

The oscilloscope screen dump of the signals is shown in figure 5.8.a.

DISCUSSION

Comparison of the traces in figure 5.8.a indicates a considerable loss of signal amplitude and high frequency range, which was to be expected because of the damping effect of the animal tissue. A similar result might be expected from a dry skull with animal tissue, but it was considered necessary to confirm this by experiment.

EXPERIMENT 5.9.

SIMULATED PRESENCE OF SOFT TISSUES ON A DRY SKULL

METHOD

The experiment was carried out as described in experiment 5.6 except that a layer of animal tissue, approximately 4mm thick and contained in polyethene film, was interposed between the sensor and the point of application to the hard tissues. The sensor and the animal tissue was held in place by elastic bands placed circumferentially about the skull. The maxilla was struck in the midline with a plastic hand tapper. The experiment was repeated without the layer of animal tissue. Signals were recorded in a similar manner to that described in experiment 5.1.a.

RESULTS

The oscilloscope screen dump of the signals is shown in figure 5.9.a.

DISCUSSION

Comparison of the traces in figure 5.9.a with those in figures 5.6.a and 5.6.d indicates a considerable loss of signal amplitude and high frequency range, which is not surprising in view of the damping effect of the animal tissue. These results are in accord with experiment 5.8 and emphasise the usefulness of simple models.

EXPERIMENT 5.10.

EXPERIMENT ON A DRY SKULL WITH SIMULATED SOFT TISSUES AND WITH A SIMULATED PERIODONTIUM

METHOD

A dry skull was prepared as described in experiment 5.9. In addition the root of a tooth was laminated with a film of natural rubber to simulate a periodontal membrane and replaced in its socket without cementation. The maxilla was struck with a plastic hand tapper, firstly in the midline in a similar manner to that described in experiment 5.9, then through a cusp of the tooth. Signals were recorded in a similar manner to that described in experiment 5.1.a.

RESULTS

The oscilloscope screen dump of the signals is shown in figure 5.10.a.

DISCUSSION

Comparison of the traces in figure 5.10.a indicates a further loss of signal amplitude and high frequency range when the tooth is struck. The signal has undergone

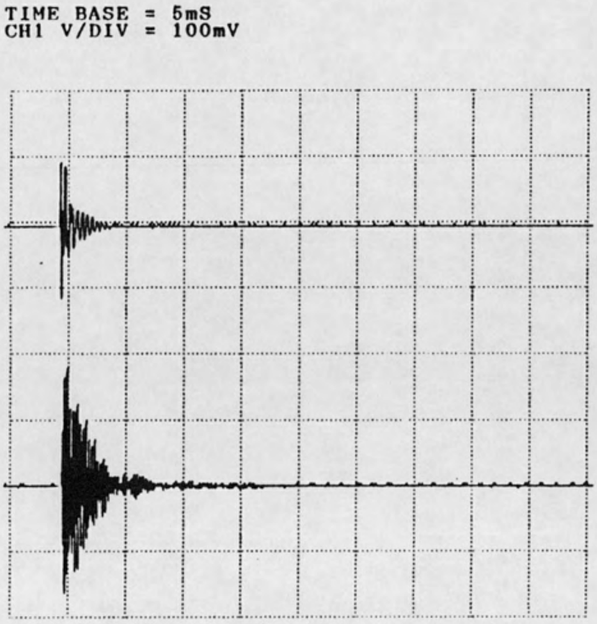


Fig.5.8.a. Steel rod in an acrylic block. Sensor at right angles to axis. Rod struck axially.
Upper trace: Soft tissue between sensor and block.
Lower trace: Sensor directly attached to block.

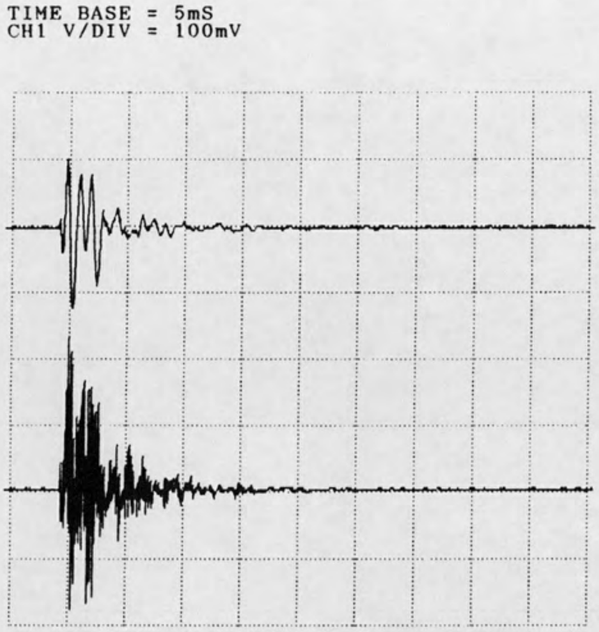


Fig.5.9.a. Dry skull, sensor in the glabella area.
Upper trace: Soft tissue between sensor and bone.
Lower trace: Sensor attached directly to the bone.

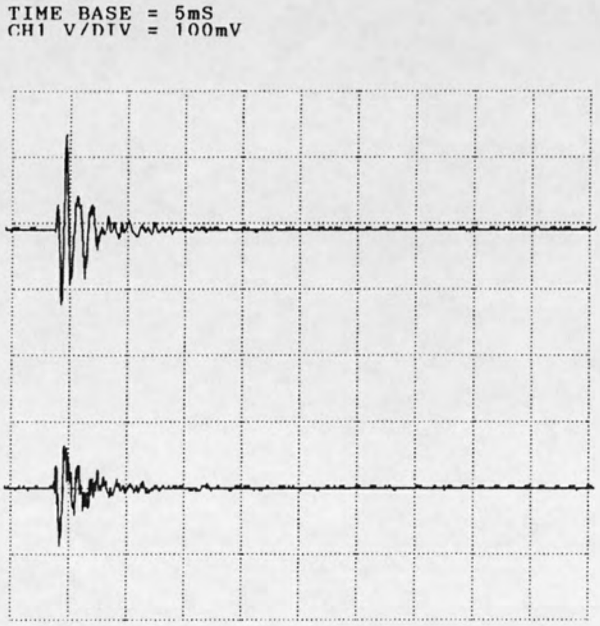


Fig.5.10.a. Dry skull, soft tissue between the sensor and the glabella.
Upper trace: Maxilla struck in the midline.
Lower trace: Premolar with simulated periodontal membrane struck.

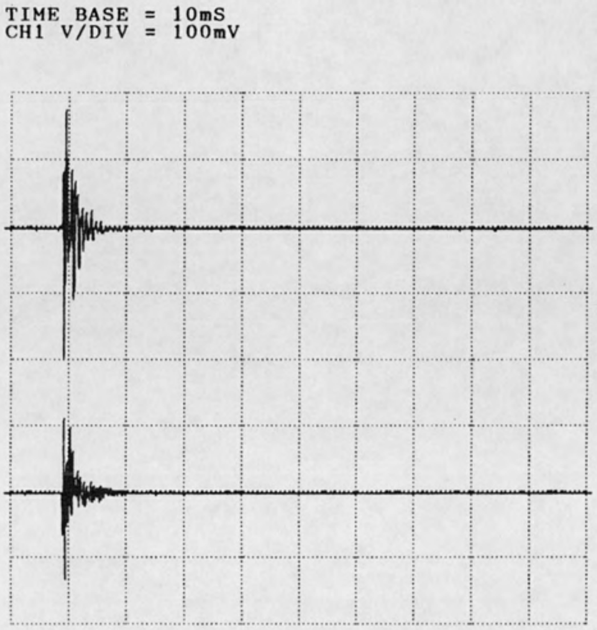


Fig.5.10.b. Traces similar to figure 5.10.a captured at a 10ms timebase appearing as commonly published gnathosonic traces.

two modifications by simulated soft tissues as it passes firstly through the simulated periodontium and secondly through the simulated soft tissues on the forehead. This is a closer approximation to the *in vivo* situation but of course the dry skull itself is still undamped.

GENERAL DISCUSSION OF EXPERIMENTS 5.8-10.

Experiments 5.8-10 were designed to simulate soft tissues *in vitro*. It is evident from the experiments in Part III that the resilient layers reduced both the amplitude and high frequency content of the signals. The cushioning effect of the simulated soft tissues in experiments 5.8 and 5.9 indicate that the presence of soft tissue between the skull and sensor leads to loss of signal amplitude and high frequency. The presence of a periodontal membrane appears to lead to a further reduction in both parameters. The overall result appears to be a reduction in the excitation of the resonant frequency of the sensor and the signals are similar to those in the literature, as illustrated by figure 5.10.b where signals similar to those in figure 5.9.a are reproduced with a longer timebase. This implies that the model is a good representation of the clinical situation and that the accelerometer is therefore a satisfactory sensor.

OVERALL DISCUSSION OF FURTHER *IN VITRO* MODELLING.

It has been the purpose of the work reported in this section to study, by models and a dry skull, the effects of both the placement of the sensor and the presence of soft tissues on the vibrations transmitted from a point of impact to a point of sensing.

The position of choice for a sensor would appear to be the glabella, although it has been shown in experiment 5.7 that even small variations in position can lead to differences in the detected wave forms. Precise signal reproducibility is therefore highly unlikely either *in vivo* or *in vitro* but although the constituent waveforms are not reproducible there is similarity of the signal shape, or envelope, derived from similar impacts. The glabella is accessible and the sensor can be easily applied.

Signals from impacts in the region of the maxilla sensed at the lambda, as shown in experiment 5.4, are significantly distorted by natural resonances of the skull. The same conditions may reasonably be assumed to exist at the vertex. *In vivo* of course, the presence of hair in these areas in the majority of patients would make the sensor difficult to apply.

Signals sensed bilaterally, as in experiment 5.5, in the zygomatic or temporomandibular regions were rejected in this work because of the complication introduced by crosstalk between the two sides.

One area which does not appear to have been studied by other workers in the field is the mandible. On occlusion of the teeth equal impacts are delivered to both maxilla and mandible. Preliminary experiments by the author indicate that vibrations from the mandible are severely attenuated by the soft tissues of the temporomandibular joint *in vivo*. This is an area which could form a useful part of any future work. For example, the author has made preliminary studies of sensing in this area, directly from bone by using a sensor attached to a hypodermic needle to record the signals produced by the percussion of titanium implants. Further reference to this technique is made for studies *in vivo* reported elsewhere in this thesis.

CONCLUSIONS

1) The presence of soft tissues between the point of impact and the sensor cause attenuation of the signal in both amplitude and high frequency range.

2) Sensing in the area of the calvarium should be

rejected on the grounds of signal distortion and inconvenience.

3) Bilateral sensing is not satisfactory for simple gnathosonics.

4) The glabella appears to be the position of choice as an area giving a readable signal and where the sensor is easily placed.

5) Although the constituent waveforms are not reproducible, the overall shape or envelope of signals derived from similar impacts are themselves similar.

CHAPTER 6

SELECTION OF HARDWARE

SELECTION OF HARDWARE

It is clear from the model experiments in the previous chapter that the selection of a suitable digital sampling system is critical to any gnathosonic study. Further it was established that to capture the sounds of tooth collision such a system would be required to capture capture signals in the range of 0-6±1KHz, necessitating a capture rate of at least 14KHz to avoid signal aliasing. However the transducer which proved to be satisfactory for recording collisions has a resonant frequency of 12.5KHz, therefore the minimum capture rate must be 25KHz as this transducer was chosen as the sensor to be used for gnathosonic recordings.

The major purpose of the project was to provide the practitioner with a low cost signal capture system. Therefore central to the choice of equipment was the selection of a data logger. A computer was chosen as an instrument which can not only log data but is commonly found in homes and practices. At the time this work was started there were a number of low cost computers available but these were mostly for home use and not suitable for data logging. More powerful and expensive machines could have been used but this project was intended to demonstrate that digital signal capture of gnathosonic signals could be effected in the dental surgery using a low cost system. The major criteria were therefore:

1) Low cost
2) Availability
3) Ease of data logging
4) A sampling rate of at least 25KHz

When this work was begun the only low cost microcomputers which could have been considered as 'professional' and particularly suited to laboratory experiments were of the BBC series. This series was designed for use as low cost work stations, having a number of user ports which could be connected to a wide range of peripheral equipment. Further they were popular in the home as well as in schools and other educational establishments.

There are numerous specialist appliances incorporating computers available, together with expensive peripheral equipment for general research purposes, some specifically developed for dental use. For the most part the price of such instrumentation precludes its use within the general dental surgery.

CHOICE OF COMPUTER

The BBC computer series fulfilled the criteria of cost, availability, common usage and versatility. Initially designed for the educational market the BBC series has the useful feature of several peripheral ports allowing various items of experimental apparatus to be attached.

The BBC Master 128 was chosen as the latest in the series, with more memory available for data storage. Manufacturers of peripheral equipment developed a number of data-logging accessories, which have been necessarily low cost because they were aimed at the educational market. Software for this project was not available and was written specifically for this project.

SIGNAL CAPTURE

The computer requires information to be in digital form. Therefore all external electrical signals must be converted from analogue to digital form before processing. One disadvantage of the BBC microcomputers is that the internal analogue to digital (A-D) converter samples at only 100Hz and can therefore only reliably read to 50Hz. Fortunately external A-D converters are available and couple to the computer through one of its ports. An interface such as the Unilab Interface (Unilab. UK) has a sampling rate of 8us, reading a signal 125,000 times a second at a minimum of two readings per cycle means that using the interface frequencies of up to 62.5KHz can be reliably read.

OTHER ESSENTIAL HARDWARE REQUIREMENTS

The only other essential hardware is a suitable monitor and data storage facility. In the present study the microcomputer was supported by a Microvitec colour monitor (Cub type 1451 medium resolution) and an Akhter double 5.25 inch disc drive.

THE SENSOR

The accelerometer selected as a sensor was the BU1771 (Knowles Laboratories UK) which was used in the previous chapter. It was chosen for its frequency response, small size and because it has been in use for a number of years as a transducer in clinical gnathosonics by the author.

CHAPTER 7

DEVELOPMENT OF SOFTWARE

SOFTWARE DEVELOPMENT

INTRODUCTION

One of the most important features of digital signal capture is the sampling rate, because it determines the highest signal frequency which can be reliably detected. In turn, the sampling rate depends on both the inherent operating speed of the computer, i.e. the clock rate of its central processing unit, and the running time of the sampling software.

Software speed can vary considerably for at least two reasons, the more important of which is the language or code in which the software is written. The fastest language is that which is understood directly by the central processor, i.e. machine code. Machine code can be put together by hand as a sequence of numbers, but is more easily written in a low level language called assembly language.

Higher level languages normally resemble written English and must be translated by the computer into machine code. For some languages this translation is performed at the time of writing, producing machine code directly. Such languages normally have simplified commands that can easily produce machine code, and a typical example is PASCAL. More complicated higher level languages offer more commands but only at the expense of not directly producing machine code. Some of these higher languages instead produce an intermediate code at the time of writing, which is converted into machine code on execution. Since the conversion takes a finite time, such languages are inherently slower than machine code. An example of such a language is C-CODE. Other higher languages are stored simply as the English instructions until the moment of execution, when they are converted to machine code. Such languages are normally slower still, and a typical example is BASIC.

There is also another factor affecting software speed of course, namely the efficiency with which the software has been written, i.e. the minimising of the machine code steps involved.

THE BBC MICROCOMPUTER

The BBC microcomputer is an 8-bit machine with a 6502 central processor operating at 2MHz. The computer has both BASIC and 6502 assembly language as standard, although other languages can also be installed if required. Signal sampling can be effected through a built-in analogue-digital port, but the sampling rate for this input is fixed at 100 sec^{-1} which would limit the upper detectable frequency to 50Hz, a figure far too low for gnathosonic sampling. Alternatively, an external fast analogue-digital converter can be attached through a port which operates at 1MHz (the '1MHz Bus'), located on the underside of the computer. This port is connected to a single dedicated byte in the computer's memory, and an external A-D converter would continually alter this byte so that the computer need only read its value to determine any digital conversion. A peculiarity of this system is that at the moment of taking a reading the computer slows its 2MHz CPU clock to 1MHz to synchronise with the 1MHz bus, a factor which must be taken into account when calculating the execution time of sections of machine code.

THE UNILAB EXTERNAL INTERFACE

The external analogue-digital converter selected for the current study was a Unilab Interface model no. 532.001 (Unilab UK) capable of accepting input signals of up to +/- 10V, with an inherent sampling rate of 125,000 sec^{-1}. The interface also carries an internal clock which can be used as a sampling timer if required, and has four input channels which are software-selectable.

A NOTE ON MACHINE CODE

Machine code is really just a sequence of numbers which have different meanings for the central processor and cause it to perform different operations. Each number is called an 'opcode' and is specified by the CPU manufacturer as taking a fixed number of cycles to execute. The execution time of a complete sequence of machine code can therefore be calculated from the manufacturer's table of opcode timings. The only complicating factor as far as the BBC computer is concerned is that when the CPU clock slows from 2MHz to 1MHz to read data coming through the 1MHz bus, one or more cycles of the particular opcode timing involved will be effectively doubled in length. The number of cycles affected by reading the 1MHz bus is not well documented but can be readily determined by experiment (as in this thesis).

In addition, machine code may be executed just once, or may repeat itself. Sequentially reading and storing data in digital signal capture is one example of such a repetitive process. This is accomplished by opcodes for branching and jumping, which allow the machine code to go back on itself and re-execute selected machine code segments. Such machine code is conveniently viewed as a 'loop', and of course there may also be loops within loops. Typical examples of inner loops include machine code segments to introduce delay times, and for digital signal capture perhaps there may be a trigger loop to determine if a reading has exceeded background. In the way that machine code operates, not all of these loops are used in any one pass through the code, and some of them are only active when certain preconditions are met. The important consequence is that there may be several paths through any machine code program, and since the sequence of opcodes will be different for each path the timings will vary too. Fortunately, if timings are critical the path lengths can all be adjusted by the introduction of one or more dummy opcodes which have no function but take 1 cycle to execute.

DIGITAL SIGNAL CAPTURE

The key features of digital signal capture are a fast, precise capture rate and accurate digital conversion. However, fast precise capture requires machine code controlled by a precision clock. The A-D converter in the current study has its own clock which can be set to count down between readings to provide a variable, accurate sample rate, but has the disadvantage that the clock must first be set and then read continually until it times out. These actions themselves take time and thereby limit the fastest capture rate.

Alternatively, use may be made of the fact that the computer's CPU has its own accurate clock as previously described, and that machine code times can be calculated from opcode data tables. This has the advantage of not requiring an external clock and therefore offering the fastest capture rate, but with the disadvantage that the machine code must be written with great care to ensure that all possible paths through it have the same timings.

THE SYSTEM SELECTED FOR THE CURRENT STUDY

For the current study the fastest possible capture rate was required, and the method chosen was therefore to use the CPU's own clock together with published opcode timings. Considerable attention was therefore paid to all possible paths through the machine code, which was designed to store the data sequentially in a memory buffer and therefore required an internal loop to update the storage address within the buffer after each reading. In addition, it was desired to have a variable preselectable capture rate entailing a delay loop, and the option of a triggered capture requiring a separate trigger loop to compare any reading with the trigger threshold. The memory in the BBC computer is divided into 'pages' of 256 bytes, and among other inevitable machine code loops it was necessary to update the buffer address pointer at each page boundary.

The necessity for these loops meant that various paths through the software were possible, and all had to have the same timing. In addition, the machine code was shorter when a delay loop was omitted, and two forms of code were therefore written, one with a delay loop and one without. The faster version was able to sample data with a calculated sampling time of 14.5 microsecs, whereas the incorporation of a delay loop, even with a delay set to zero, produced a fastest sampling time of 18 microsecs. For each version of the code, it was also found more efficient to have separate machine codes for triggered and untriggered signal capture. Four versions of the central machine code were therefore prepared as follows:

1. fastest capture rate, untriggered
2. fastest capture rate, triggered
3. user-variable delay loop incorporated, untriggered
4. user-variable delay loop incorporated, triggered

A list of all relevant opcodes and their timings is shown in Table 7, and the calculation of all possible path timings through the four versions of the code is given in figs.7.1-4. These data are included in the main text, and not placed in an appendix, because the timings of the capture routines are critical and are central to the whole project.

Experimental verification of these codes (chapter 8) eventually showed that the reading of the converted data by the CPU slowed its clock by one cycle (0.5 microsec) so that all calculated sampling times had to be increased by this amount. For example, the fastest sampling time became 15 microsec rather than the calculated 14.5 microsec.

A NOTE ON TRIGGERING

Triggering of signal capture, whereby capture is delayed until a preset signal threshold is reached, is a normal feature of electronic apparatus and is usually chosen to occur either on a negative or a positive edge, but not both. In the current study triggering is controlled by the machine code software, which has been written to allow separately adjustable positive and negative threshold levels, and the triggering loop compares background readings with each threshold until one or other is exceeded. In this way the software triggers on both positive and negative edges, so that no initial part of any signal is lost.

PROGRAM CONTROL

Machine code sampling was controlled by a suite of programs written in BASIC, which offered the user a setup facility then selected the appropriate code from diskette. The captured signal could then be displayed, manipulated in various ways, and saved to diskette for future study. Among the facilities incorporated were:

SETUP

- load previous data
- capture new data
- select input channel
- select input voltage range
- select sampling rate (15-653 usec.)
- select trigger level
- triggering ON or OFF

CAPTURE

- oscilloscope simulation to preview background trigger level adjustment
- sampling commences on key press

DISPLAY

- save data
- load data
- plot with points shown
- plot without points
- fast plot using limited points
- slow plot with all points
- zoom any part of plot
- expand/contract X or Y axis
- calculate frequency of single wave
- add own user notes
- dump to printer
- plot with digital plotter
- abandon and capture new data

MEMORY USAGE

The memory usage of the capture software is outlined in fig.7.5. Stored signals were saved to disk complete with control data such as sampling rate and any added user notes.

PROGRAM SUITE

The full program suite with the four machine code files is provided on a diskette at the end of this thesis, and includes a text file called README which describes the filename and purpose of each file in the suite.

TABLE 7

6502 CPU OPCODES USED IN THIS STUDY

OPCODE DESCRIPTION	MNEMONIC	CYCLES
Load accumulator with number N	LDA #N	2
Load accumulator with contents of address A: zero page	LDA &A	3
other pages	LDA &A	4
Store accumulator in zero page address A	STA &A	3
Store accumulator in address given by: (A+256*(A+1))+Y where A is zero page address	STA (A),Y	6
Increment contents of zero page address A by 1	INC &A	5
Load the X register with number N	LDX #N	2
Decrement the X register by 1	DEX	2
Load the Y register with number N	LDY #N	2
Increment the Y register by 1	INY	2
Clear the carry flag	CLC	2
Compare the accumulator with number N	CMP #N	2
Compare the Y register with number N	CPY #N	2
Branch to label if result zero	BEQ Label	2
Branch to label if result not zero	BNE Label	2
Branch to label if carry flag set	BCS Label	2
Branch to label if carry flag clear	BCC Label	2
(all + 1 cycle if branch condition met + 2 cycles if to new page)		
Jump to label	JMP Label	3
No operation (ie dummy opcode)	NOP	2
Set interrupt disable flag	SEI	2
Clear interrupt disable flag	CLI	2
Return from subroutine	RTS	6

```
 10 REM signal capture
 20 REM flatout without trigger
 30 REM delay 14.5 microsecs
 40 REM not allowing for CPU slowing
 50 FOR PASS=0 TO 3 STEP 3
 60 P%=&C00
 70 [
 80 OPT PASS
 90 SEI
     2

100 LDA #0:STA &70
     2 ────→ 3

110 LDA #&E:STA &71
     2 ────→ 3
120
130 .go LDY #0
          2
140
150 .loop1 NOP

             2
160

170 NOP:NOP:NOP
     2 → 2 → 2
180
190 NOP:NOP:NOP
     2 → 2 → 2
200
210 .loop2 LDA &FCC0
             4 (+1)
220
230 STA (&70),Y
     6
240
250 INY:BNE loop1
     2   2-3
260
270 NOP:INC &71:LDA &71:CMP #&5D:BNE loop2
     2   5       3        2        2-3
280
290 CLI
300 RTS
310 .end
320 ]
330 NEXT
340 OSCLI"SAVE FastCODE C00 "+STR$~end
```

Time from entering machine code to start of taking 1st reading = 28 cycles
= 14 microsecs.

Fig. 7.1.a Fast capture without trigger.
Time from entering machine code to 1st reading.

```
 10 REM signal capture
 20 REM flatout without trigger
 30 REM delay 14.5 microsecs
 40 REM not allowing for CPU slowing
 50 FOR PASS=0 TO 3 STEP 3
 60 P%=&C00
 70 [
 80 OPT PASS
 90 SEI
      2

100 LDA #0:STA &70
      2      3

110 LDA #&E:STA &71
      2       3
120
130 .go LDY #0
          2
140
150 .loop1 NOP
             2 ←
160

170 NOP:NOP:NOP
      2→2→2
180
190 NOP:NOP:NOP
      2→2→2
200
210 .loop2 LDA &FCC0
         ► 4 (+1)
220
230 STA (&70),Y
      6
240
250 INY:BNE loop1
      2→2-3
260
270 NOP:INC &71:LDA &71:CMP #&5D:BNE loop2
      2    5      3      2       2-3
280
290 CLI
300 RTS
310 .end
320 ]
330 NEXT
340 OSCLI"SAVE FastCODE C00 "+STR$~end
```

Time to taking the next
and subsequent readings,
stored in the same page
of memory = 30 cycles
= 15 usecs.

(this includes the (+1)
cycle as the reading
is taken)

Fig. 7.1.b Fast capture without trigger.
Time for subsequent readings in same page.

```
 10 REM signal capture
 20 REM flatout without trigger
 30 REM delay 14.5 microsecs
 40 REM not allowing for CPU slowing
 50 FOR PASS=0 TO 3 STEP 3
 60 P%=&C00
 70 [
 80 OPT PASS
 90 SEI
     2

100 LDA #0:STA &70
     2      3

110 LDA #&E:STA &71
     2       3
120
130 .go LDY #0
         2
140
150 .loop1 NOP

             2
160                          Time taken to the next reading
                             when the memory changes page:
170 NOP:NOP:NOP                        = 30 cycles
     2   2   2                         = 15 usec.
180
190 NOP:NOP:NOP              After this Fig. 5.1.b is
     2   2   2               reactivated until the next
200                          page boundary.
210 .loop2 LDA &FCC0 ←
          ► 4 (+1)
220
230 STA (&70),Y
     6
240  ↓
250 INY:BNE loop1
     2 → 2-3
260
270 NOP:INC &71:LDA &71:CMP #&5D:BNE loop2
     2 → 5    →   3   →    2   →    2-3
280
290 CLI
300 RTS
310 .end
320 ]
330 NEXT
340 OSCLI"SAVE FastCODE C00 "+STR$~end
```

Fig. 7.1.c Fast capture without trigger.
Sample time when crossing page boundary.

```
 10 REM signal capture
 20 REM flatout with trigger
 30 REM delay 14.5 microsecs
 40 REM not allowing for CPU slowing
 50 FOR PASS=0 TO 3 STEP 3
 60 P%=&C00
 70 [
 80 OPT PASS
 90 SEI
     2
100 LDA #0:STA &70
     2      3
110 LDA #&E:STA &71
120  2      3
130 .trigger LDY #0
140          2
150 .loop LDA &FCC0
160         4 (+1)
170 STA (&70),Y
180  6
190 INY
200  2
210 CLC
220  2
230 .max CMP #128
240       2
250 BCS capture1
260 2-3
270 .min CMP #127
280       2
290 BCC capture2
300 2-3
310 CPY #255:BEQ trigger
320  2       2-3
330 .next JMP loop
340         3
350 .loop1 NOP:NOP
360          2   2
370 .capture1 NOP:NOP
380             2   2
390 .capture2 NOP:NOP:NOP
400             2   2   2
410 .loop2 LDA &FCC0
420          4 (+1)
430 STA (&70),Y
440  6
450 INY:BNE loop1
460  2  2-3
470 NOP
480  2
490 INC &71:LDA &71:CMP #&5D:BNE loop2
500  5       3       2       2-3
510 CLI
520 RTS
530 .end
540 ]
550 NEXT
560 OSCLI"SAVE FastTCODE C00 "+STR$~end
570 PRINT"max trigger level byte is &";~(max+1)
580 PRINT"min trigger level byte is &";~(min+1)
```

Time from entering machine
code to start of taking 1st
reading for comparison with
trigger thresholds:
= 14 cycles
= 7 usec.

Fig. 7.2.a Fast capture with trigger.
Time to first reading.

```
 10 REM signal capture
 20 REM flatout with trigger
 30 REM delay 14.5 microsecs
 40 REM not allowing for CPU slowing
 50 FOR PASS=0 TO 3 STEP 3
 60 P%=&C00
 70 [
 80 OPT PASS
 90 SEI
     2
100 LDA #0:STA &70
     2       3
110 LDA #&E:STA &71
120  2       3
130 .trigger LDY #0
140                2
150 .loop LDA &FCC0
160             4 (+1)
170 STA (&70),Y
180  6
190 INY
200  2
210 CLC
220  2
230 .max CMP #128 *
240           2
250 BCS capture1
260 2-3
270 .min CMP #127 *
280           2
290 BCC capture2
300 2-3
310 CPY #255:BEQ trigger
320  2          2-3
330 .next JMP loop
340          3
350 .loop1 NOP:NOP
360            2   2
370 .capture1 NOP:NOP
380               2    2
390 .capture2 NOP:NOP:NOP
400                2    2    2
410 .loop2 LDA &FCC0
420            4 (+1)
430 STA (&70),Y
440  6
450 INY:BNE loop1
460  2   2-3
470 NOP
480  2
490 INC &71:LDA &71:CMP #&5D:BNE loop2
500  5        3        2        2-3
510 CLI
520 RTS
530 .end
540 ]
550 NEXT
560 OSCLI"SAVE FastTCODE C00 "+STR$~end
570 PRINT"max trigger level byte is &";~(max+1)
580 PRINT"min trigger level byte is &";~(min+1)
```

This loop captures a max. of 256 bytes, checking to see if trigger activated. If not, line 310 checks to see if last byte of page memory has been reached. If so, line 310 will start new capture at line 130, filling up the same page again.

* Nominal values. Set to chosen max. and min. from software.

The loop shown does not activate a trigger.
Loop = 30 cycles
= 15 usec.

Fig. 7.2.b Fast capture with trigger.
Stores first page repeatedly.

```
 10 REM signal capture
 20 REM flatout with trigger
 30 REM delay 14.5 microsecs
 40 REM not allowing for CPU slowing
 50 FOR PASS=0 TO 3 STEP 3
 60 P%=&C00
 70 [
 80 OPT PASS
 90 SEI
     2
100 LDA #0:STA &70
     2      3
110 LDA #&E:STA &71
120  2      3
130 .trigger LDY #0
140                2
150 .loop LDA &FCC0
160            4 (+1)
170 STA (&70),Y
180  6
190 INY
200  2
210 CLC
220  2
230 .max CMP #128 *
240            2
250 BCS capture1
260 2-3
270 .min CMP #127 *
280            2
290 BCC capture2
300 2-3
310 CPY #255:BEQ trigger
320  2         2-3
330 .next JMP loop
340            3
350 .loop1 NOP:NOP
360             2   2
370 .capture1 NOP:NOP
380                2   2
390 .capture2 NOP:NOP:NOP
400                2   2   2
410 .loop2 LDA &FCC0
420             4 (+1)
430 STA (&70),Y
440  6
450 INY:BNE loop1
460  2  2-3
470 NOP
480  2
490 INC &71:LDA &71:CMP #&5D:BNE loop2
500  5       3       2        2-3
510 CLI
520 RTS
530 .end
540 ]
550 NEXT
560 OSCLI"SAVE FastTCODE C00 "+STR$~end
570 PRINT"max trigger level byte is &";~(max+1)
580 PRINT"min trigger level byte is &";~(min+1)
```

Time as for Fig.5.2.b,
but reaching the end
byte of page.

Loop = 30 cycles
= 15 usec.

* Nominal values
see Fig.5.2.b

Fig. 7.2.c Fast capture with trigger.
Last byte of trigger page reached.

```
 10 REM signal capture
 20 REM flatout with trigger
 30 REM delay 14.5 microsecs
 40 REM not allowing for CPU slowing
 50 FOR PASS=0 TO 3 STEP 3
 60 P%=&C00
 70 [
 80 OPT PASS
 90 SEI
     2
100 LDA #0:STA &70
     2      3
110 LDA #&E:STA &71
120  2       3
130 .trigger LDY #0
140               2
150 .loop LDA &FCC0
160             4 (+1)
170 STA (&70),Y
180  6
190 INY
200  2
210 CLC
220  2
230 .max CMP #128
240           2
250 BCS capture1
260 2-3
270 .min CMP #127
280           2
290 BCC capture2
300 2-3
310 CPY #255:BEQ trigger
320  2          2-3
330 .next JMP loop
340           3
350 .loop1 NOP:NOP
360             2   2
370 .capture1 NOP:NOP
380                2   2
390 .capture2 NOP:NOP:NOP
400                 2   2   2
410 .loop2 LDA &FCC0
420             4 (+1)
430 STA (&70),Y
440  6
450 INY:BNE loop1
460  2  2-3
470 NOP
480  2
490 INC &71:LDA &71:CMP #&5D:BNE loop2
500  5       3       2       2-3
510 CLI
520 RTS
530 .end
540 ]
550 NEXT
560 OSCLI"SAVE FastTCODE C00 "+STR$~end
570 PRINT"max trigger level byte is &";~(max+1)
580 PRINT"min trigger level byte is &";~(min+1)
```

Path taken in response to
a positive trigger.
From reading to reading
time = 30 cycles
     = 15 usecs.

Fig. 7.2.d Fast capture with trigger.
Response to a positive trigger.

```
  10 REM signal capture
  20 REM flatout with trigger
  30 REM delay 14.5 microsecs
  40 REM not allowing for CPU slowing
  50 FOR PASS=0 TO 3 STEP 3
  60 P%=&C00
  70 [
  80 OPT PASS
  90 SEI
      2
 100 LDA #0:STA &70
      2      3
 110 LDA #&E:STA &71
 120  2        3
 130 .trigger LDY #0
 140           2
 150 .loop LDA &FCC0
 160        4 (+1)
 170 STA (&70),Y
 180  6
 190 INY
 200  2
 210 CLC
 220  2
 230 .max CMP #128
 240       2
 250 BCS capture1
 260 2-3
 270 .min CMP #127
 280       2
 290 BCC capture2
 300 2-3
 310 CPY #255:BEQ trigger
 320  2        2-3
 330 .next JMP loop
 340        3
 350 .loop1 NOP:NOP
 360         2   2
 370 .capture1 NOP:NOP
 380           2   2
 390 .capture2 NOP:NOP:NOP
 400            2   2   2
 410 .loop2 LDA &FCC0
 420         4 (+1)
 430 STA (&70),Y
 440  6
 450 INY:BNE loop1
 460  2  2-3
 470 NOP
 480  2
 490 INC &71:LDA &71:CMP #&5D:BNE loop2
 500  5       3       2       2-3
 510 CLI
 520 RTS
 530 .end
 540 ]
 550 NEXT
 560 OSCLI"SAVE FastTCODE C00 "+STR$~end
 570 PRINT"max trigger level byte is &";~(max+1)
 580 PRINT"min trigger level byte is &";~(min+1)
```

Path taken in response to
a negative trigger.
From reading to reading
time = 30 cycles
     = 15 usecs.

Fig. 7.2.e Fast capture with trigger.
Response to a negative trigger.

```
 10 REM signal capture
 20 REM flatout with trigger
 30 REM delay 14.5 microsecs
 40 REM not allowing for CPU slowing
 50 FOR PASS=0 TO 3 STEP 3
 60 P%=&C00
 70 [
 80 OPT PASS
 90 SEI
     2
100 LDA #0:STA &70
     2      3
110 LDA #&E:STA &71
120  2       3
130 .trigger LDY #0
140              2
150 .loop LDA &FCC0
160            4 (+1)
170 STA (&70),Y
180  6
190 INY
200  2
210 CLC
220  2
230 .max CMP #128
240          2
250 BCS capture1
260 2-3
270 .min CMP #127
280          2
290 BCC capture2
300 2-3
310 CPY #255:BEQ trigger
320  2        2-3
330 .next JMP loop
340            3
350 .loop1 NOP:NOP
360             2   2
370 .capture1 NOP:NOP
380                2    2
390 .capture2 NOP:NOP:NOP
400                2   2   2
410 .loop2 LDA &FCC0 ←
420             4 (+1)
430 STA (&70),Y
440  6
450 INY:BNE loop1
460  2 →2-3
470 NOP
480  2
490 INC &71:LDA &71:CMP #&5D:BNE loop2
500  5 ——→ 3 ——→ 2 —— 2-3
510 CLI
520 RTS
530 .end
540 ]
550 NEXT
560 OSCLI"SAVE FastTCODE C00 "+STR$~end
570 PRINT"max trigger level byte is &";~(max+1)
580 PRINT"min trigger level byte is &";~(min+1)
```

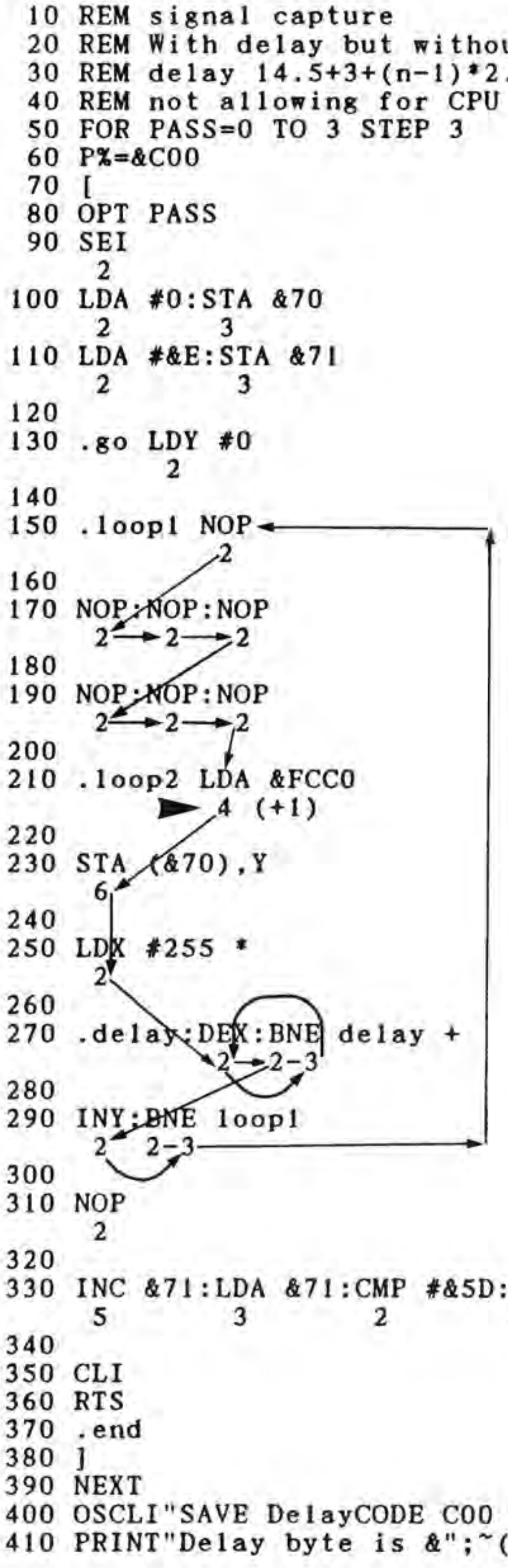
After triggering
the capture loop
is entered as in
Fig. 5.1.c.
Time = 15 usec.
per sample.

Fig. 7.2.f Fast capture with trigger.
Loop entered after triggering.

```
 10 REM signal capture
 20 REM With delay but without trigger
 30 REM delay 14.5+3+(n-1)*2.5 usecs
 40 REM not allowing for CPU slowing
 50 FOR PASS=0 TO 3 STEP 3
 60 P%=&C00
 70 [
 80 OPT PASS
 90 SEI
     2
100 LDA #0:STA &70
     2      3
110 LDA #&E:STA &71
     2      3
120
130 .go LDY #0
          2
140
150 .loop1 NOP
            2
160
170 NOP:NOP:NOP
     2   2   2
180
190 NOP:NOP:NOP
     2   2   2
200
210 .loop2 LDA &FCC0
            4 (+1)
220
230 STA (&70),Y
     6
240
250 LDX #255
     2
260
270 .delay:DEX:BNE delay
            2   2-3
280
290 INY:BNE loop1
     2   2-3
300
310 NOP
     2
320
330 INC &71:LDA &71:CMP #&5D:BNE loop2
     5       3       2        2-3
340
350 CLI
360 RTS
370 .end
380 ]
390 NEXT
400 OSCLI"SAVE DelayCODE C00 "+STR$~end
410 PRINT"Delay byte is &";~(delay-1)
```

Time from entering machine code to start taking 1st reading = 28 cycles = 14 usec.

Fig. 7.3.a Delayed capture without trigger.
Time from entering machine code to 1st reading.



```
 10 REM signal capture
 20 REM With delay but without trigger
 30 REM delay 14.5+3+(n-1)*2.5 usecs
 40 REM not allowing for CPU slowing
 50 FOR PASS=0 TO 3 STEP 3
 60 P%=&C00
 70 [
 80 OPT PASS
 90 SEI
     2
100 LDA #0:STA &70
     2      3
110 LDA #&E:STA &71
     2        3
120
130 .go LDY #0
         2
140
150 .loop1 NOP
            2
160
170 NOP:NOP:NOP
     2   2   2
180
190 NOP:NOP:NOP
     2   2   2
200
210 .loop2 LDA &FCC0
            4 (+1)
220
230 STA (&70),Y
     6
240
250 LDX #255 *
     2
260
270 .delay:DEX:BNE delay +
            2   2-3
280
290 INY:BNE loop1
     2   2-3
300
310 NOP
     2
320
330 INC &71:LDA &71:CMP #&5D:BNE loop2
     5       3       2        2-3
340
350 CLI
360 RTS
370 .end
380 ]
390 NEXT
400 OSCLI"SAVE DelayCODE C00 "+STR$~end
410 PRINT"Delay byte is &";~(delay-1)
```

This loop captures and stores readings within one page of memory.
At fastest, the delay loop at line 270 is 4 cycles so the main loop takes 36 cycles = 18 usec. Each delay subloop then adds 5 cycles = 2.5 usec.

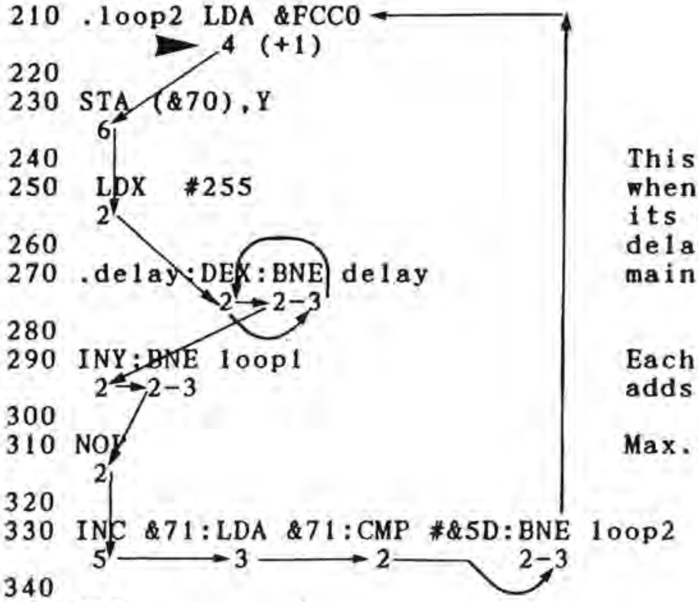
Max. delay = 18+254x2.5 usec.
= 653 usec.

* Value altered by setting delay time through software.
max. = 255 min. = 1

\+ This subloop is executed 254 times for max. delay, or 0 times for min. delay.

Fig. 7.3.b Delayed capture without trigger.
Variable delay loop incorporated.

```
 10 REM signal capture
 20 REM With delay but without trigger
 30 REM delay 14.5+3+(n-1)*2.5 usecs
 40 REM not allowing for CPU slowing
 50 FOR PASS=0 TO 3 STEP 3
 60 P%=&C00
 70 [
 80 OPT PASS
 90 SEI
     2
100 LDA #0:STA &70
     2      3
110 LDA #&E:STA &71
     2       3
120
130 .go LDY #0
         2
140
150 .loop1 NOP
             2
160
170 NOP:NOP:NOP
     2   2   2
180
190 NOP:NOP:NOP
     2   2   2
200
210 .loop2 LDA &FCC0
              4 (+1)
220
230 STA (&70),Y
     6
240
250  LDX  #255
     2
260
270 .delay:DEX:BNE delay
             2  2-3
280
290 INY:BNE loop1
     2  2-3
300
310 NOP
     2
320
330 INC &71:LDA &71:CMP #&5D:BNE loop2
     5      3       2        2-3
340
350 CLI
360 RTS
370 .end
380 ]
390 NEXT
400 OSCLI"SAVE DelayCODE C00 "+STR$~end
410 PRINT"Delay byte is &";~(delay-1)
```



This loop changes page when storing data. At its fastest subloop delay is 4 usec, so main loop = 36 cycles = 18 usec.

Each delay subloop adds 5 cycles = 2.5 us.

Max. delay = 18+254x2.5 = 653 usec.

Fig. 7.3.c Delayed capture without trigger.
Loop followed when page boundary is crossed.

```
 10 REM signal capture  - delay with trigger
 30 REM delay 14.5+3+(n-1)*2.5 usecs
 30 FOR PASS=0 TO 3 STEP 3
 40 P%=&C00
 50 [OPT PASS
 60 SEI
      2
 70 LDA #0:STA &70:LDA #&E:STA &71
 80  2          3          2          3
 90 .trigger LDY #0
100              2
110 .loop LDA &FCC0:STA (&70),Y
120           4 (+1)     6
130 INY
130  2
150 .mem1 LDX #255
160           2
170 .delay1 DEX:BNE delay1
180             2  2-3
190 CLC
200  2
210 .max CMP #128
220          2
230 BCS capture1
240 2-3
250 .min CMP #127
260          2
270 BCC capture2
280 2-3
290 CPY #255:BEQ trigger
300  2         2-3
310 .next JMP loop
320           3
330 .loop1 NOP:NOP
340             2   2
350 .capture1 NOP:NOP
360                2   2
370 .capture2 NOP:NOP:NOP
380                2   2   2
390 .loop2 LDA &FCC0:STA (&70),Y
400            4 (+1)     6
410 .mem2 LDX #255
420           2
430 .delay2 DEX:BNE delay2
440             2  2-3
450 INY:BNE loop1
460  2  2-3
470 NOP:INC &71:LDA &71:CMP #&5D:BNE loop2
480  2   5       3       2         2-3
490 CLI
500 RTS
510 ]
520 NEXT
530 OSCLI"SAVE DelayTCODE C00 "+STR$~end
540 PRINT"Delay bytes are &";~(mem1+1);" and &";~(mem2+1)
550 PRINT"max trigger byte is &";~(max+1)
560 PRINT"min trigger byte is &";~(min+1)
```

Time to start of 1st reading
= 14 cycles
= 7 usec.

After the first reading at line 110, by comparison with Figs 5.2.a-f and Figs 5.3.a-c it can be seen that all loops are 18 usec. + multiples of 2.5 usec. up to 18+254x2.5 us. ie. 653 usec. depending on the level of delay required.

Fig. 7.4.a Delayed capture with trigger
Time from entering machine code to 1st reading.

SIGNAL CAPTURE

MASTER 128 MEMORY USAGE AND DATAFILE LAYOUT

Datafiles are *LOADed and *SAVEd using memory addresses **&E00-&5EFF**
The actual memory within the computer is allocated as follows:

&E00-&5CFF	the captured signal (20224 points)
&5D00	delay [15 if address contents=0] [18+2.5*(address contents-1) if contents>0] times in microsecs
&5D01	trigger setting ON/OFF 0=off 1=ON
&5D02	trigger offset level if trigger active Set to 0 if trigger OFF
&5D03	Range setting 0=+10V 1=+1V 2=+0.1V 3=+var 4=+/-5V 5=+/-0.5V 6=+/-0.05V 7=+/-var
&5D04-&5D0F	reserved for future expansion, currently zero
&5D10	Title string for graph (30 digits max) default "None"
&5D80	Filename if SAVEd (10 digits max in ADFS) default "None"
&5D90	String for date and time of capture
&5E00	Notes string for graph (255 digits max) default "None"

The program itself sits at PAGE=&5F00 and is only compatible with the Master 128 computer.

Fig.7.5. BBC Master128: Memory usage and datafile layout.

CHAPTER 8

VERIFICATION OF THE SIGNAL CAPTURE PROGRAM AND VALIDATION OF THE ASSOCIATED HARDWARE

VERIFICATION OF THE SIGNAL CAPTURE PROGRAM AND VALIDATION OF THE ASSOCIATED HARDWARE

The experimental design, shown in Plate 8.1, developed in this work allows two methods of capturing gnathosonic signals, either direct capture by computer or recording signals on a cassette tape recorder for later replay into the computer. As with any such experimental design, it is necessary that both hardware and software to effect signal capture should be tested and validated. Clearly it is necessary that all components of the assembled hardware and software are capable of capturing signals without alteration and that this be verified by experiment. Central to signal capture is the software timings, since unless these timings are exact the whole system will fail.

The experiments described in this chapter are designed to verify each section of the assembled system separately using a storage oscilloscope as a comparative standard. These experiments are carried out according to the following protocol.

1) Software capture rate verification.

2) Tape recorder standardisation.

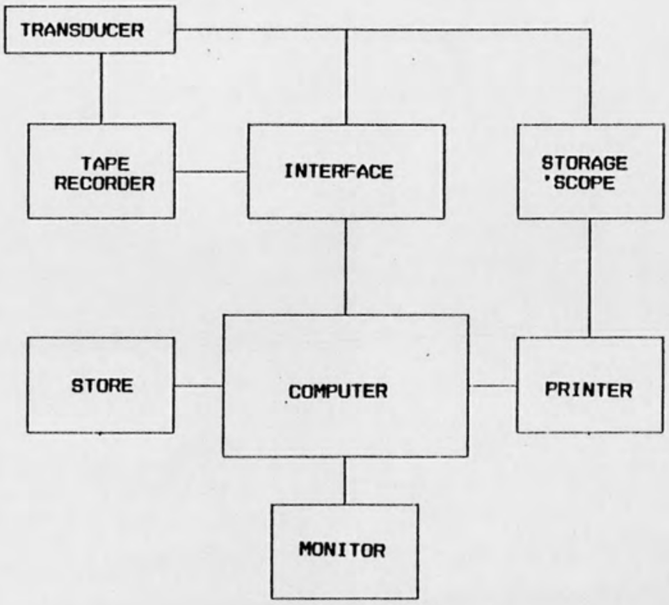


Plate 8.1 Assembly of tape recorder, sensor, interface, computer and printer.
Above: Schematic diagram.

3) Characteristics of sensor with computer and recorder.

EXPERIMENT 8.1.

VERIFICATION OF SOFTWARE CAPTURE RATES

INTRODUCTION

As described in Chapter 7 software capture times were based on the calculation of the interval required by the CPU to execute the various opcodes in the capture programs. These timings are published by the manufacturer of the CPU, and the timings of operations are dependent upon the clock of the CPU running accurately at 2MHz. However all the calculations are theoretical and require experimental verification.

METHOD

A function generator (Thandar TG102 RS Components Ltd UK), seen in Plate 8.2, was used to provide saw tooth waveforms of 100Hz, 1KHz, 10KHz, 20KHz, 30KHz and 40KHz. The output signals were divided between a storage oscilloscope (Thurlby DSA524, Thurlby Electronics Ltd UK) and a computer interface (Unilab Interface 532.001, Unilab UK) attached to the computer (BBC Master 128, Acorn Computers UK) through the 1MHz bus port. The

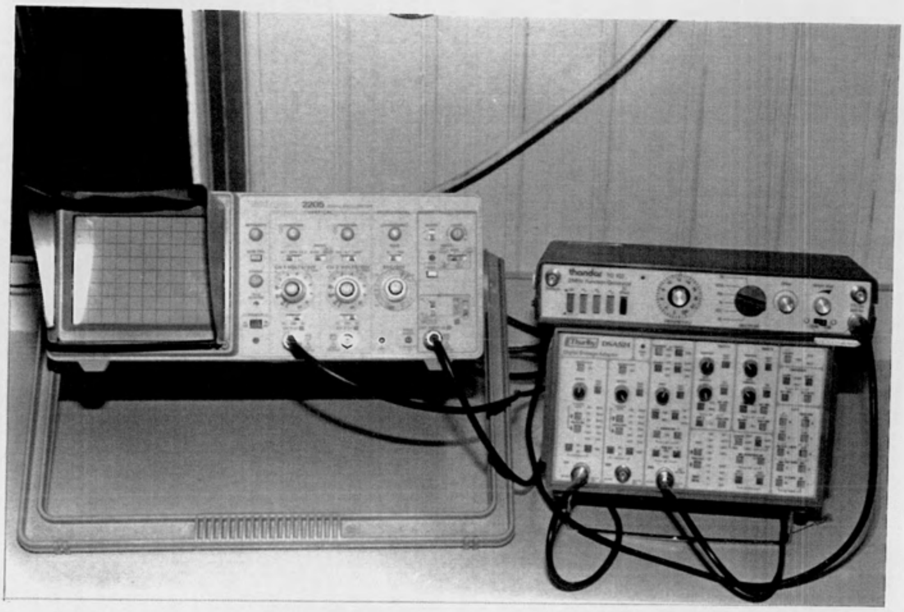


Plate 8.2 Function generator with oscilloscope and storage adaptor.

signals were captured without triggering at a sampling time of 15us. Screen dumps were made by both instruments after a sample of each signal was captured. Some of the screen dumps were plotted as points.

RESULTS

The results of experiment 8.1 are shown in figures 8.1.a-f as either oscilloscope or computer screen dumps.

DISCUSSION

It should be noted that the actual opcode timings give an incorrect frequency and a correction of 0.5us has to be added to each pass of the capture loop. The error is due to the CPU running at 2MHz whereas the data bus operates at only 1MHz. As a result the CPU must slow by some whole number of cycles while the data from the interface is read. Since each cycle of the CPU takes 0.5us, the error in software timings is a simple multiple of this, and since the reading of the data takes nominally 4 cycles, the maximum possible error is 2us. It is a simple matter to use standard signals such as sine or saw tooth waves of known frequency to determine the error, which was found by preliminary experiments to be 0.5us. The CPU therefore only slows down for 1 cycle as data from the interface is read.

For this purpose, the function generator provided a series of saw tooth waveforms which were captured by the computer program and oscilloscope.

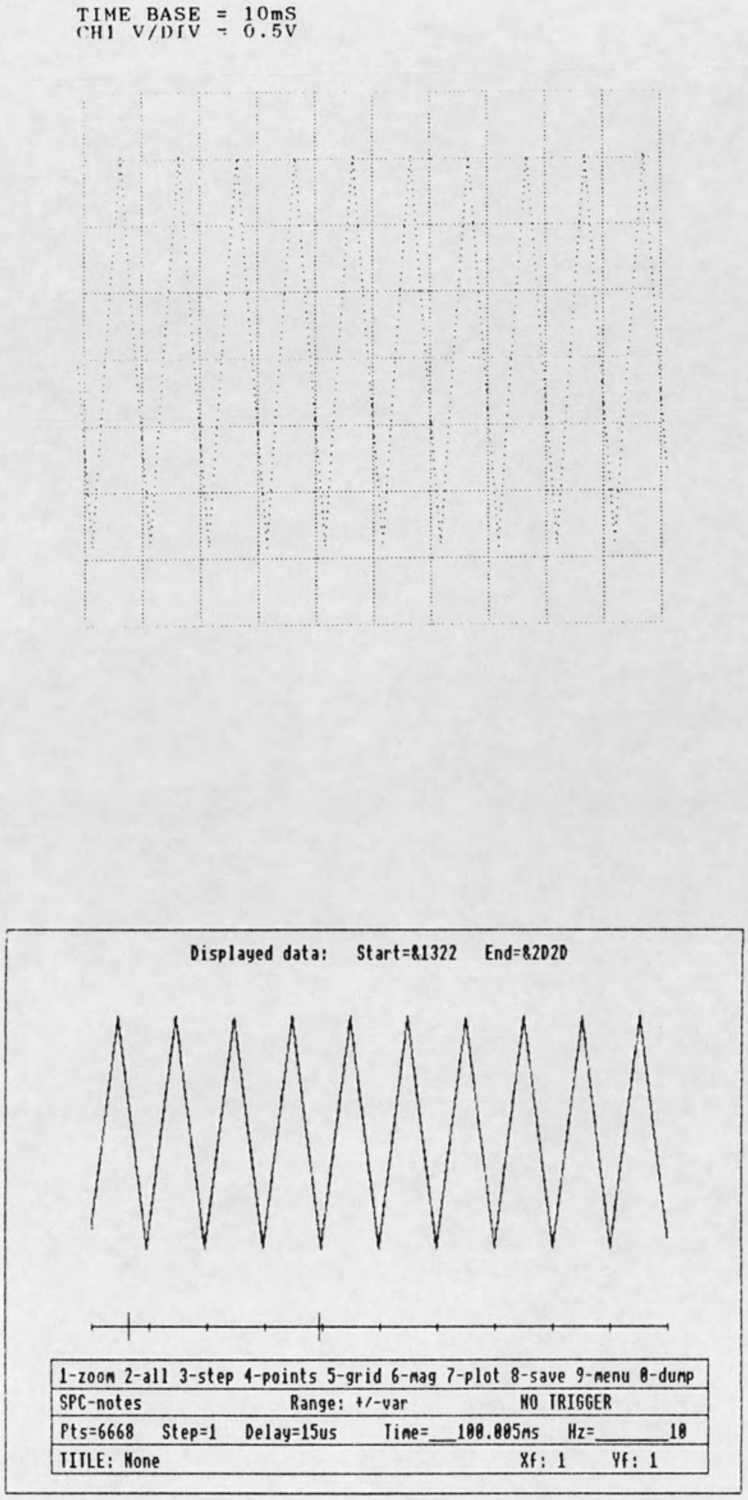
Saw-tooth waveforms were generated because each slope is a straight line, which makes comparison simpler. The storage oscilloscope displays 1024 readings per sweep which are shown in some figures as individual points rather than joined together to demonstrate the number of points plotted. This facility allows accurate frequency readings to be made. For example, a 1KHz signal displayed at a timebase of 1ms will show one peak in each of the ten divisions of the display, plotting a total of 1024 points for a full scale sweep. From this a more precise frequency from the generator may be calculated than can be visualised from a trace on a graticule. The computer program however not only records the number of points plotted but can also mark the position of the points on the traces if required.

Prior to dumping, the computer screen displays were adjusted to show ten cycles of a captured signal from which its frequency was estimated. Clearly the greater the number of cycles shown in a display, the greater will be the estimated accuracy of the frequency.

It can be seen from figures 8.1.a-e that there is a close correlation between the frequencies displayed by the computer and oscilloscope. For example, the oscilloscope set to a timebase of 100us will plot 102.4 points per screen division. At two cycles per division each cycle will be plotted by 50.12 points, each point separated by a time interval of 0.1us. The accuracy of the oscilloscope at 20KHz is therefore ±0.05us. The computer capture routine however, takes a reading every 15us therefore at 20KHz there will be 33.3 readings per cycle with an accuracy of ±7.5us (0.15% error). Taken over a sequence of 10 cycles the error would be reduced by a factor of ten.

At 30KHz in figure 8.1.e, the signals can still be seen to represent the frequency, but the computer appears to be approaching its limit of resolution, which is a minimum of two points per cycle. For the computer this limit is 33.3KHz because the maximum sampling rate of the computer program is 15us, ie. 66.6KHz.

At 40KHz in figure 8.1.f it can be seen that the computer captured frequency is no longer similar to that captured by the oscilloscope. As the frequency under investigation is now in excess of half the computer sampling rate, the resultant signal has been aliased and appears not as 40KHz but as a longer wavelength.

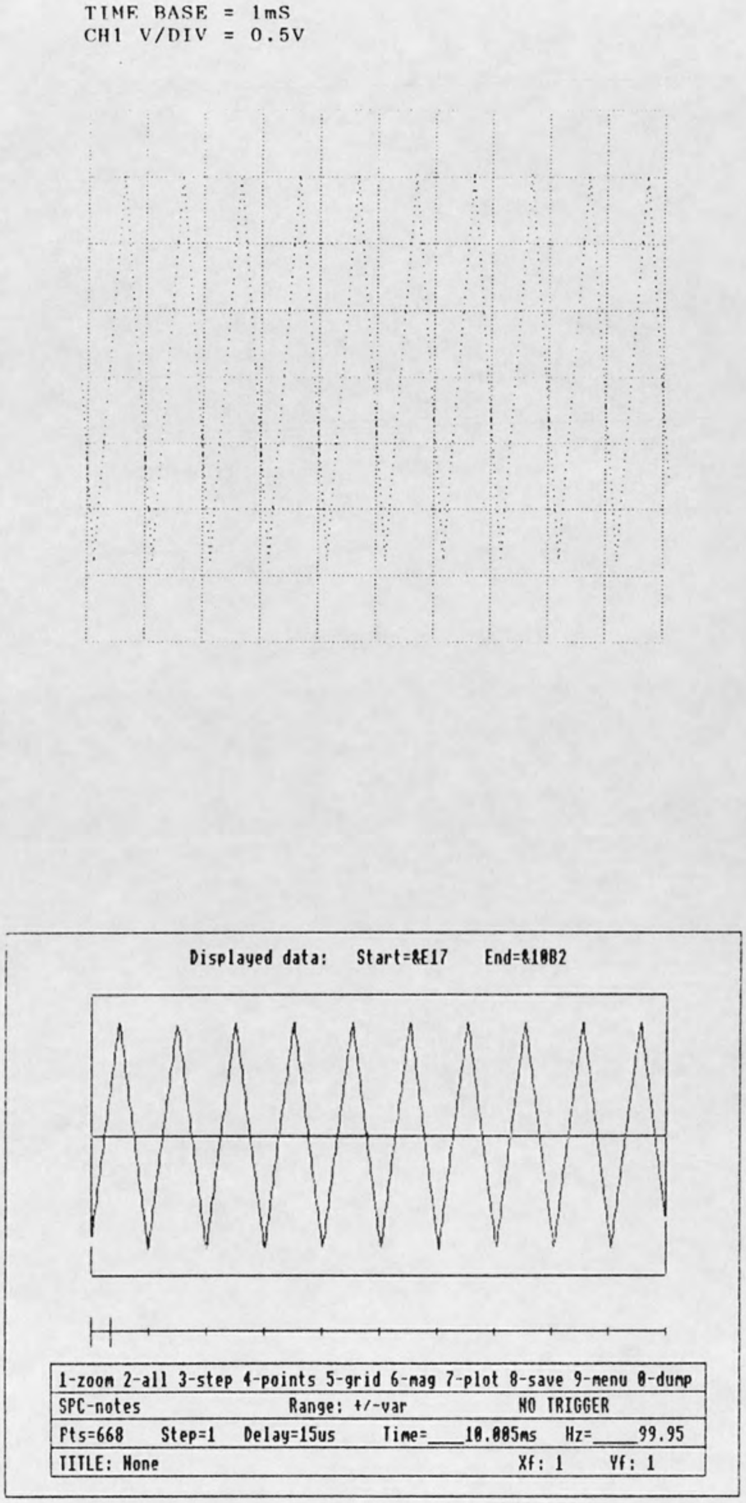


```
TIME BASE = 10mS
CH1 V/DIV = 0.5V
```

```
Displayed data:   Start=&1322   End=&2D2D

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                  Range: +/-var           NO TRIGGER
Pts=6668   Step=1   Delay=15us    Time=___100.005ms   Hz=________10
TITLE: None                                        Xf: 1     Yf: 1
```

Fig.8.1.a. Screen dumps of 100Hz signal.
Upper trace: Storage oscilloscope.
Lower trace: Computer.

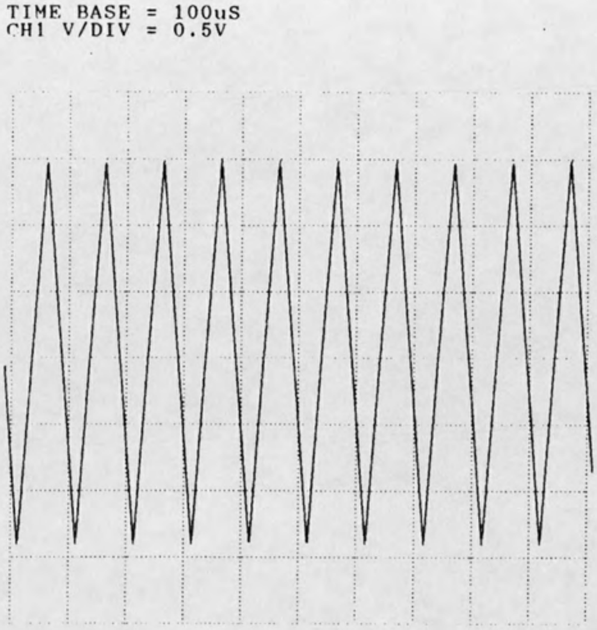


```
TIME BASE = 1mS
CH1 V/DIV = 0.5V
```

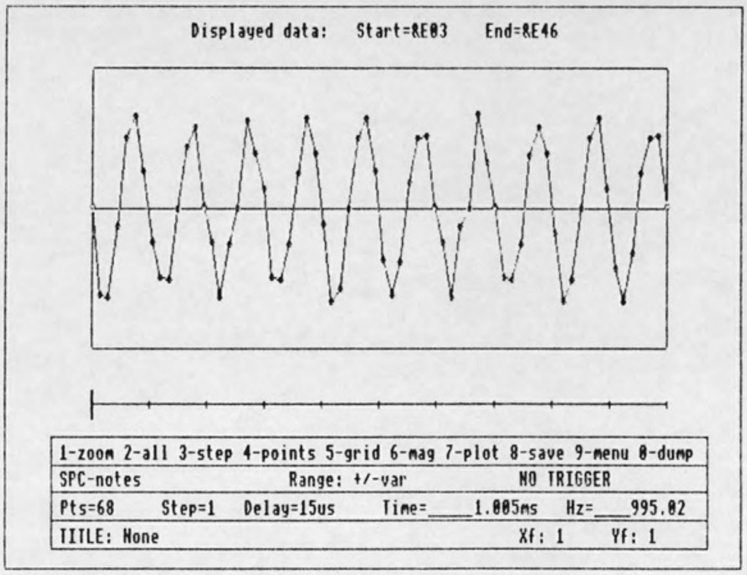
```
Displayed data:   Start=&E17   End=&10B2
```

```
SPC-notes                Range: +/-var           NO TRIGGER
Pts=668    Step=1   Delay=15us    Time=____10.005ms  Hz=_____99.95
TITLE: None                                      Xf: 1    Yf: 1
```

Fig.8.1.b. Screen dumps of 1KHz signal.
Upper trace: Storage oscilloscope.
Lower trace: Computer.

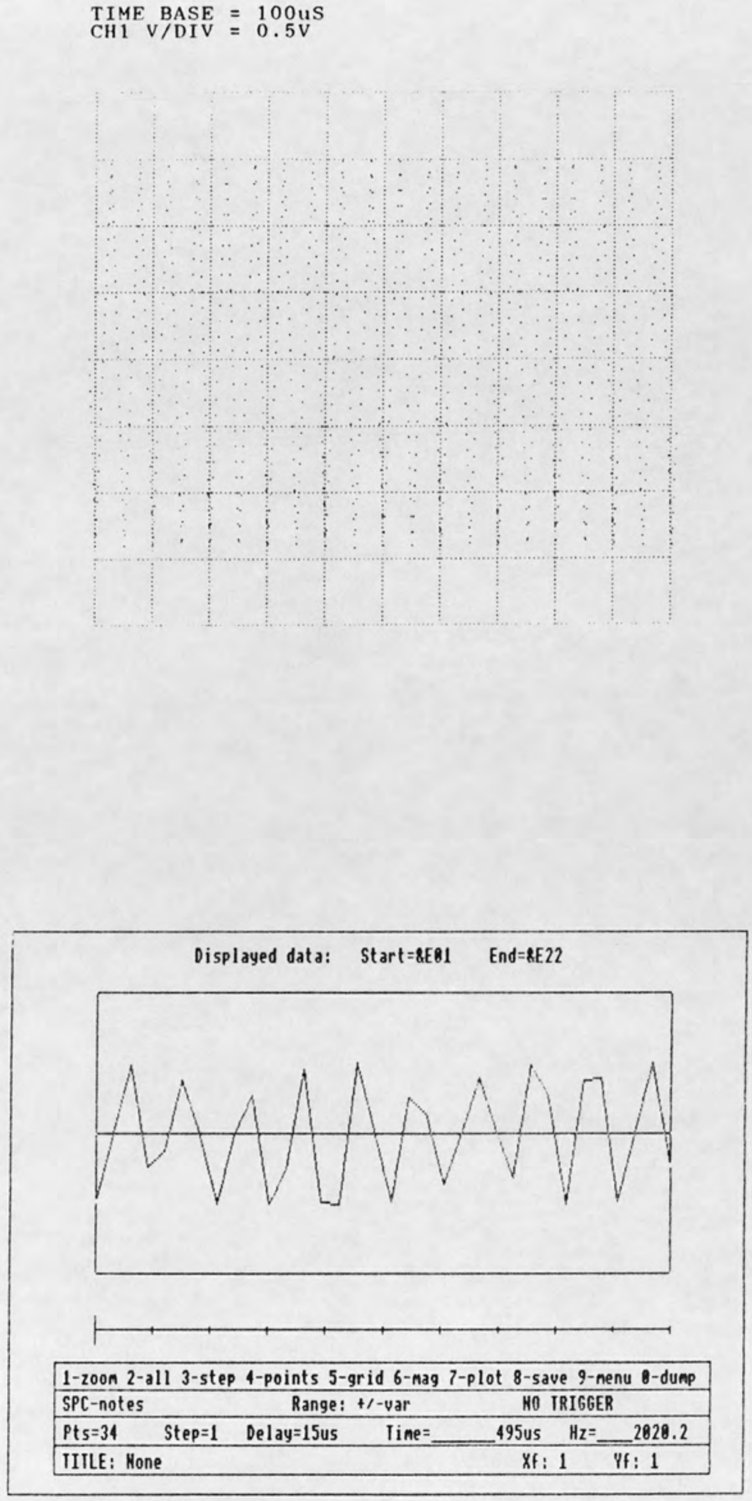


```
TIME BASE = 100uS
CH1 V/DIV = 0.5V
```



```
Displayed data:   Start=&E03   End=&E46
SPC-notes                Range: +/-var              NO TRIGGER
Pts=68     Step=1   Delay=15us     Time=_____1.005ms   Hz=____995.02
TITLE: None                                         Xf: 1     Yf: 1
```

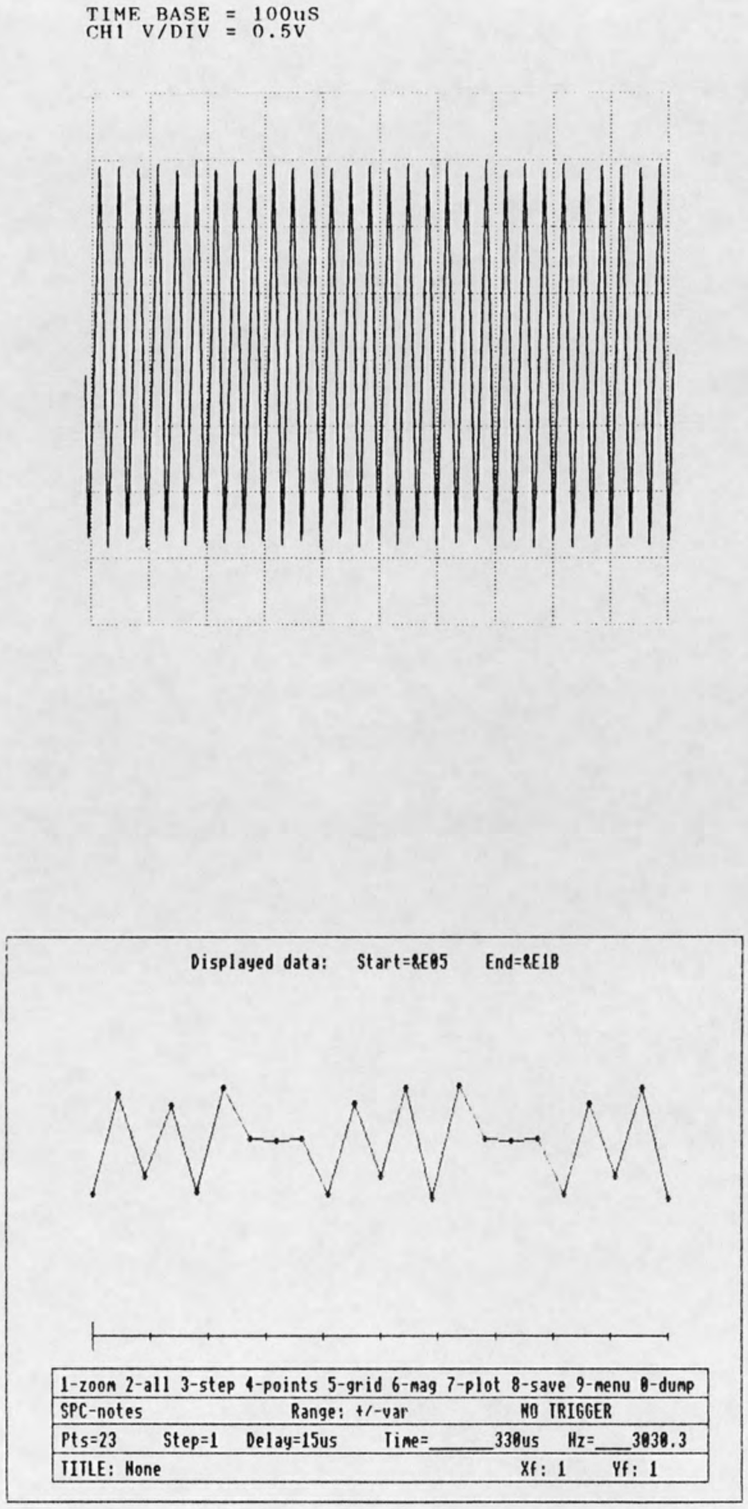
Fig.8.1.c. Screen dumps of 10KHz signal.
Upper trace: Storage oscilloscope.
Lower trace: Computer.



```
Displayed data:   Start=&E01    End=&E22
```

```
SPC-notes                 Range: +/-var              NO TRIGGER
Pts=34     Step=1   Delay=15us     Time=_______495us   Hz=____2020.2
TITLE: None                                          Xf: 1     Yf: 1
```

Fig.8.1.d. Screen dumps of 20KHz signal.
Upper trace: Storage oscilloscope.
Lower trace: Computer.

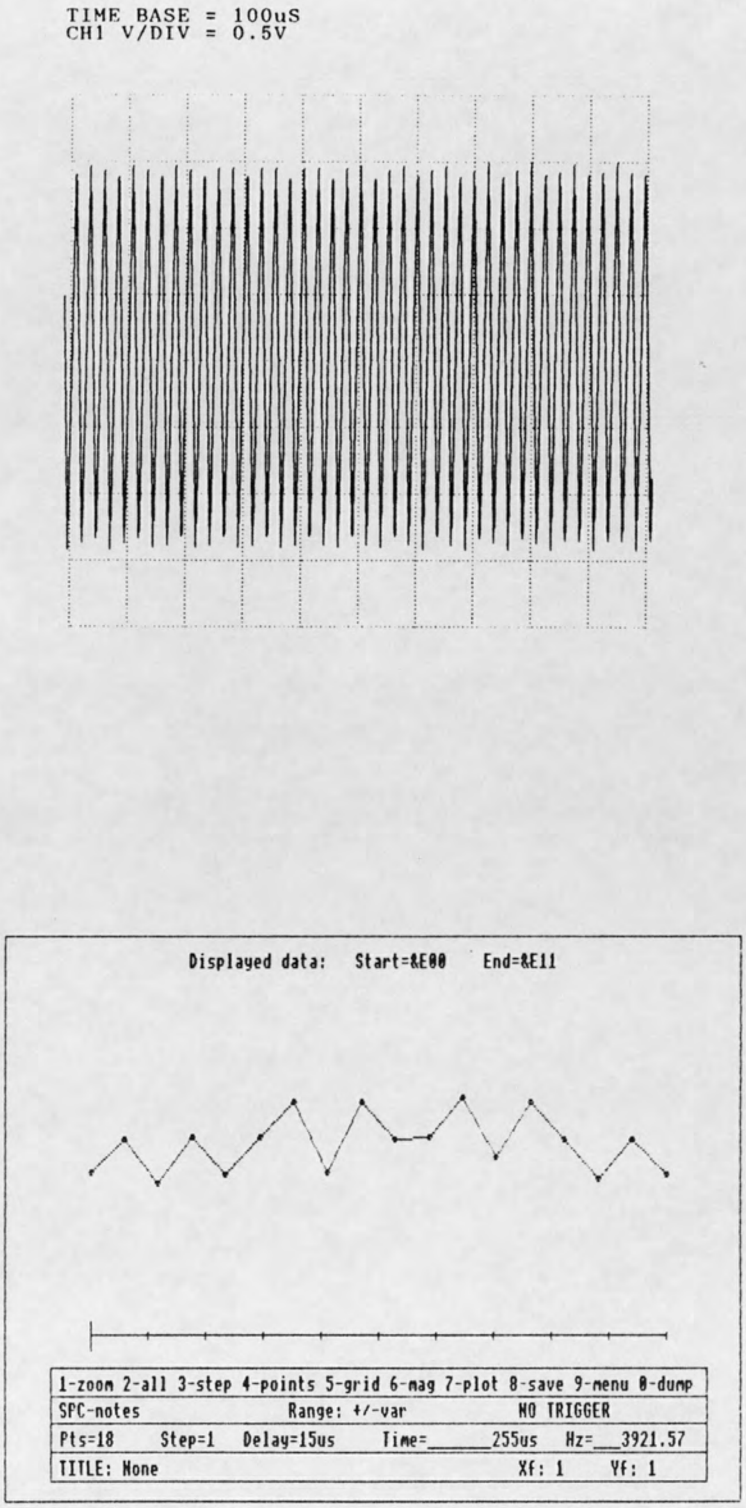


```
TIME BASE = 100uS
CH1 V/DIV = 0.5V
```

```
Displayed data:   Start=&E05    End=&E1B

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                 Range: +/-var              NO TRIGGER
Pts=23     Step=1   Delay=15us      Time=_______330us   Hz=____3030.3
TITLE: None                                          Xf: 1     Yf: 1
```

Fig.8.1.e. Screen dumps of 30KHz signal.
Upper trace: Storage oscilloscope.
Lower trace: Computer.



TIME BASE = 100uS
CH1 V/DIV = 0.5V

Displayed data: Start=&E00 End=&E11

SPC-notes Range: +/-var NO TRIGGER

Pts=18 Step=1 Delay=15us Time=______255us Hz=___3921.57

TITLE: None Xf: 1 Yf: 1

Fig.8.1.f. Screen dumps of 40KHz signal.
Upper trace: Storage oscilloscope.
Lower trace: Computer.

It is clear from this that the computer program is capable of satisfactorily capturing signals up to 33.3KHz without aliasing. It has already been demonstrated in chapter 4 that gnathosonic signals have a range of 0-6±1KHz and a sensor resonance of 12.5KHz therefore the computer program will capture gnathosonic frequencies.

EXPERIMENT 8.2

STANDARDISATION OF THE TAPE RECORDER

INTRODUCTION

The majority of clinical gnathosonic recordings are made on magnetic tape for later analysis. The recording equipment can be very sophisticated and expensive, but one of the objectives of the work in this thesis is to provide the general practitioner with an inexpensive means of gnathosonic study. The experimental design therefore incorporated a domestic cassette recorder using standard cassette tapes. It is clearly necessary that such a recorder should faithfully record and reproduce sounds generated by gnathosonic procedures. A 50ohm shunt was always used in sensor leads to avoid activating the recording automatic gain control.

METHOD

Saw tooth waveforms of 100Hz, 1KHz, 8KHz, 10KHz and 12.5KHz were produced by a function generator. The output signals were divided between the interface attached to the computer as described in experiment 8.1 and the microphone socket of the cassette recorder (Philips D6350, Philips UK.). The recorded signals were then replayed from the line out socket of the recorder directly into the Unilab interface and captured for a second time by the computer. Screen dumps were made after each capture to compare the original and replayed signals.

RESULTS

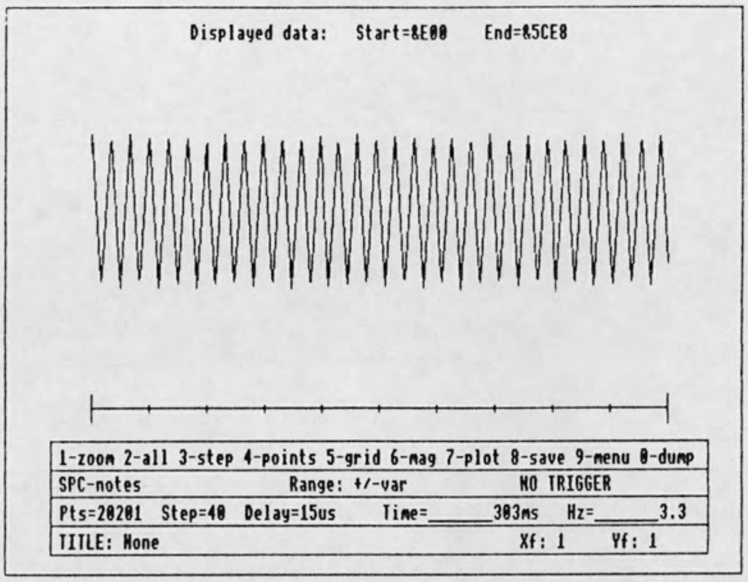
The results of experiment 8.2 are shown in figures 8.2.a-e as computer screen dumps.

DISCUSSION

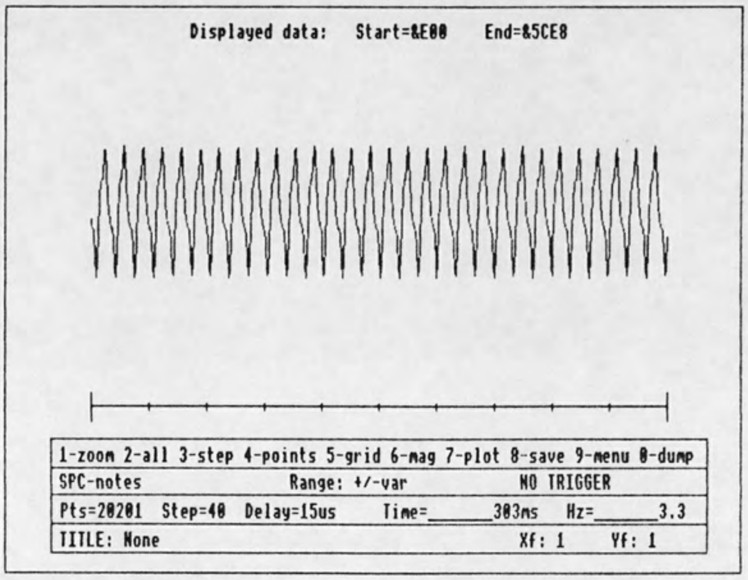
The signals replayed on the cassette recorder were captured in the same manner as those captured from the function generator, by replaying a given frequency which was captured without triggering using a sample time of 15us.

The cassette recorder selected has a specified frequency response of 100-8000Hz within 8dB, which includes the upper range of the expected frequency generated by tooth impacts. It can be seen from figures 8.2.a-c that there is a good correlation between the same signals captured directly or captured on replay from the recorder.

However it can be seen from figure 8.2.d that the replayed signal has undergone significant attenuation at 10KHz, which is 2KHz above the upper limit of the optimum frequency response range of the recorder. This is even more apparent in figure 8.2.e where the captured signal has the appearance of background noise, yet when the signal is enlarged by a factor of ten by the computer program, as can be seen in figure 8.2.f, the frequency of 12.5KHz is evident. This is convenient because the resonant frequency of the selected sensor (12.5KHz) is for practical purposes reduced to background level and even at this level will not be aliased. An added factor is that a number of commercial cassette tapes show a loss in frequency response above 8KHz.

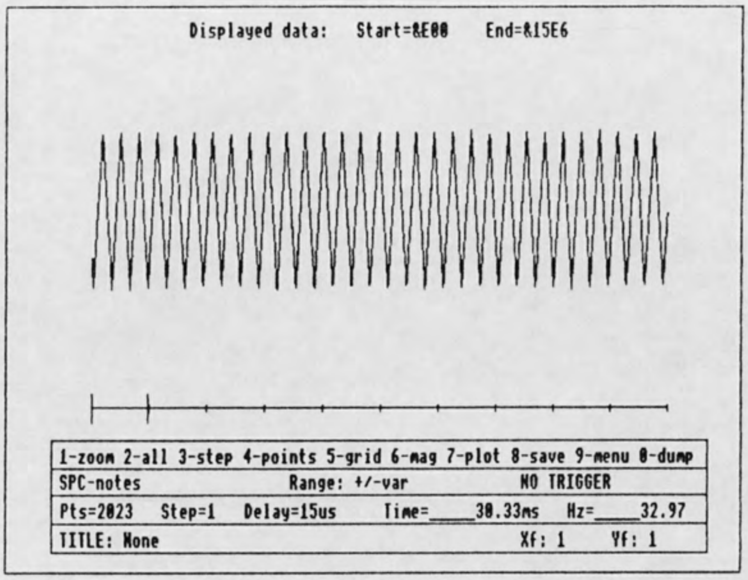


```
Displayed data:   Start=&E00    End=&5CE8
SPC-notes               Range: +/-var           NO TRIGGER
Pts=20201  Step=40  Delay=15us    Time=______303ms  Hz=______3.3
TITLE: None                                     Xf: 1    Yf: 1
```



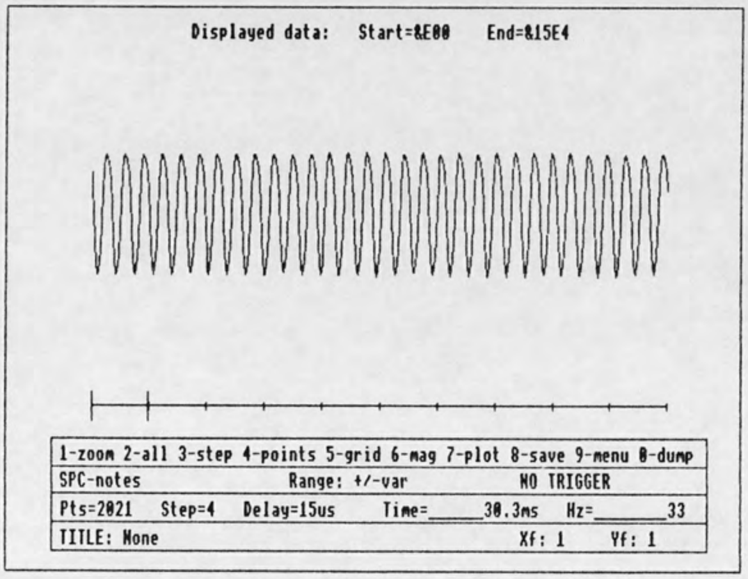
```
Displayed data:   Start=&E00    End=&5CE8
SPC-notes               Range: +/-var           NO TRIGGER
Pts=20201  Step=40  Delay=15us    Time=______303ms  Hz=______3.3
TITLE: None                                     Xf: 1    Yf: 1
```

Fig.8.2.a. Screen dumps of tape recorded/replayed 100Hz.
Upper trace: Signal captured directly by computer.
Lower trace: Replayed signal captured by computer.



```
Displayed data:   Start=&E00    End=&15E6

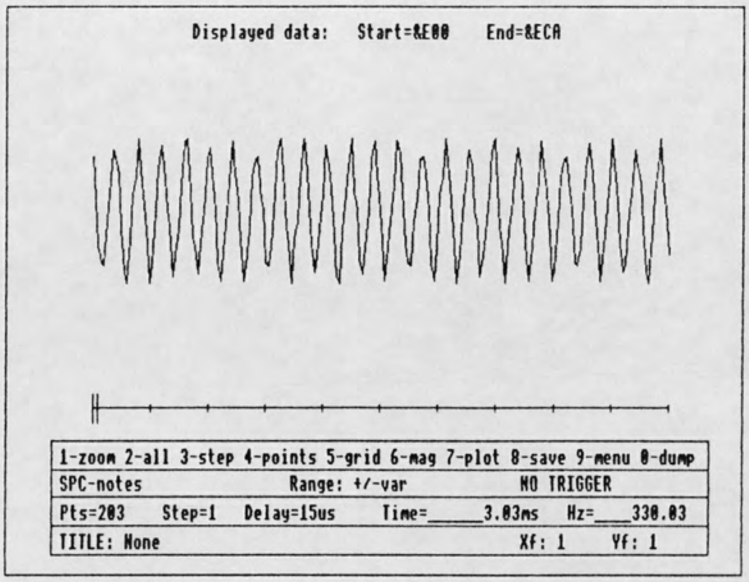
1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes              Range: +/-var              NO TRIGGER
Pts=2023   Step=1   Delay=15us      Time=____30.33ms  Hz=____32.97
TITLE: None                                      Xf: 1     Yf: 1
```



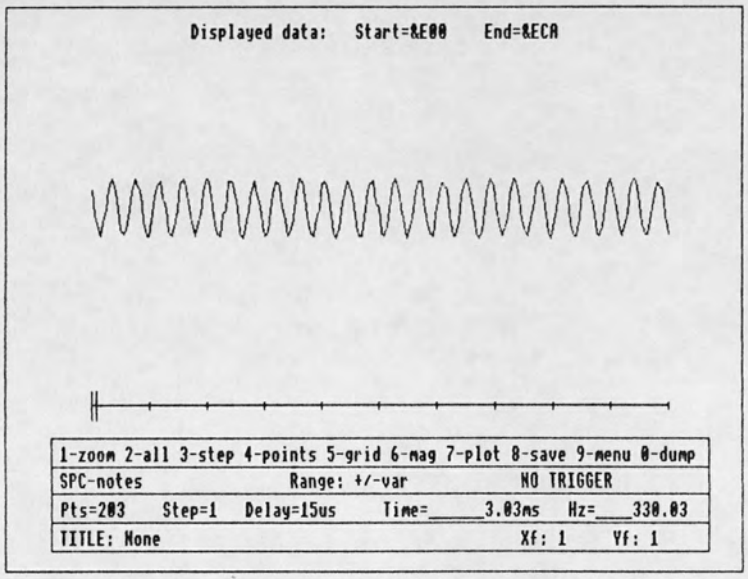
```
Displayed data:   Start=&E00    End=&15E4

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes              Range: +/-var              NO TRIGGER
Pts=2021   Step=4   Delay=15us      Time=_____30.3ms   Hz=_______33
TITLE: None                                      Xf: 1     Yf: 1
```

Fig.8.2.b. Screen dumps of tape recorded/replayed 1KHz.
Upper trace: Signal captured directly by computer.
Lower trace: Replayed signal captured by computer.

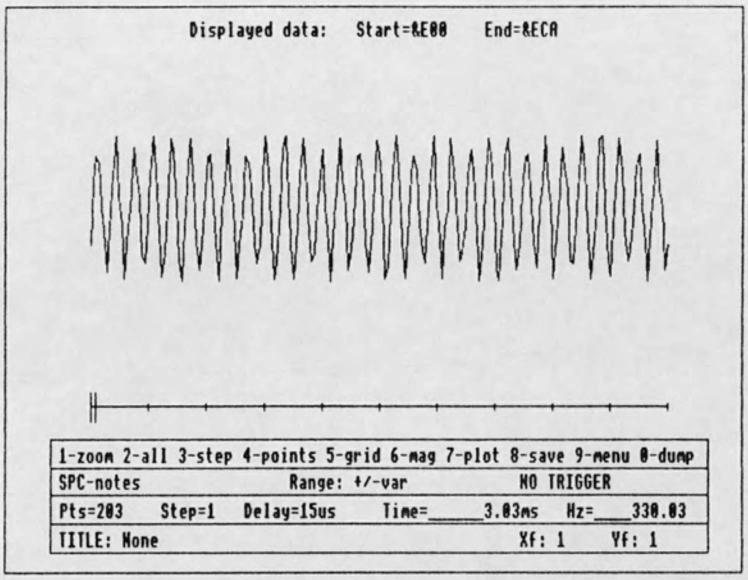


```
Displayed data:   Start=&E00    End=&ECA
SPC-notes            Range: +/-var            NO TRIGGER
Pts=203    Step=1   Delay=15us     Time=_____3.03ms   Hz=___330.03
TITLE: None                                   Xf: 1     Yf: 1
```



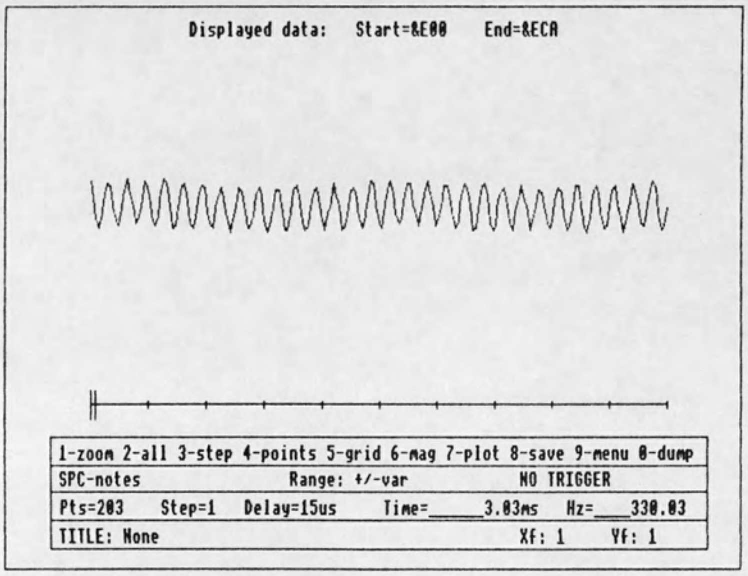
```
Displayed data:   Start=&E00    End=&ECA
SPC-notes            Range: +/-var            NO TRIGGER
Pts=203    Step=1   Delay=15us     Time=_____3.03ms   Hz=___330.03
TITLE: None                                   Xf: 1     Yf: 1
```

Fig.8.2.c. Screen dumps of tape recorded/replayed 8KHz.
Upper trace: Signal captured directly by computer.
Lower trace: Replayed signal captured by computer.



```
Displayed data:   Start=&E00     End=&ECA

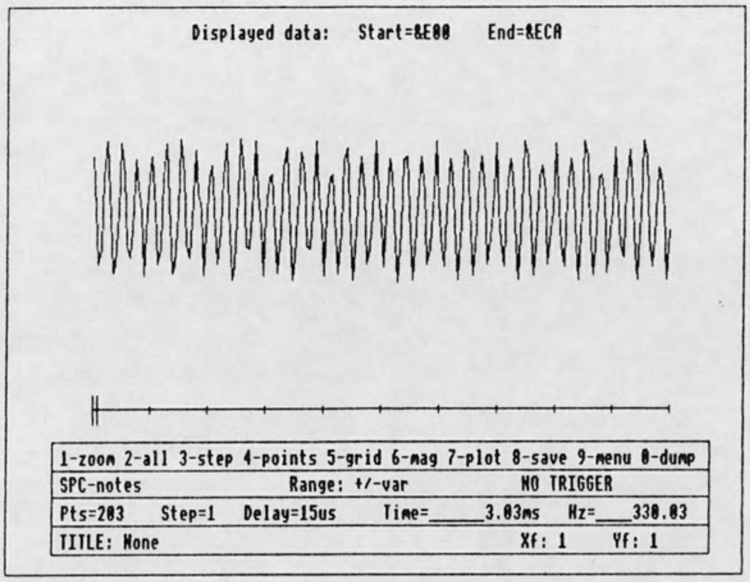
SPC-notes                   Range: +/-var                NO TRIGGER
Pts=203     Step=1   Delay=15us     Time=_____3.03ms   Hz=___330.03
TITLE: None                                              Xf: 1     Yf: 1
```



```
Displayed data:   Start=&E00     End=&ECA

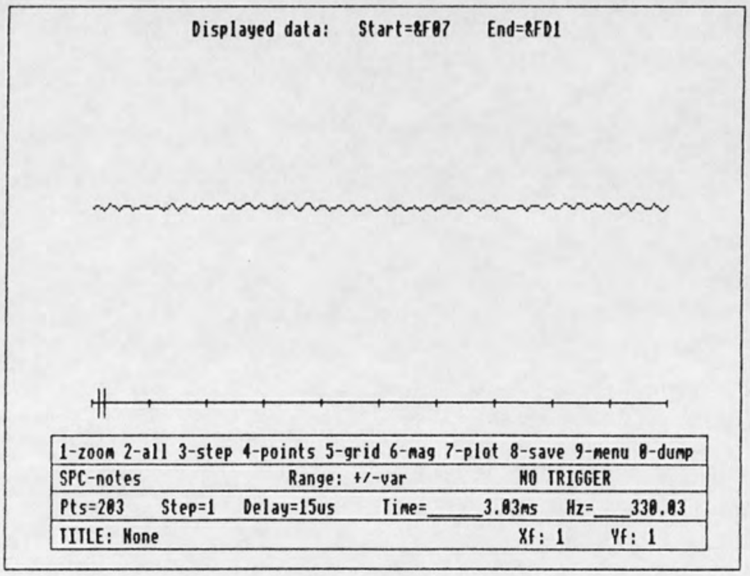
SPC-notes                   Range: +/-var                NO TRIGGER
Pts=203     Step=1   Delay=15us     Time=_____3.03ms   Hz=___330.03
TITLE: None                                              Xf: 1     Yf: 1
```

Fig.8.2.d. Screen dumps of tape recorded/replayed 10KHz.
Upper trace: Signal captured directly by computer.
Lower trace: Replayed signal captured by computer.



```
Displayed data:   Start=&E00    End=&ECA
```

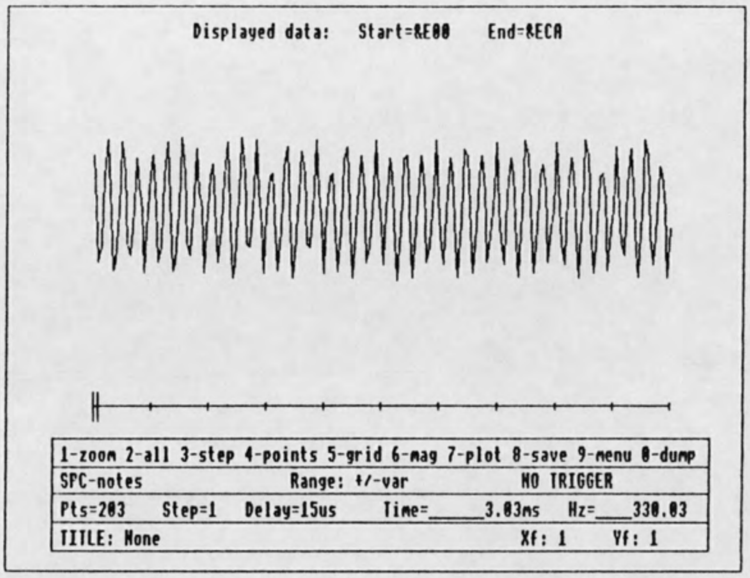
```
SPC-notes                Range: +/-var         NO TRIGGER
Pts=203    Step=1   Delay=15us     Time=______3.03ms  Hz=____330.03
TITLE: None                                    Xf: 1     Yf: 1
```



```
Displayed data:   Start=&F07    End=&FD1
```

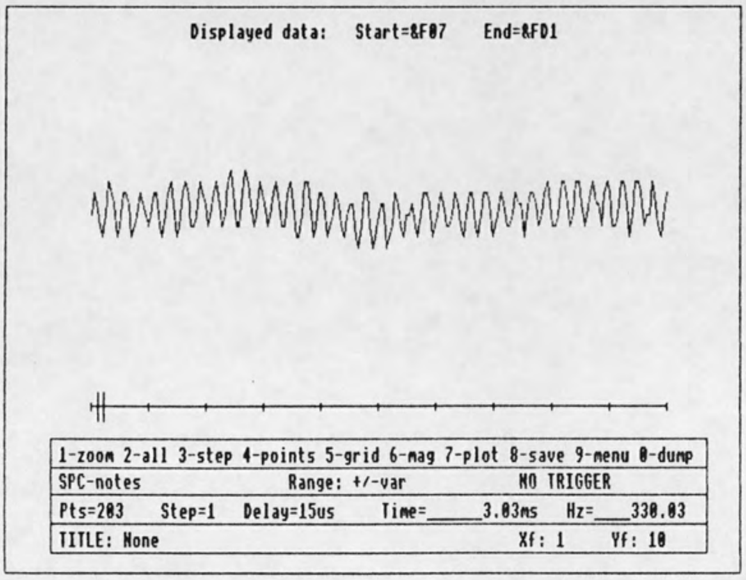
```
SPC-notes                Range: +/-var         NO TRIGGER
Pts=203    Step=1   Delay=15us     Time=______3.03ms  Hz=____330.03
TITLE: None                                    Xf: 1     Yf: 1
```

Fig.8.2.e. Screen dumps of tape recorded/replayed 12.5KHz.
Upper trace: Signal captured directly by computer.
Lower trace: Replayed signal captured by computer.



```
Displayed data:   Start=&E00    End=&ECA

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 0-save 9-menu 0-dump
SPC-notes               Range: +/-var            NO TRIGGER
Pts=203    Step=1   Delay=15us    Time=______3.03ms   Hz=____330.03
TITLE: None                                      Xf: 1     Yf: 1
```



```
Displayed data:   Start=&F07    End=&FD1

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 0-save 9-menu 0-dump
SPC-notes               Range: +/-var            NO TRIGGER
Pts=203    Step=1   Delay=15us    Time=______3.03ms   Hz=____330.03
TITLE: None                                      Xf: 1     Yf: 10
```

Fig.8.2.f. Screen dumps of tape recorded/replayed 12.5KHz.
Upper trace: Signal captured directly by Computer.
Lower trace: Replayed signal captured by computer x10.

EXPERIMENT 8.3.

CHARACTERISATION OF THE SENSOR RESPONSE

INTRODUCTION

The accelerometer selected for the work described in this thesis (BU1771 Knowles Laboratories UK.) was chosen for its lightness, frequency response and low cost. The resonant frequency is stated by the manufacturer to be approximately 12.5KHz, well above the expected frequency range for gnathosonic study established in chapter 4. The accelerometer was tested for the suitability of its response when used with either the computer or cassette recorder.

METHOD

A function generator (Thandar TG102, RS Components Ltd UK) was connected to a small loud speaker (40mm RS Components Ltd UK), and an accelerometer (BU1771 Knowles Laboratories UK) was held lightly against the cone of the speaker by elastic bands as shown in Plate 8.3. Saw tooth wave forms of 100Hz, 1KHz, 8KHz, 10KHz and 12.5KHz were produced by the function generator and the output signals divided between the interface (Unilab Ltd UK) attached to a computer (BBC Master128, Acorn Computers

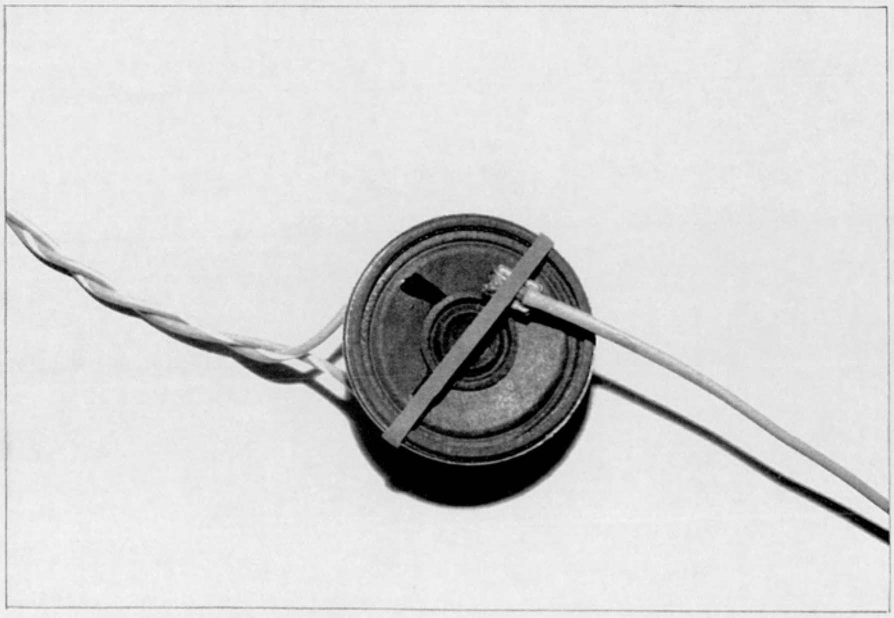


Plate 8.3 Sensor attached to a small loudspeaker to register frequencies produced by the function generator.

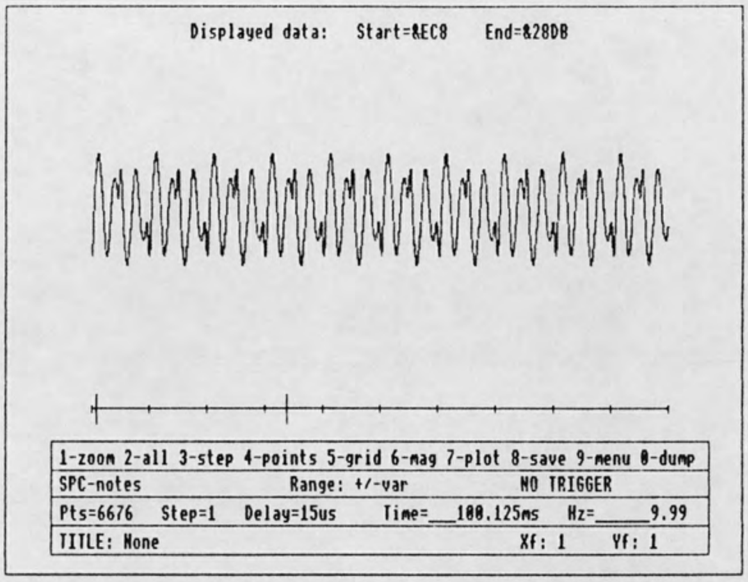
UK) and the microphone socket of the cassette recorder (Philips D6350, Philips UK). The recorded signals were then replayed directly into the interface and captured for a second time by the computer, as described in experiment 8.2. Screen dumps were made after each computer capture to compare the original and replayed signals.

RESULTS

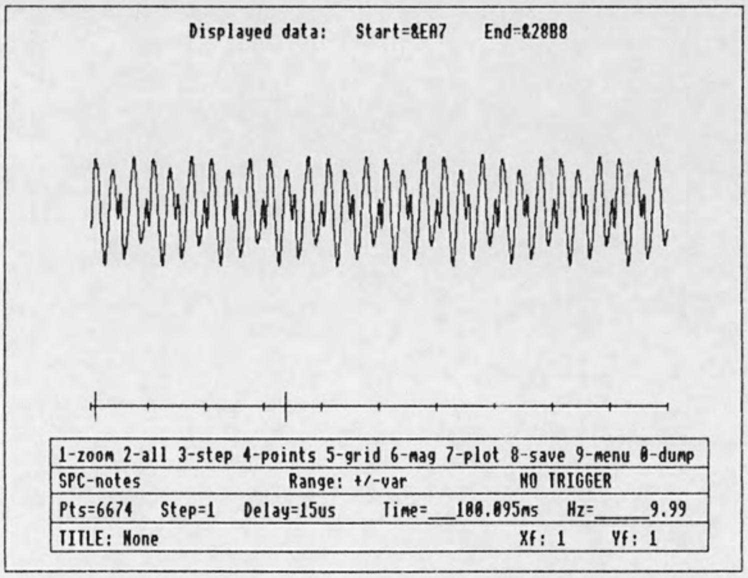
The results of experiment 8.3 are shown in figures 8.3.a-e as computer screen dumps.

DISCUSSION

It can be seen from figures 8.3.a-e that there appears to be a good correlation between the frequencies of the signals driving the loud speaker and the signals recorded by the equipment. The loss of amplitude in the high frequency range of the directly captured signals, shown in the upper traces of figures 8.3.c and 8.3.d is assumed to be due to the characteristics of the loud speaker. The upper trace in figure 8.3.e shows a gain in amplitude at 12.5KHz which is assumed to be due to the resonant frequency of the sensor. However the lower traces in the same figures demonstrate the progressive loss in amplitude due to the the inability of the tape

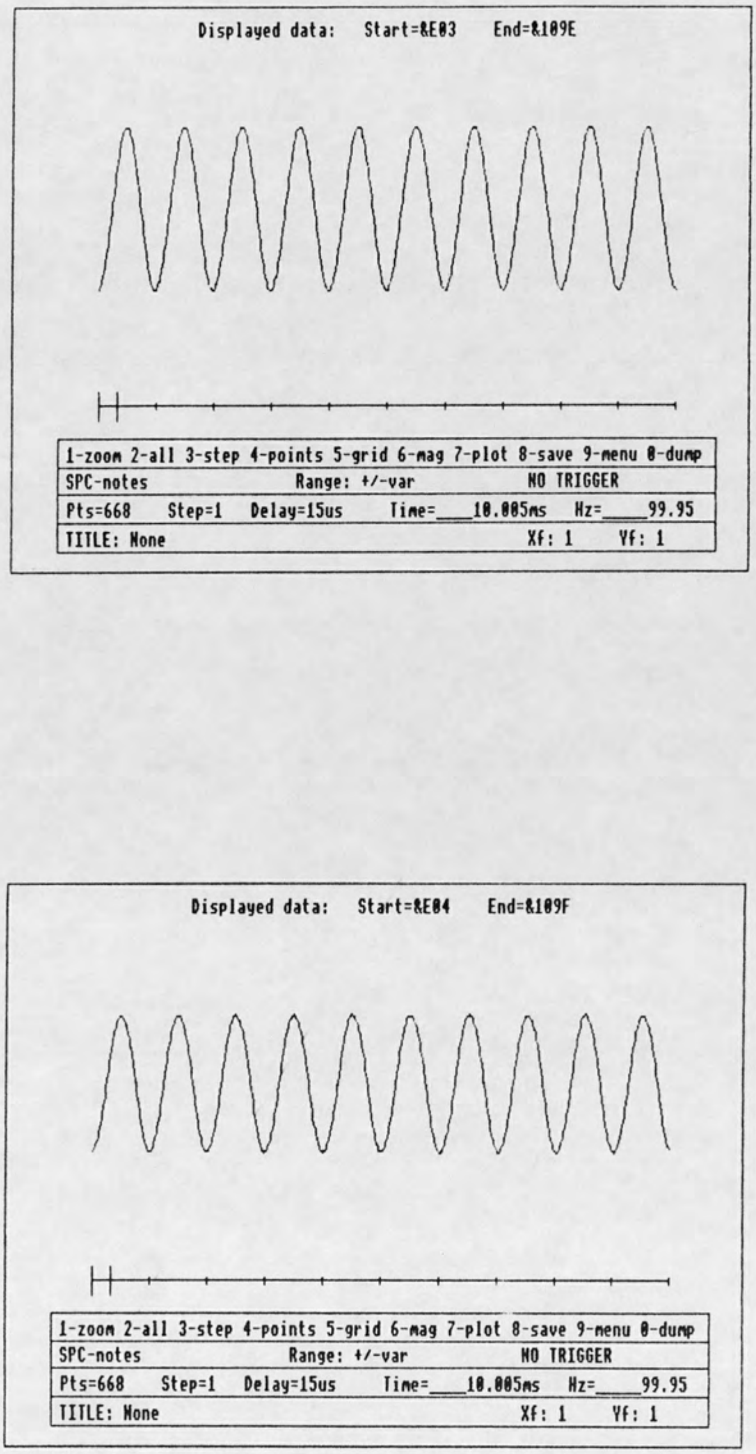


```
Displayed data:   Start=&EC8    End=&28DB
SPC-notes                 Range: +/-var             NO TRIGGER
Pts=6676   Step=1   Delay=15us     Time=___100.125ms   Hz=______9.99
TITLE: None                                         Xf: 1     Yf: 1
```



```
Displayed data:   Start=&EA7    End=&28B8
SPC-notes                 Range: +/-var             NO TRIGGER
Pts=6674   Step=1   Delay=15us     Time=___100.095ms   Hz=______9.99
TITLE: None                                         Xf: 1     Yf: 1
```

Fig.8.3.a. Loudspeaker, 100Hz accelerometer sensed.
Upper trace: Signal captured from sensor by computer.
Lower trace: Replayed signal captured by computer.



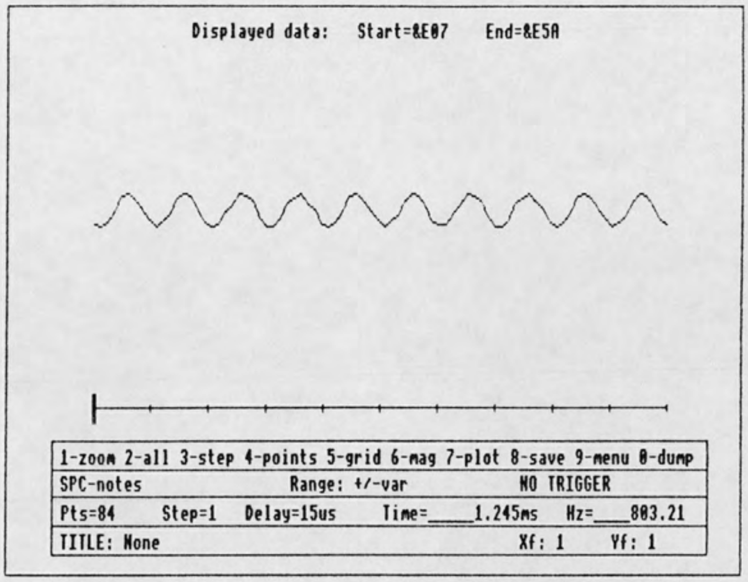
```
Displayed data:   Start=&E03    End=&109E

SPC-notes                  Range: +/-var              NO TRIGGER
Pts=668     Step=1   Delay=15us     Time=____10.005ms   Hz=_____99.95
TITLE: None                                         Xf: 1     Yf: 1
```

```
Displayed data:   Start=&E04    End=&109F

SPC-notes                  Range: +/-var              NO TRIGGER
Pts=668     Step=1   Delay=15us     Time=____10.005ms   Hz=_____99.95
TITLE: None                                         Xf: 1     Yf: 1
```

Fig.8.3.b. Loudspeaker, 1KHz accelerometer sensed.
Upper trace: Signal captured from sensor by computer.
Lower trace: Replayed signal captured by computer.

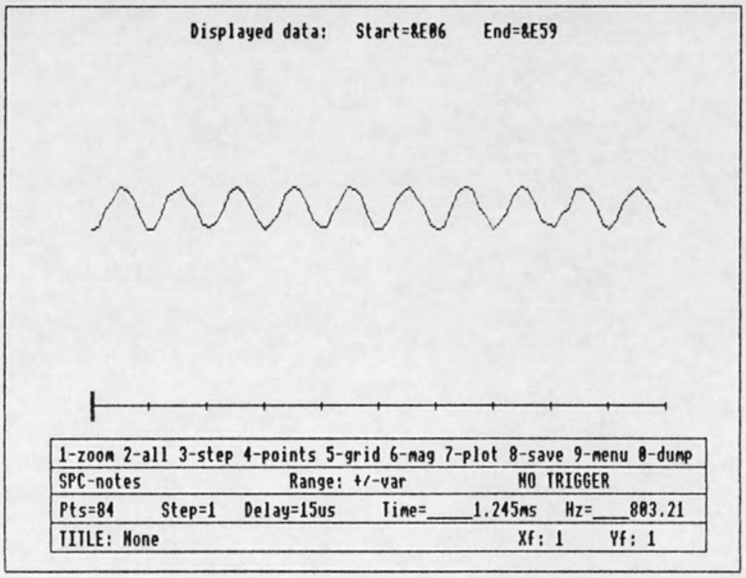


Displayed data: Start=&E07 End=&E5A

SPC-notes Range: +/-var NO TRIGGER

Pts=84 Step=1 Delay=15us Time=____1.245ms Hz=____803.21

TITLE: None Xf: 1 Yf: 1



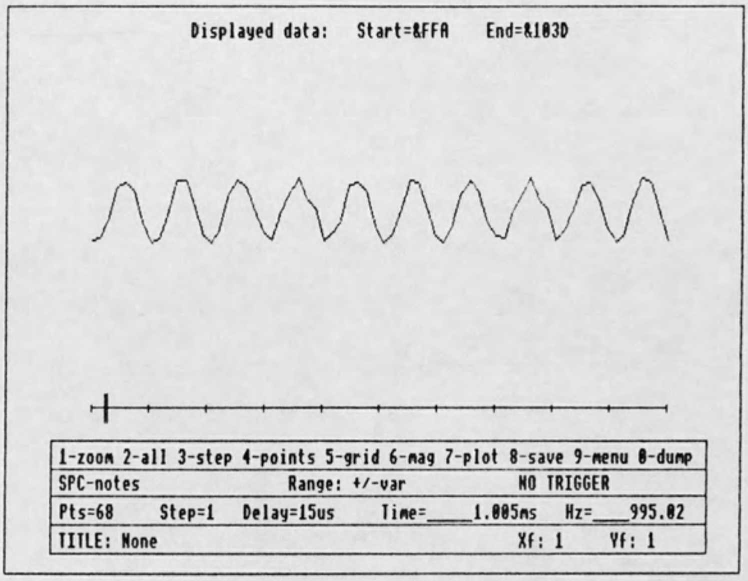
Displayed data: Start=&E06 End=&E59

SPC-notes Range: +/-var NO TRIGGER

Pts=84 Step=1 Delay=15us Time=____1.245ms Hz=____803.21

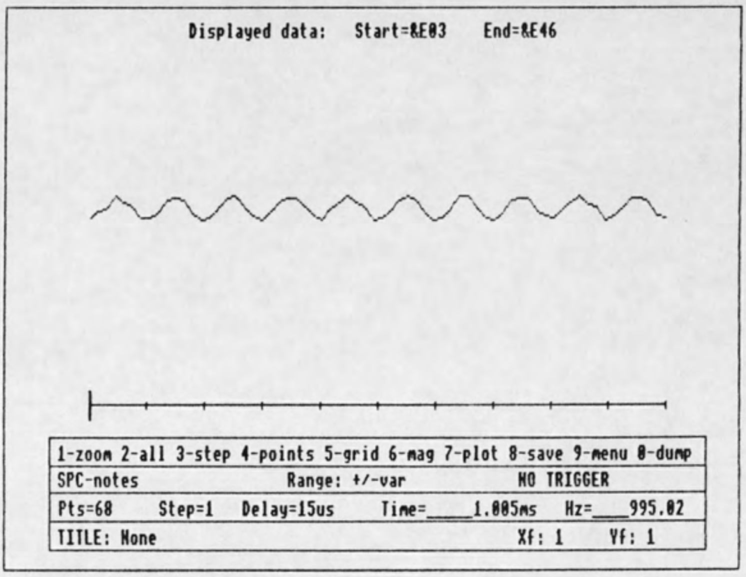
TITLE: None Xf: 1 Yf: 1

Fig.8.3.c. Loudspeaker, 8KHz accelerometer sensed.
Upper trace: Signal captured from sensor by computer.
Lower trace: Replayed signal captured by computer.



```
Displayed data:   Start=&FFA    End=&103D

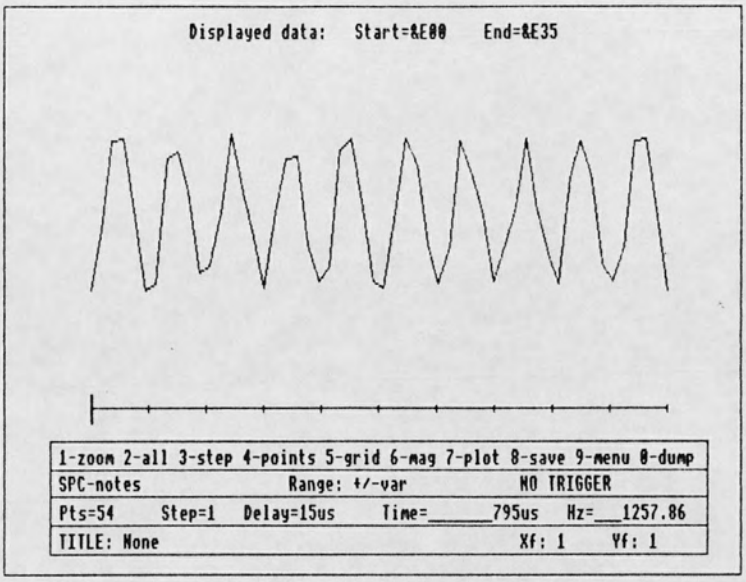
1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes               Range: +/-var               NO TRIGGER
Pts=68    Step=1   Delay=15us    Time=_____1.005ms  Hz=____995.02
TITLE: None                                  Xf: 1      Yf: 1
```



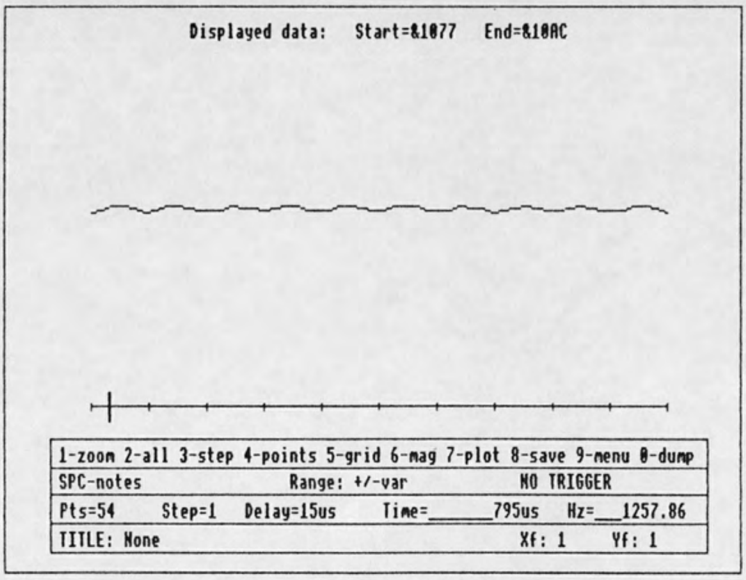
```
Displayed data:   Start=&E03    End=&E46

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes               Range: +/-var               NO TRIGGER
Pts=68    Step=1   Delay=15us    Time=_____1.005ms  Hz=____995.02
TITLE: None                                  Xf: 1      Yf: 1
```

Fig.8.3.d. Loudspeaker, 10KHz accelerometer sensed.
Upper trace: Signal captured from sensor by computer.
Lower trace: Replayed signal captured by computer.



```
Displayed data:   Start=&E00    End=&E35
SPC-notes                Range: +/-var            NO TRIGGER
Pts=54     Step=1   Delay=15us     Time=______795us  Hz=__1257.86
TITLE: None                                   Xf: 1     Yf: 1
```



```
Displayed data:   Start=&1077   End=&10AC
SPC-notes                Range: +/-var            NO TRIGGER
Pts=54     Step=1   Delay=15us     Time=______795us  Hz=__1257.86
TITLE: None                                   Xf: 1     Yf: 1
```

Fig.8.3.e. Loudspeaker, 12.5KHz accelerometer sensed.
Upper trace: Signal captured from sensor by computer.
Lower trace: Replayed signal captured by computer.

recorder to register a frequency such as 12.5KHz which has therefore fallen to background level. However the frequencies themselves have been faithfully reproduced by the sensor. These are however simple standard waveforms and are uncharacteristic of gnathosonic waveforms. It was therefore considered necessary to carry out further experiments more closely related to normal gnathosonic traces, particularly in regard to signal amplitudes and overall shape, recorded directly by the computer against those recorded and replayed by the cassette recorder. It is of course, upon the interpretation of such signals that the study of gnathosonics rests.

EXPERIMENT 8.4.

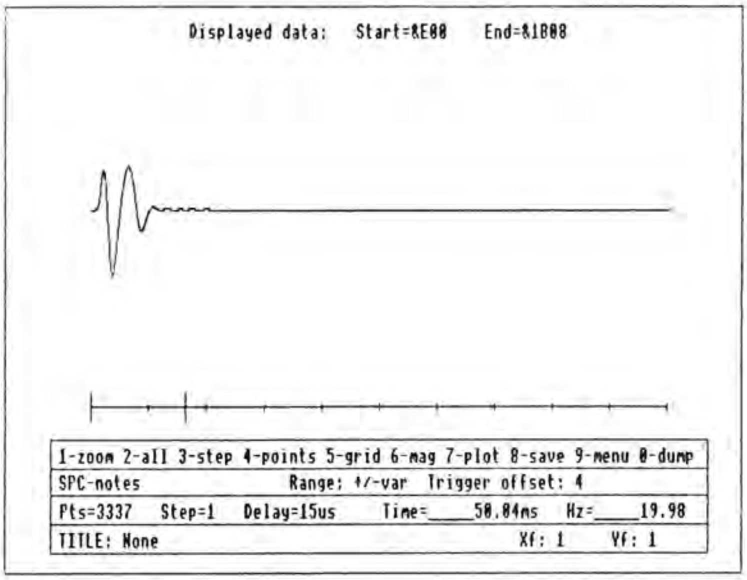
COMPARISON OF IMPACTS - DIRECT AND REPLAYED

INTRODUCTION

The frequencies recorded in experiment 8.3 were based on transfer of signals from a small loudspeaker to the sensor. It was shown however that although there was a loss in amplitude the frequencies were faithfully transmitted. It was considered that impact signals should be recorded for comparison, carried out in a similar manner to the *in vitro* studies in chapter 5, to assess the comparability of signals captured directly or from replayed tape recordings, before undertaking *in vivo* studies.

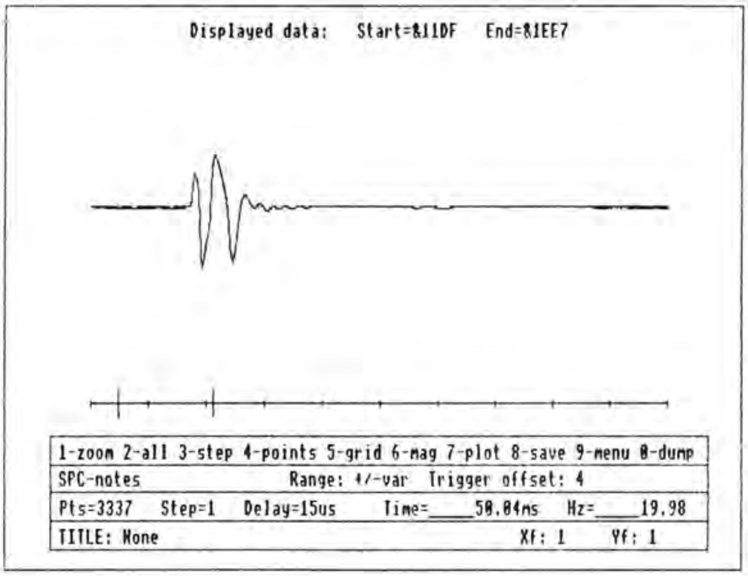
METHOD

The experiment was carried out as described in experiment 4.6. An accelerometer (Knowles Laboratories Ltd UK.) was attached to the base of a 2cm x 2cm acrylic cylinder using a minimum of model cement. The curved surface of the cylinder was laminated with a 3mm layer of natural rubber which was then held in a bench clamp. A 3mm thick layer of natural rubber was attached to the flat surface of the cylinder opposite the sensor with a minimum of model cement, and was struck with a hand held plastic tapper. As described in experiment 8.3 the signal produced by the accelerometer was divided between the computer and the cassette recorder (Philips D6350, Philips UK). The recorded signal was replayed directly into the interface and captured for a second time by the computer. The signal was replayed on a second recorder (same model) and captured for a third time. Screen dumps were made after each computer capture to compare the original and replayed signals.



```
Displayed data:  Start=&E00   End=&1B08

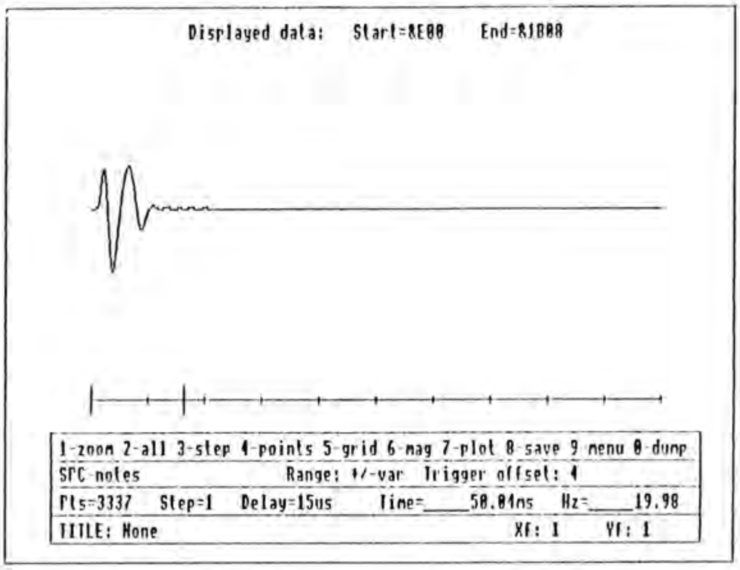
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=3337   Step=1   Delay=15us    Time=____50.04ms  Hz=____19.98
TITLE: None                                 Xf: 1     Yf: 1
```



```
Displayed data:  Start=&11DF   End=&1EE7

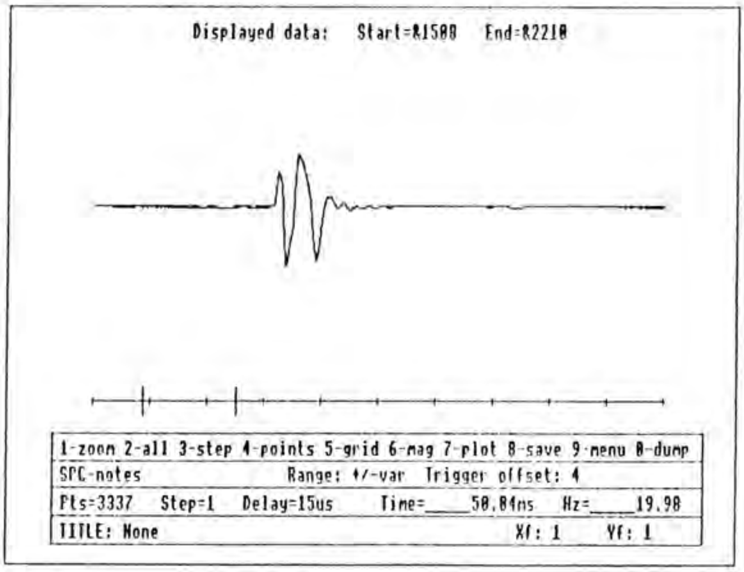
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=3337   Step=1   Delay=15us    Time=____50.04ms  Hz=____19.98
TITLE: None                                 Xf: 1     Yf: 1
```

Fig.8.4.a. Impact sound captured by computer and recorder.
Upper trace: Signal captured directly by computer.
Lower trace: Tape recorded signal captured by computer.



```
Displayed data:   Start=&E00   End=&1000

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes               Range: +/-var  Trigger offset: 4
Pts=3337   Step=1   Delay=15us     Time=____50.04ms   Hz=____19.98
TITLE: None                                  Xf: 1     Yf: 1
```



```
Displayed data:   Start=&1500   End=&2210

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes               Range: +/-var  Trigger offset: 4
Pts=3337   Step=1   Delay=15us     Time=____50.04ms   Hz=____19.98
TITLE: None                                  Xf: 1     Yf: 1
```

Fig.8.4.b. Impact sound shown in fig.8.4.a replayed on a second recorder of the same model.
Upper trace: Duplicate of fig.8.4.a, upper trace.
Lower trace: Tape recorded signal shown in fig.8.4.a replayed on a second recorder and captured by computer.

RESULTS

The results of experiment 8.4 are shown in figures 8.4.a and 8.4.b as computer screen dumps.

DISCUSSION

The layer of natural rubber was added to the face of the cylinder to avoid complicating the signal by exciting the resonance of the sensor. It can be seen from figures 8.4.a and 8.4.b that the screen dump of the directly captured signal appears to be closely similar to those derived from the signal recorded on tape and captured again on replay either on the same recorder or on another of the same model.

It seems therefore reasonable to conclude that the cassette tape recorder should be satisfactory for the initial capture and storage of gnathosonic data for later analysis.

CONCLUSIONS

It may therefore be concluded that:

1) The computer capture program can be used for gnathosonic studies as an accurate data

logger.

2) A domestic cassette recorded can be an adequate apparatus to capture and store gnathosonic data.

3) The selected sensor can adequately record the vibrations generated during gnathosonic procedures.

4) The overall shape or envelope of a signal is more reproducible and may be a more useful parameter than the fine wave structure in general use of gnathosonics.

CHAPTER 9

IN VIVO CONTROL STUDIES

INTRODUCTION

The work described in this thesis is intended to demonstrate that gnathosonic studies can be carried out using a low cost system which may therefore be added to the diagnostic and recording equipment of the general practitioner. As part of the novel experimental design it has been necessary to demonstrate that the various components are each capable of processing gnathosonic signals, and that the assembled whole introduces no spurious elements into the signals either during or subsequent to capture. In addition it has been necessary to carry out investigations to find the most satisfactory site for placement of the sensor to register the optimum signal. The glabella has been selected as the most satisfactory site for non-invasive recording of occlusal sounds, and accelerometers as the sensors of choice. The complete range of frequencies produced by impact of the teeth can then be captured without spurious data such as might arise from signal aliasing.

All of this work has necessarily been studied *in vitro* as a controlled environment. It was considered essential therefore to demonstrate a similar reproducibility *in vivo* before applying the technique more generally *in vivo*.

EXPERIMENT 9.1.

IN VIVO EXPERIMENTS ON SENSOR POSITION

METHOD

A capture system was set up as described in Chapter 8, comprised of a sensor (BU1771 Knowles Laboratories UK.), a fast A-D converter (Unilab Interface, Unilab UK.) and computer (BBC Master 128, Acorn Computers UK.). The accelerometer was held against the scalp of a volunteer in the area of the lambda with an elasticated strap, as shown in Plate 9.1. The incisal edge of an upper left central incisor was struck in the long axis of the tooth with a hand held plastic tapper using a force similar to that when percussing a tooth in the clinical situation, and the signal generated captured using triggering and a sample time of 15us. The experiment was repeated with the sensor placed first in the area of the vertex, followed by the zygomatic area and finally the area of the glabella.

RESULTS

The computer screen dumps of the captured signals

Plate 9.1 Above. Sensor applied to the lambda by elasticated strap.
Below. Sensor applied to the glabella.

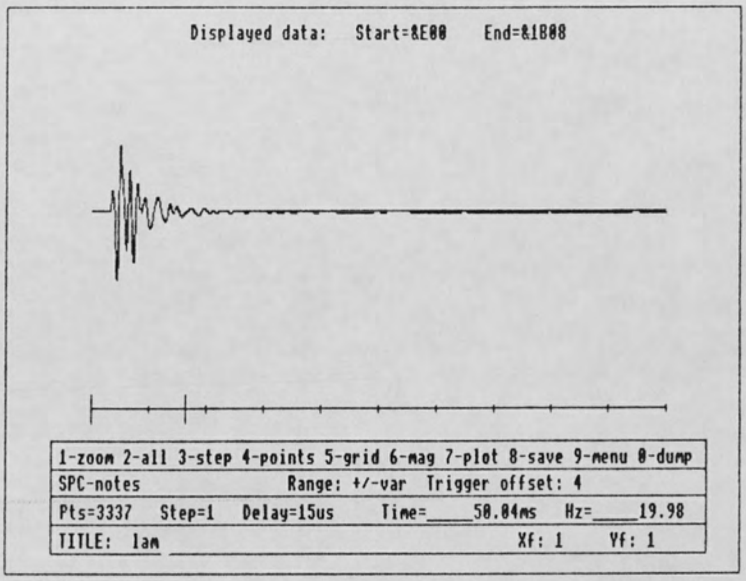
can be seen in figures 9.1.a-d.

DISCUSSION

It can be seen from figure 9.1.a that placing a sensor at the lambda results in a poor signal, both in amplitude and wave content, by comparison with the signals registered at the zygoma or glabella in figures 9.1.c and 9.1.d respectively. This is in accordance with the data for a dry skull in experiment 5.4, where the signal sensed at the lambda was not only significantly attenuated but also suffered from skull resonance problems. Fig 9.1.a however suggests that *in vivo* skull resonance appears to be almost completely attenuated by the presence of soft tissues. A similar result can be seen in figure 9.1.b for a sensor placed at the vertex. It should however be noted that placement of the sensor in the areas of the lambda or vertex is not simple in the majority of patients due to the presence of hair.

Striking the central incisor tooth when sensing at the zygoma (figure 9.1.c) produces a signal of reasonable amplitude, but such signals are of course 'sided' in that the sensor is placed unilaterally, with the associated problems discussed in experiment 5.5.

Signals sensed at the glabella in figure 9.1.d



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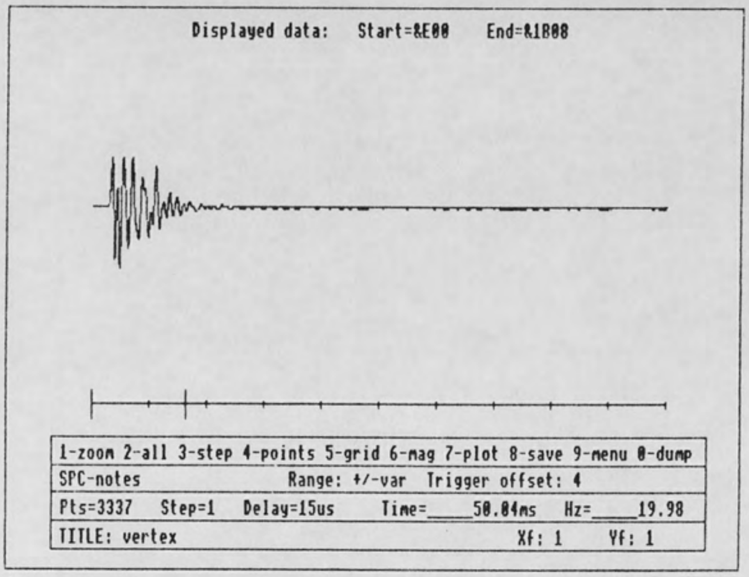
TITLE: lam                                   Xf: 1     Yf: 1
```

Fig.9.1.a. In vivo, sensor placed at lambda. Signal registered by tapping a central incisor.



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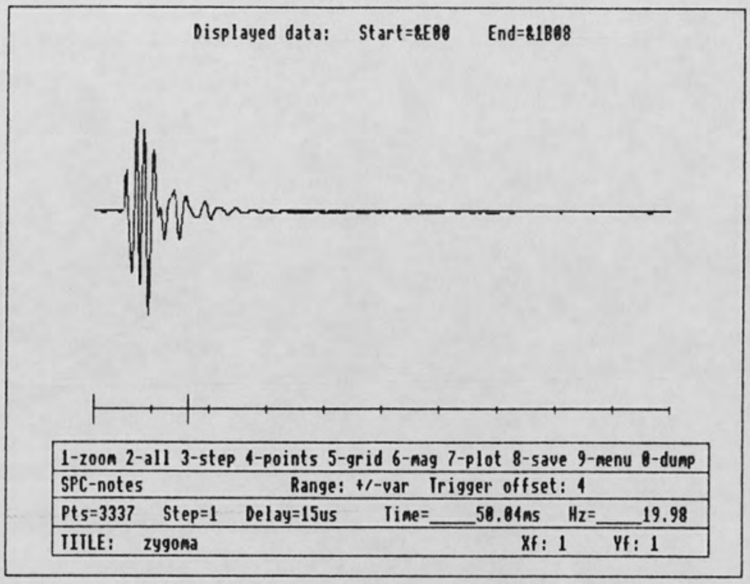
TITLE: vertex                                Xf: 1     Yf: 1
```

Fig.9.1.b. In vivo, sensor placed at vertex. Signal registered by tapping a central incisor.



```
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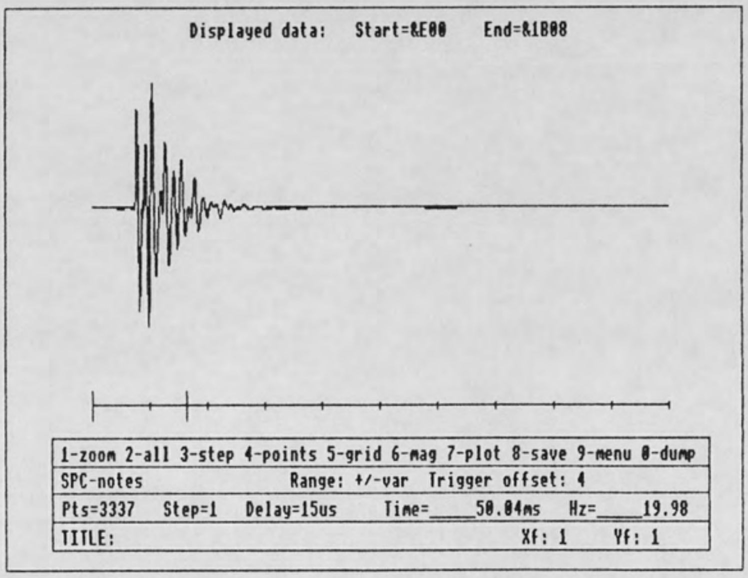
Pts=3337   Step=1   Delay=15us     Time=____50.04ms   Hz=____19.98
TITLE:   zygoma                                Xf: 1     Yf: 1
```

Fig.9.1.c. In vivo, sensor placed on zygoma. Signal registered by tapping a central incisor.



```
Displayed data:   Start=&E00    End=&1B08
SPC-notes                 Range: +/-var  Trigger offset: 4
Pts=3337   Step=1   Delay=15us     Time=____50.04ms   Hz=____19.98
TITLE:                                         Xf: 1     Yf: 1
```

Fig.9.1.d. In vivo, sensor placed at glabella. Signal registered by tapping a central incisor.

confirm this area as the position of choice for a single sensor, in agreement with dry skull experiments 5.6 and 5.9. Placement of the sensor is simple and the signal recorded appears to be of good amplitude and content. There remains the question of the effects on the recorded signal of the mass, area covered and pressure of application of the sensor. Further experiments were therefore carried out to examine the effects of these factors.

EXPERIMENT 9.2.

THE EFFECT OF VARYING ACCELEROMETER MASS

METHOD

The apparatus was set up as described in experiment 9.1, and the sensor was held in place in the area of the glabella by an elasticated strap. The upper left central incisor was struck on the incisal edge with a hand held plastic tapper with the force normally used when percussing teeth in the clinical situation. The signal generated was captured as described in experiment 9.1, using triggering and a sample time of 15us. The procedure was then repeated with the accelerometer fixed with a minimum of model cement to a 29.5g lead disc, of which the opposite face was applied to the skin as shown in Plate 9.2. In a further experiment the 29.5g lead disc was replaced with an 88.2g disc of equal diameter.

RESULTS

The computer screen dumps of the signals are shown in figures 9.2.a-c.

EXPERIMENT 9.3.

THE EFFECT OF VARYING ACCELEROMETER CONTACT AREA

METHOD

The experiment was carried out as described in experiment 9.2 except that 2mm thick aluminium discs of 1cm and 4cm diameter were used in separate experiments.

RESULTS

The computer screen dumps of the signals are shown in figures 9.3.a-c.

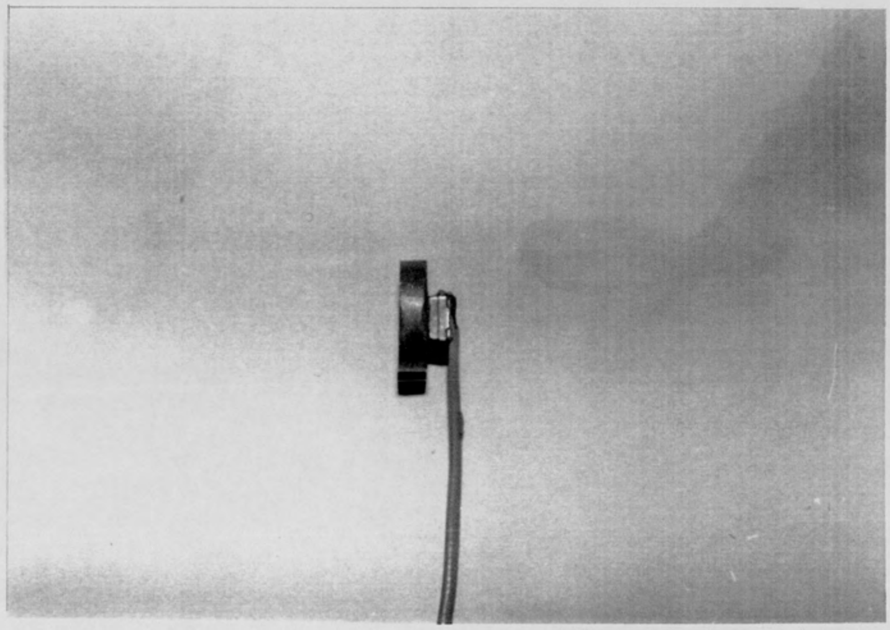


Plate 9.2 Sensor attached to a lead disc.

EXPERIMENT 9.4.

THE EFFECT OF VARYING THE PRESSURE APPLIED TO THE SENSOR

METHOD

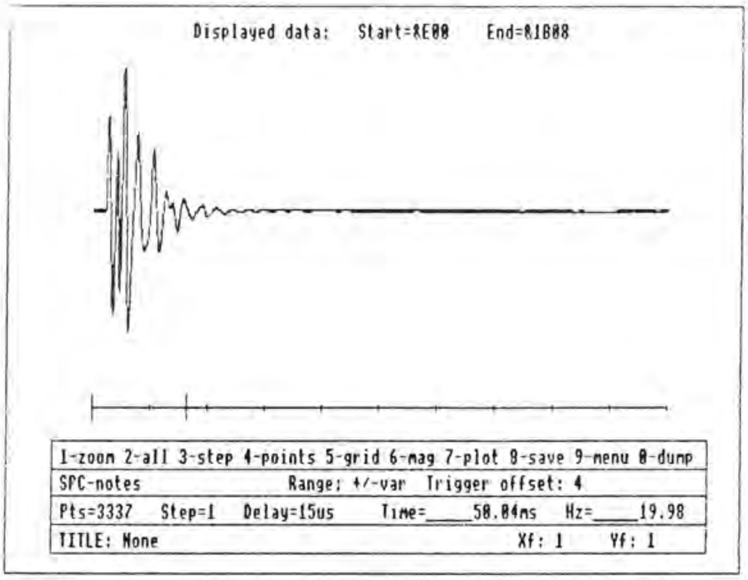
The experiment was carried out as described in experiment 9.1 with the sensor positioned at the glabella, using a triggered sample time of 15us. The experiment was repeated firstly increasing the pressure applied to the sensor by the fabric strap and secondly by decreasing the applied pressure.

RESULTS

The computer screen dumps of the signals are shown in figures 9.4.a-c.

DISCUSSION OF EXPERIMENTS 9.2-4

It is clear from figures 9.2.a-c that the signal frequency recorded is affected by the sensor mass, as was found by Békésy in experiments using accelerometer-type sensors on vibrations in the head.[10] The greater the mass, the lower are the frequencies recorded. Accelerometer mass is therefore an important parameter and should be included in the



```
Displayed data:   Start=&E00    End=&1B00
```

```
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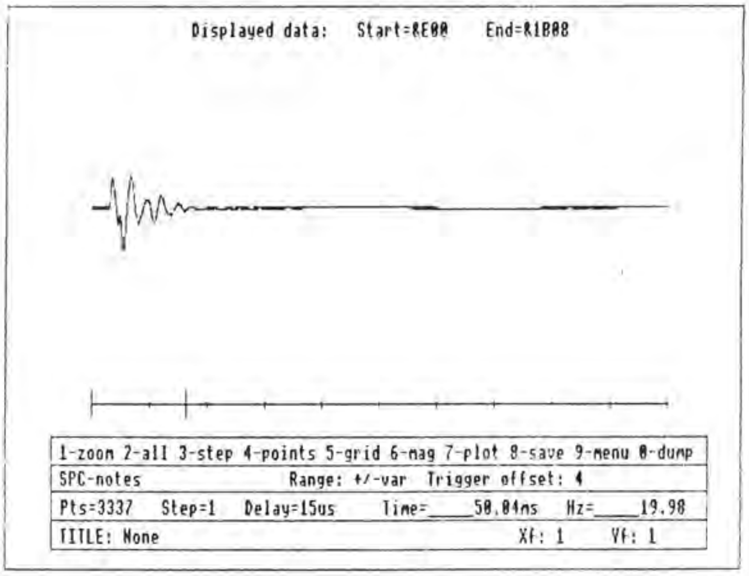
SPC-notes                    Range: +/-var  Trigger offset: 4
Pts=3337   Step=1   Delay=15us     Time=____50.04ms   Hz=____19.98
TITLE: None                                        Xf: 1     Yf: 1
```

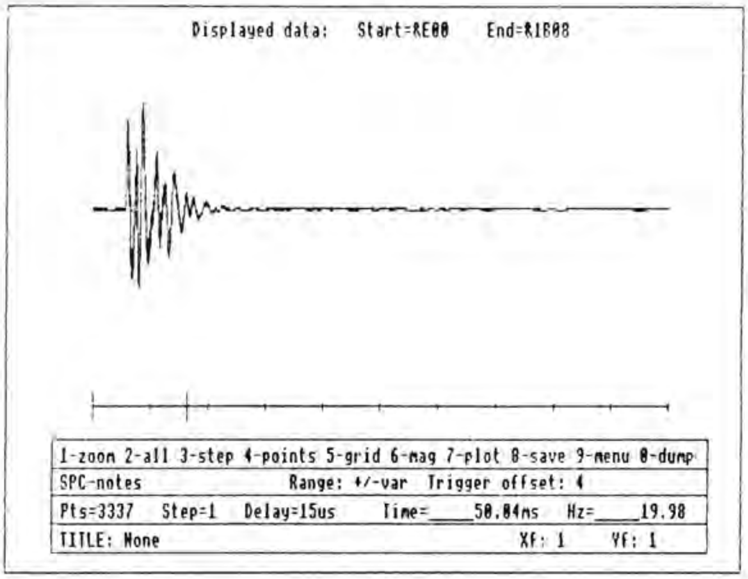
Fig.9.2.a. Varying sensor mass. Unweighted sensor placed at the glabella, signal registered by tapping a central incisor.



```
Displayed data:   Start=&E00    End=&1B00
```

```
1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                    Range: +/-var  Trigger offset: 4
Pts=3337   Step=1   Delay=15us     Time=____50.04ms   Hz=____19.98
TITLE: None                                        Xf: 1     Yf: 1
```

Fig.9.2.b. Varying sensor mass. Sensor weighted with a 29.5gm lead disc, signal registered by tapping a central incisor.



```
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```

```
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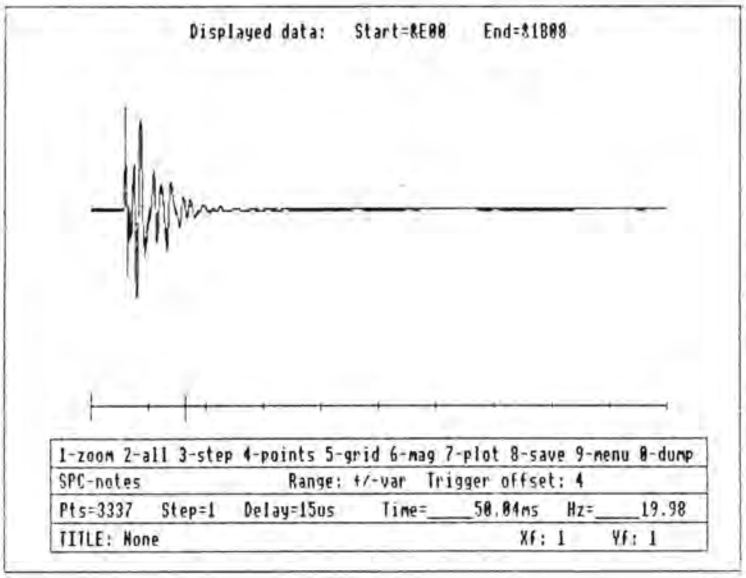
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=3337   Step=1   Delay=15us     Time=____50.04ms  Hz=____19.98
TITLE: None                                        Xf: 1     Yf: 1
```

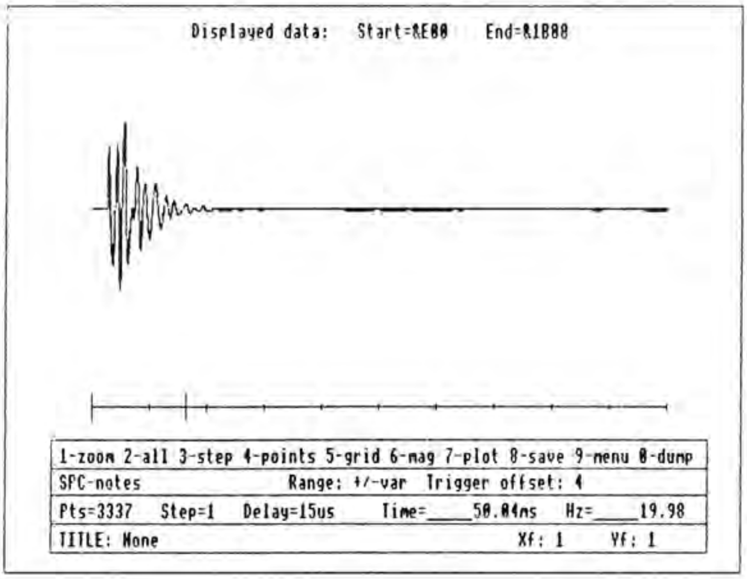
Fig.9.3.b. Varying sensor contact area. Sensor applied attached to a 1cm aluminium disc, signal registered at the glabella by tapping a central incisor.



```
Displayed data:   Start=&E00   End=&1B08
```

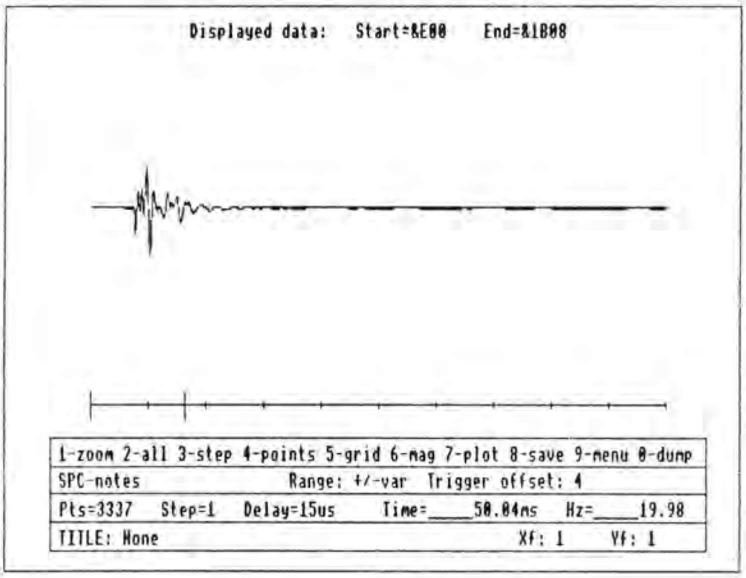
```
1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=3337   Step=1   Delay=15us     Time=____50.04ms  Hz=____19.98
TITLE: None                                        Xf: 1     Yf: 1
```

Fig.9.3.c. Varying sensor contact area. Sensor applied attached to a 4cm aluminium disc, signal registered at the glabella by tapping a central incisor.



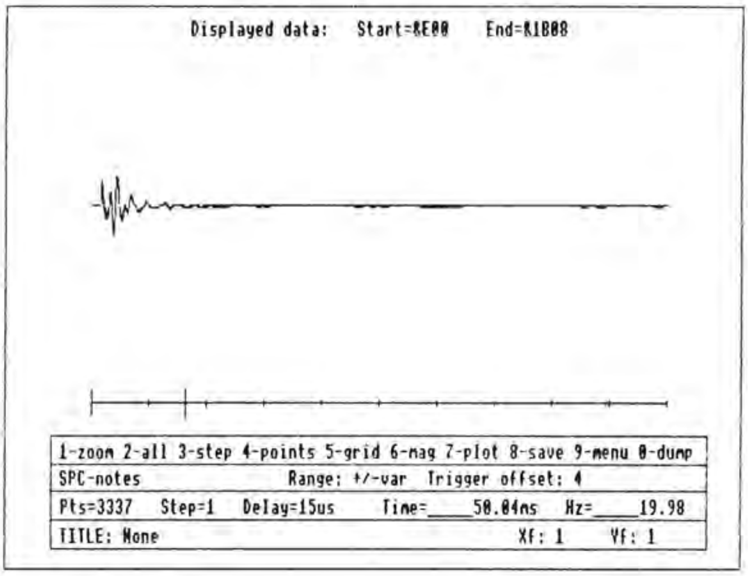
```
Displayed data:   Start=&E00    End=&1B00
SPC-notes                  Range: +/-var  Trigger offset: 4
Pts=3337   Step=1   Delay=15us     Time=____50.04ms  Hz=____19.98
TITLE: None                                    Xf: 1    Yf: 1
```

Fig.9.4.a. Pressure of sensor application. Standard or medium pressure exerted by elasticated mounting strap.



```
Displayed data:   Start=&E00    End=&1B00
SPC-notes                  Range: +/-var  Trigger offset: 4
Pts=3337   Step=1   Delay=15us     Time=____50.04ms  Hz=____19.98
TITLE: None                                    Xf: 1    Yf: 1
```

Fig.9.4.b. Pressure of sensor application. Increased force exerted by elasticated mounting strap.



```
Displayed data:   Start=&E00   End=&1B08
```

```
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=3337   Step=1   Delay=15us     Time=____50.04ms  Hz=____19.98
TITLE: None                                  Xf: 1    Yf: 1
```

Fig.9.4.c. Pressure of sensor application. Decreased force exerted by elasticated mounting strap.

specifications of any recording apparatus.

The results shown in figures 9.3.a-c indicate that the surface area of tissue covered by a sensor has little effect on the frequencies recorded, but this can only be said for a light accelerometer such as the BU1771 (Knowles Laboratories UK). Normally the sensor is held in place by an elasticated fabric strap, tensioned about the head firmly but not uncomfortably tight, exerting a steady pressure. Variations in this pressure also affect the signal as can be seen in figures 9.4.a-c. Quantitative experiments in any future work may be used to measure the force precisely and may show a mathematical relationship between the signal characteristics and the applied force.

CONCLUSION

It is clear from these studies that for gnathosonic research to be repeatable by others it is necessary not only to state the frequency response of the sensor but also to include details of the type of sensor, its mass, area of contact and method of application (including pressure). There have never been any standard experimental procedures or parameters laid down for workers against which instruments or results can be measured, and it is therefore difficult to make comparisons among previously published works.

9.5 COMPARISON OF RESULTS OBTAINED IN THIS WORK WITH PREVIOUSLY PUBLISHED DATA

Although it is difficult to compare the data in the gnathosonic literature, it is now possible to compare the controlled work in this thesis with the previous literature. It is generally accepted that early work by Brenman laid the foundation of modern gnathosonics,[9,11,16] and that that of Watt led to a classification of dental occlusion based on gnathosonics.[12,21] Surprisingly however, the postulate put forward by Brenman that occlusal sounds consist of an alpha and beta component, representing a slide of cusps over each other before terminal contact into full occlusion respectively, has not been challenged in the literature.

It is of course difficult for one worker to reproduce and perhaps challenge the work of another especially when there are no controls against which systems designs can be standardised. Such work is therefore not properly comparable and it is intended to show in this section that work carried out on gnathosonics without controls can lead to errors being compounded yet presented as scientific research.

AN EXAMPLE OF INACCURATE BUT UNCHALLENGED INFORMATION

Brenman postulated that occlusal sounds consisted of two parts, the first or alpha waveform being produced by the cusps contacting and sliding over one another, and the second or beta wave form by the sound of terminal closure [occlusion proper].[9,11,16] By way of illustration, sound patterns were depicted to demonstrate the wave forms generated by different types of sound as shown in figure 9.5.a. The illustration was first published in 1959[9] and reproduced in 1963.[11] Waveform 'A' in figure 9.5.a was said to show a sound wave travelling through a vacuum,[9] later modified to a partial vacuum.[11] It is of course impossible for a sound wave to pass through a vacuum.

Sound 'C' in figure 9.5.a was stated by Brenman to illustrate the sound produced either by a patient without occlusal discrepancies or by striking a piano key. A piano is a percussion instrument and does not produce sounds such as that illustrated, but rather produces transient sounds with multiple harmonics as shown in figure 9.5.b which is a recording made from the frame of a piano when the note of middle 'A' is struck. The recording was made by the author using an accelerometer and tape recorder as described in experiment 5.4, but without the oscilloscope. Replay was through the interface (Unilab Ltd UK) and computer (BBC Master128 Acorn Ltd UK). A patient occluding without occlusal discrepancies would be making direct enamel-enamel impacts which have been shown in experiments 4.4 and 4.5 to produce mainly high frequency in the established 0-6±1KHz range. Such low frequency pure sine waves generated by middle 'A' at 440Hz would be therefore atypical.

Sound 'F' in figure 9.5.a is stated by Brenman to illustrate a high frequency discordant sound in the first part of the signal as the teeth slide over each other followed by the regular pattern which 'is the impact signal of actual closure'. A gnathosonic signal could therefore be expected to normally consist of two distinguishable waveforms.

These assertions have not been challenged by others in the literature, but rather have been used uncritically as the basis of further research. For example, Fuller[32] analysed the wave forms produced by occlusion of the teeth based on the alpha and beta components described by Brenman. By measuring the duration of the alpha component in relation to that of the whole signal Fuller came to a number of conclusions which suggested that the alpha component of the waveform

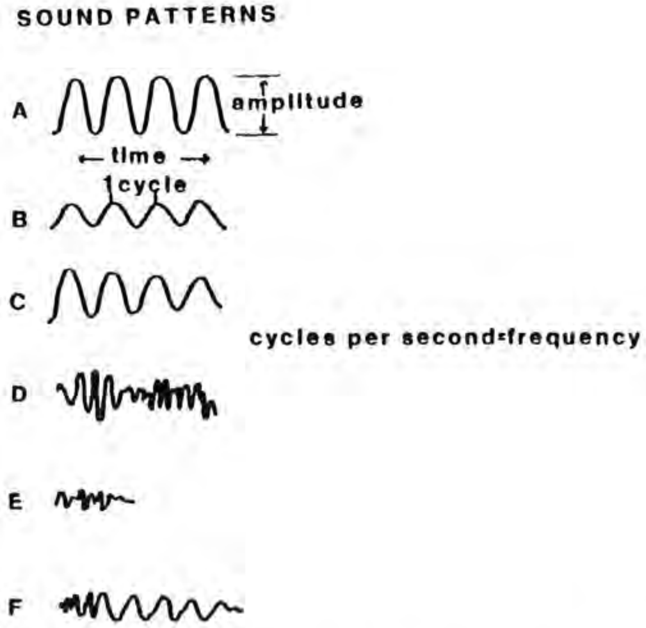


FIG. 6.- When sounds are fed into an oscilloscope electronically, they appear on the screen as characteristic wave patterns, travelling from left to right with the passage of time. A clear steady sound produces a uniform repeating pattern like A. The difference between A and B is amplitude of the wave; a sound travelling in a partial vacuum and forming signal A would be transformed into pattern B in the air; the amplitude would decrease with the greater resistance of the new medium.

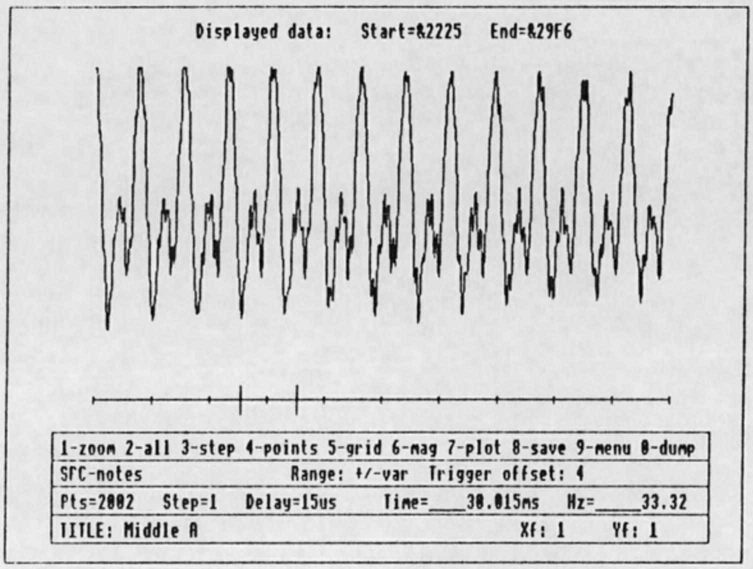
C is the pattern produced by a single sound of short duration, such as the striking of a piano key or a jaw closure in which the teeth meet perfectly and simultaneously. Because the single sharp sound is not sustained, the amplitude falls off with time.

D is a discordant sound, such as a cymbal crash or the breaking of a pane of glass, composed of many frequencies simultaneously presented. There is no apparent symmetry to the pattern.

E, also an erratic pattern, is of lower amplitude than D. If a patient's bite from primary contact to terminal closing is a smooth slide, his occlusogram, while erratic, will be of low amplitude and may look like E. Should the slide be rough and grating, he might produce an occlusogram like D.

F is a composite of D and C and represents occlusal discrepancies, which present a sequence of patterns on the occlusogram. The first part of the signal, similar to D, occurs as the teeth slide over one another; the second part, as in C, is the impact signal of actual closure.

Fig.9.5.a. Sound patterns, after Brenman.



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SFC-notes                    Range: +/-var  Trigger offset: 4
Pts=2002   Step=1   Delay=15us     Time=____30.015ms  Hz=_____33.32
TITLE: Middle A                                    Xf: 1     Yf: 1
```

Fig.9.5.b. Waveform of middle 'A' taken from a piano frame.

might be the most useful.

To illustrate the problems arising in such work more clearly, it was considered appropriate to reproduce the sensing system used by Fuller as far as it could be deduced from the text and illustrations[32] and to compare the results with that obtained by the system developed in this thesis.

EXPERIMENT 9.6.

COMPARISON OF A GNATHOSONIC SIGNAL RECORDED SIMULTANEOUSLY BY AN ACCELEROMETER AND A MICROPHONE

METHOD

A condenser microphone (electret condenser microphone EM-106 Altai Ltd UK.) was connected by a short rubber tube to a stethoscope bell, and a gauge 21 hypodermic needle was used to provide an air vent to balance the air pressure as shown in Plate 9.3. The microphone was held against the forehead of a volunteer by an elasticated strap, in a similar manner to that described by Fuller.[32] An accelerometer (BU1771 Knowles Laboratories UK) was attached to a hypodermic needle as shown in Plate 9.4. The point of the needle was passed through the labial mucosa at right angles to

Plate 9.3 Microphone attached to the forehead - after Fuller.

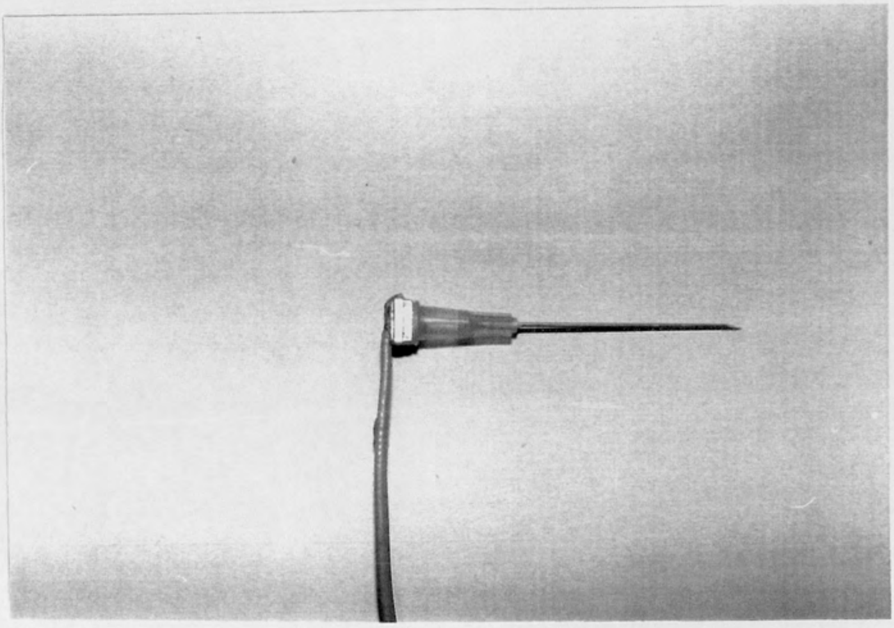


Plate 9.4 Sensor attached to a 21 gauge hypodermic needle.

the alveolar bone and held firmly against the bone in the region of the apex of the upper left central incisor tooth. The volunteer snapped the jaws together into centric occlusion and the outputs of the microphone and accelerometer were recorded simultaneously on the two channels of a storage oscilloscope (Thurlby DSA524, Thurlby Electronics Ltd UK). A further experiment was carried out by the same method except that the microphone was replaced by an accelerometer (BU1771 Knowles Laboratories UK).

RESULTS

The results of experiment 9.6 are shown in figures 9.6.a and 9.6.b as oscilloscope screen dumps.

DISCUSSION

It can be seen from figure 9.6.a that the signal from the microphone has produced a trace which could arguably be divided into alpha and beta components. Seen in isolation this trace appears to demonstrate the initial slide followed by the impact signal of actual closure. However the trace must be considered in conjunction with the signal from the accelerometer shown in figure 9.6.a. Both traces were triggered by the oscilloscope at the same instant by a voltage on the upper channel, and no part of either signal can be lost as the storage oscilloscope is set to display one screen division of signal prior to triggering. As both channels were triggered at the same instant, the time history of each trace will begin at the same point in the X axis. It is clear from figure 9.6.a therefore, that whilst the microphone trace shows two types of waveforms the accelerometer trace only shows one. The first part of the microphone waveform is similar to and occurs at the same time as that of the accelerometer, while the second part of the microphone waveform is not shown by the accelerometer. It appears therefore that the second part of the microphone waveform is an artifact.

It could be argued that the signal apparently sensed by the microphone was genuine whereas the signal was not sensed by the accelerometer due to some characteristic of that sensor. However the accelerometer used has a specified uniform response in the frequency range in question (0.5-3KHz). Further, the vibrations from the teeth were passed directly to the accelerometer from the alveolar bone by the hypodermic needle. This strongly suggests that the accelerometer senses the complete signal while the microphone senses additional spurious data. By using accelerometers only, the signals detected at the alveolus and glabella are similar as shown in figure 9.6.b. Preliminary experiments by the

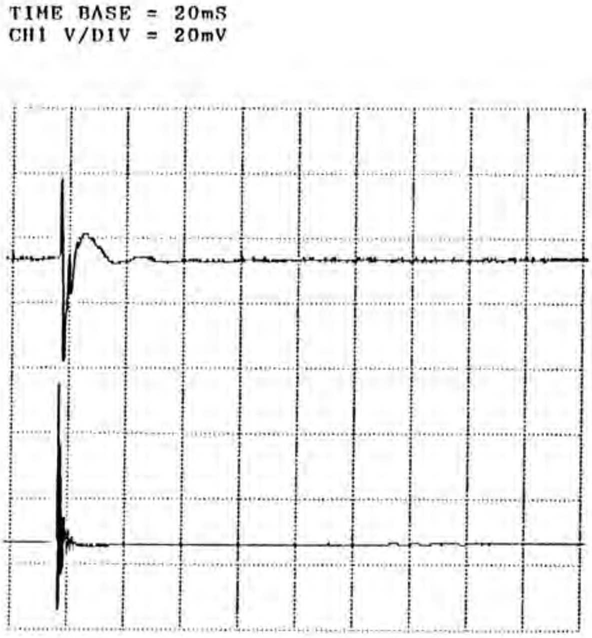


Fig.9.6.a. Signal registered by occluding the teeth.
Upper trace: Microphone at glabella.
Lower trace: Accelerometer applied by needle at incisor apex.

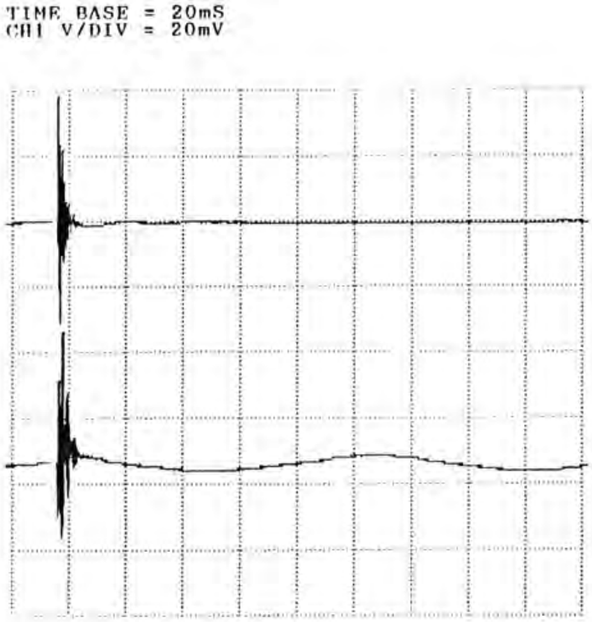


Fig.9.6.b. Signal registered by occluding the teeth.
Upper trace: Accelerometer at glabella.
Lower trace: Accelerometer applied by needle at incisor apex.

author with microphones suggested that the artifact may be due to residual vibrations of the area of skin enclosed by the stethoscope bell, the volume of air between the skin surface and the microphone, and venting of the enclosed air to the atmosphere to avoid imbalances in pressure.

It would appear that the problem of skin surface and sensor interface, particularly when air is a medium of transmission, requires thorough elucidation. However, sensors such as accelerometers in direct surface contact with the tissues must be placed under proper conditions as shown in experiments 9.2-4.

Of course it could be argued that percussion is not the same as occlusal impact, and for this reason a final experiment was carried out to directly compare occlusal and percussive sounds from a volunteer who possessed a stable occlusion.

EXPERIMENT 9.7.

COMPARISON OF SOUNDS GENERATED BY PERCUSSION AND BY OCCLUSION OF THE TEETH

METHOD

The experiment was carried out in a similar manner to and on the same volunteer as experiment 9.1, with the accelerometer placed at the glabella. Sounds were recorded from both percussion and occlusion of the teeth.

RESULTS

The results of experiment 9.7. are shown in figures 9.7.a and 9.7.b as oscilloscope screen dumps.

DISCUSSION

It can be seen from figure 9.7.a that the traces produced by percussion and closure of a stable occlusion are similar. The similarity of the wave envelope may be noted in figure 9.7.b where the traces have been overlaid for comparison.

Experiment 9.6 is of course just one example of spurious data recorded by the uncontrolled use of a sensor, but in the light of the results it is possible to re-examine the previous literature, as the following examples illustrate.

BRENMAN

Apart from the original figure published first in

1959[9] and again in 1963[11] about which comment has already been made, there are other figures of interest such as those published in 1966[16] and 1974.[22] Relevant data from these figures are shown in figures 9.7.c-e.

Figure 9.7.c[22] shows an 'occlusal event' which takes place 'in the 30ms or so time interval between primary tooth contact and terminal closure'. From an earlier publication[16] shown in figure 9.7.d it could be inferred that 'a' constitutes the alpha component and 'b' the beta component. However if this were the case then a significant part of the beta waveform would not be at a lower regular frequency compared to that of the alpha waveform. The two components might therefore be taken as 'x' and 'y' respectively, in which case there would be agreement with figure 9.7.e, published in the same paper,[22] where the two wave forms are clearly indicated. The latter interpretation appears to be the one placed on the work by almost all other researchers.

Once such a postulate becomes firmly established it is possible to see alpha and/or beta components in all gnathosonic tracings. The current work however suggests that in reality Brenman's work cannot be properly interpreted because of the lack of control experiments. The problem is illustrated by the fact that Brenman was able to present differing interpretations of similar data in successive publications.[16,22]

WATT

Figure 9.7.f shows a gnathosonic trace[14] which might be divided into alpha and beta components, but in figure 9.7.g Watt shows the effect of replaying sounds recorded on magnetic tape at different speeds, which has a similar effect to altering the timebase of an oscilloscope. It is clear from this illustration that record/replay rates of 15/15 inches per second (i.p.s.) respectively appear to show a single sharp occlusal sound, whereas a record/replay rate of 15/1.8 i.p.s. of the same signal shows what might be considered to be a long alpha component followed by a short beta component. Traces published without providing a timebase could therefore be misleading. An example of such conditions can be seen in figure 9.7.h.

Watt classified occlusions into stable, mixed and unstable groups according to the duration of the occlusal sounds, ie, Class A less than 30ms, Class B mixed and Class C greater than 30ms in duration. Published data[26] shown in figure 9.7.i depicts class A, B and C occlusal sounds. It appears from the figure however that the Class A sounds are in the order of 10ms and Class B up to 18ms in duration. Such discrepancies might possibly be due to problems in interpretation and clarity. One further example has been taken from an unpublished series of records kept by Watt of students at the Edinburgh Dental School. Figure 9.7.j shows repeated occlusal sounds, a vertical line marking where the end of the event was considered to be on the upper trace. The upper and lower traces were sensed at the same time in the left and right infraorbital regions, yet even taking into account the fact that the traces are slightly out of register on the recording paper, the lower trace being approximately 2mm in advance of the upper, the traces are quite different in what could be termed the beta component. If the beta component were to be disregarded as an artifact then the signal times would be reduced to the order of 4ms. It may be that the times suggested in Watt's classification of occlusion should be open to revision if extraneous signals generated by the type and mounting of the sensor are added to the duration of the occlusal sound proper.

STALLARD

Figure 9.7.k shows three published figures[23] illustrating a typical occlusal sound with alpha and beta components, a simple occlusal signal with both alpha and beta components, and an ideal occlusion consisting entirely of a beta component. In the case of the waveform said to show a simple signal with both alpha and beta waveforms there appears to be little

difference in frequency throughout the time depicted. The occurrence of a beta wave in isolation is difficult to understand unless of course the traces have been idealised for illustrative purposes.

FULLER

Fuller's work[32] has already been discussed, seeking to analyse the significance of the alpha and beta components of an occlusal waveform. The traces shown in figure 9.7.1 are of interest, for if the beta component is removed from the waveform the sounds all become less than 10ms in duration, bringing them into the range expected when tooth impact is sensed by a transducer attached directly to a tooth.[31] This is yet another example of the misinterpretation of gnathosonic signals through lack of control experiments.

FREER

A publication[36] by Freer seeks to examine the repeatability of gnathosonic records. However study of the figures presented suggests that the only useful information contained in these figures is that of the signal envelopes as shown in figure 9.7.m. The waveforms within the envelopes are so similar as to strongly suggest that in fact they consist of the resonant frequency of the sensor.

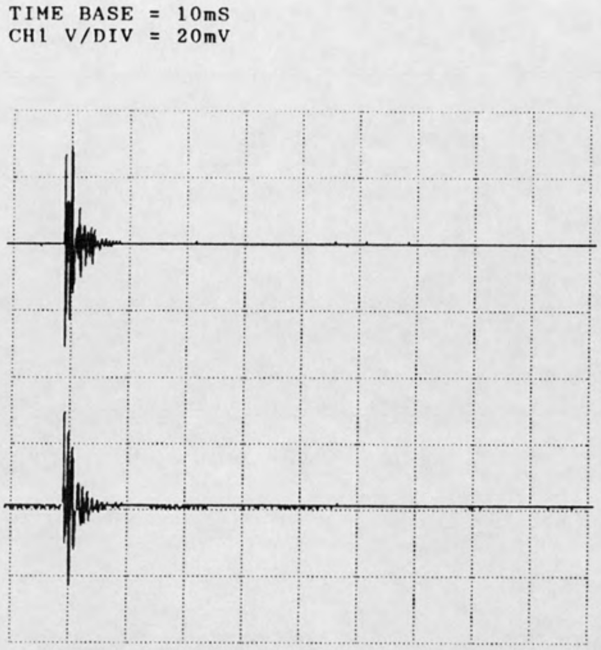


Fig.9.7.a. Comparison of percussive and occlusal sounds.
Sensor applied to the glabella.
Upper trace: Percussion of central incisor.
Lower trace: Occlusion of the teeth.

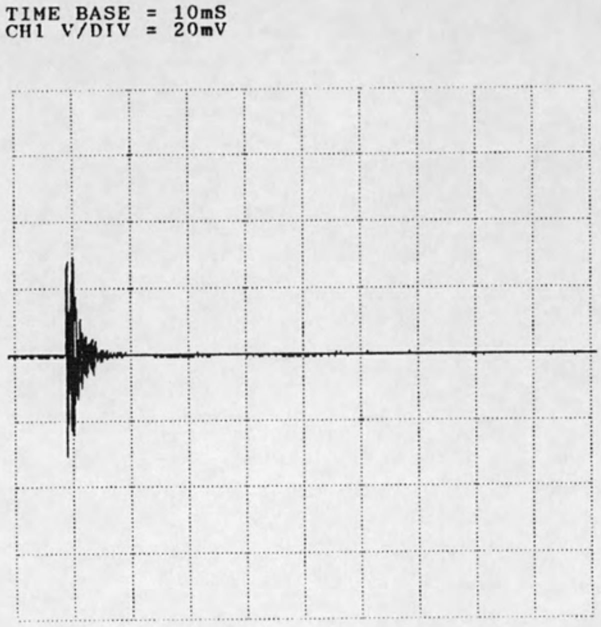


Fig.9.7.b. Traces shown in fig.9.7.a overlaid for comparison.

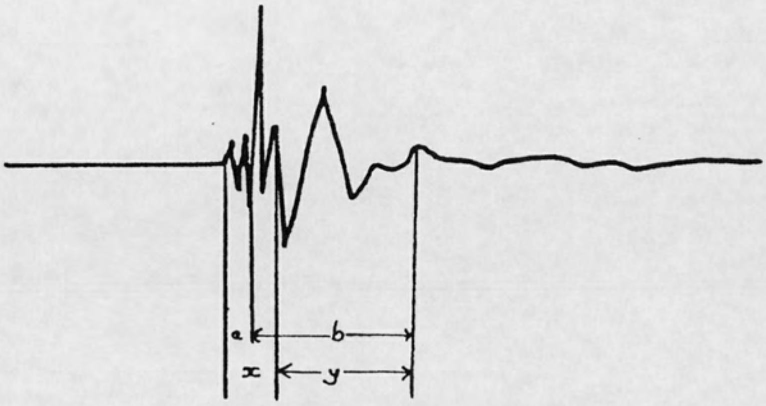


Fig.9.7.c. An occlusal event - after Brenman.
Signal showing differing wavelengths.

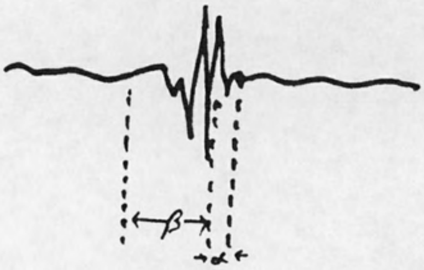


Fig.9.7.d. An occlusogram - after Brenman.
Showing an early interpretation of alpha and beta waveforms. (this figure should be read from right to left)

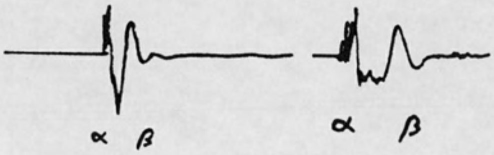


Fig.9.7.e. An occlusogram - after Brenman. Showing a later interpretation of alpha and beta waveforms.

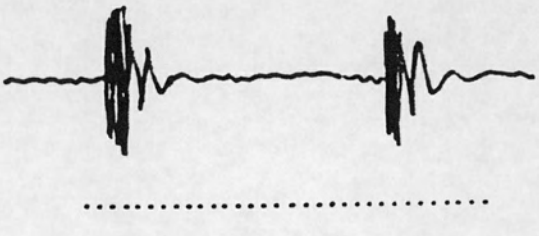


Fig.9.7.f. A gnathosonic trace - after Watt. Showing possible alpha and beta components.

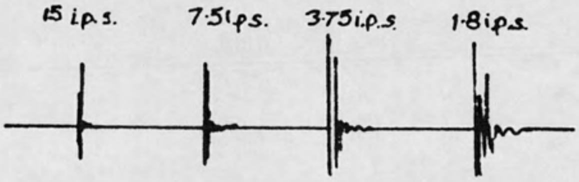


Fig.9.7.g. Differing tape replay speeds - after Watt. Showing apparent change in signal form.

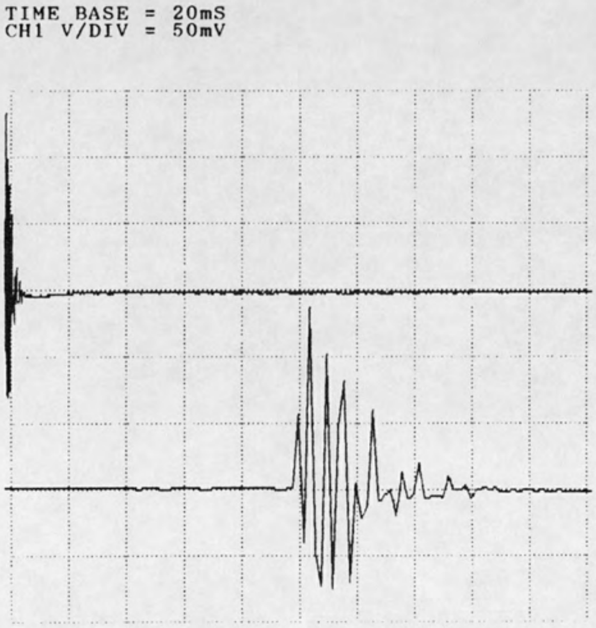


Fig.9.7.h. Demonstration of a signal appearing to change with alteration of oscilloscope timebase.

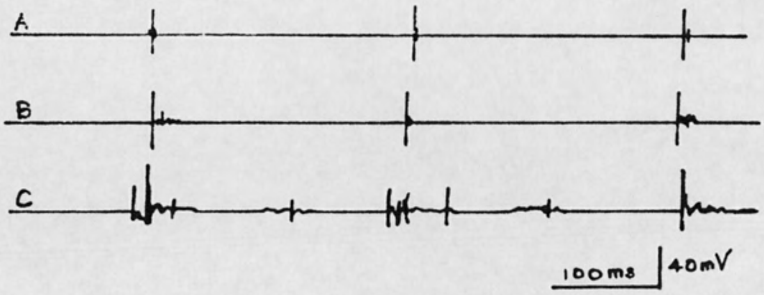


Fig.9.7.i. Class A, B and C occlusal sounds - after Watt.

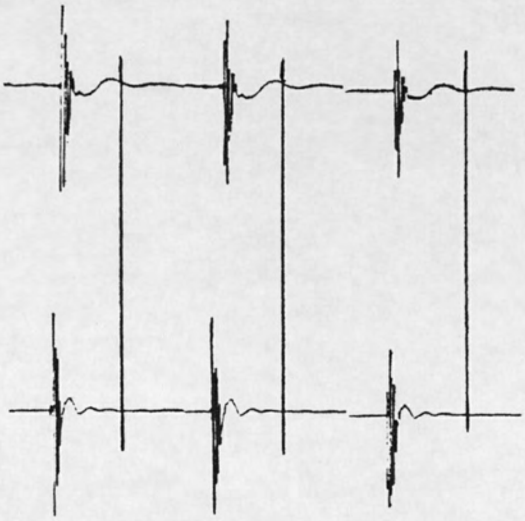


Fig.9.7.j. Gnathosonic recording of a student showing total signal recorded.

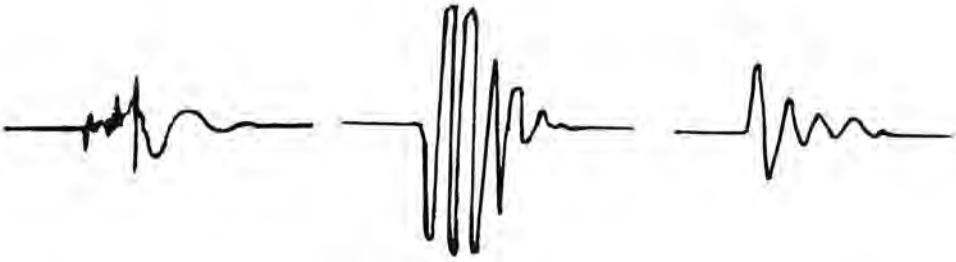


Fig.9.7.k. Waveforms - after Stallard showing a typical occlusal sound, a simple and an ideal occlusal sound.

Fig.9.7.1. Occlusal sounds - after Fuller, showing alpha and beta components.

Fig.9.7.m. Occlusal sounds - after Freer, showing similarity of basic waveform.

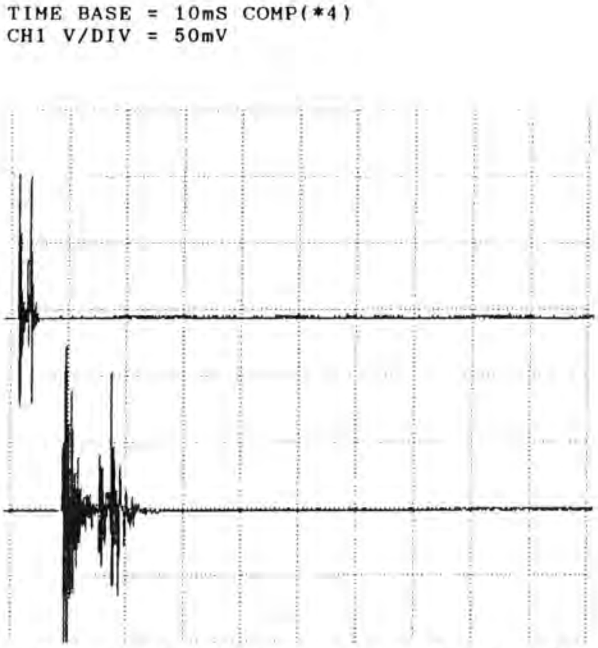


Fig.9.7.n. Gnathosonic trace registered by an accelerometer at the glabella showing a double strike of teeth on closure. Upper trace, 40ms/div. (compressed) Lower trace, 10ms/div.

A student of gnathosonics may find the literature confusing because so little data has been provided for comparisons or even reasonably informed conclusions to be drawn. However, if the beta wave form is in fact an artifact then the results from gnathosonic studies become much simpler to interpret. For example traces showing single or multiple impacts, with or without slides, would be more clearly identifiable without extraneous additions to the signals.

Superficially it appears reasonable for others to suggest that a long alpha component followed by a short beta component represents the prolonged period of engagement of the teeth before terminal closure. However, this fails to take into account the effect of shock waves from closure arriving at the sensor, as would have been shown by suitable control experiments. It is clear from experiments 9.6 and 9.7 that the beta wave is in fact a spurious component introduced by poor use of a sensor. A better interpretation of the literature is that the alpha component is the signal proper and the beta component is an artifact. In that case, the greater the jolt administered to the area of the sensor mounting the greater would be the effect causing the spurious beta wave.

The generally accepted view based on the previous literature is that poor occlusions appear to show a prolonged alpha component and short beta component, which becomes a short alpha component and long beta component as the occlusion is improved. It is now possible to offer a more rational interpretation of these observations, based on the control studies in this thesis. A poor engagement of the teeth must give rise to a prolonged alpha component before terminal closure. Since the terminal impact is cushioned by hits and slides, the sensor will register a lesser shock and give rise to a short spurious beta component. On the other hand a good occlusion with the teeth snapping cleanly together will give a very short impact sound and a sudden jolt to the tissues, producing a short alpha component followed by a larger spurious beta component.

Therefore it is suggested that care should be taken in all future research to eliminate the spurious beta component leaving the signal proper for evaluation. It appears crucial that the interface between tissue and sensor is arranged in such a way that spurious signal data cannot enter the system and further that timebases are chosen so that information is not lost through either signal stretching or contraction.

From the experimental work carried out in this thesis it is clear that some form of standardisation is required before comparisons can be made among research from different laboratories. It is a major criticism of current gnathosonic research that at present there are no such criteria, and that therefore it is difficult, if not impossible, to attempt such comparisons.

Figure 9.7.n shows a double, perhaps triple, strike of the teeth occurring in little more than 10ms registered by an accelerometer with no beta component. The duration of the signal is only meaningful when the timebase is stated. It is interesting to note that if the beta component is removed from traces with a short alpha component (a stable occlusion) the duration of the signals appears to fall below 10ms, a figure reported in the literature when sensors are attached directly to the teeth,[31] or within the external auditory meatus.[25] This reinforces the suggestion that the beta component is an artifact, and that its presence indicates deficiencies in experimental design.

SUGGESTED PARAMETERS FOR THE STANDARDISATION OF GNATHOSONIC INVESTIGATIONS

The results of the experimental work in this thesis suggest that certain parameters should be established for the instrumentation used in the investigation of sounds generated by the occlusion so that results from different laboratories may be compared. In the work reported in this thesis each component of the system has been checked for the ability to process the sounds generated by the occlusion. Firstly the problems which might arise from signal aliasing with digitised signal data have been addressed, followed by investigation of the frequencies to be expected from enamel-enamel collision. Arising from this it was possible to select hardware and to develop corresponding software to capture and process occlusal sounds without introducing spurious data. The work presented in this thesis should therefore be reproducible by any worker adhering to the specifications.

It follows from this that certain generalisations can be made concerning the reproducibility of gnathosonic data, and the following criteria are therefore suggested for the guidance of workers who propose to carry out research in the field of gnathosonics.

SENSOR A full specification must be given, including type, manufacturer, frequency response, mass and measurements. The location, method and where possible the force of application involved in attaching the sensor to the head should be stated.

HARDWARE (and software where applicable) should be fully documented and shown to be capable of capturing and processing gnathosonic signals, including any sensor resonance, without introducing distortion or spurious data.

SIGNAL STORAGE AND DISPLAY Whether signals are stored in analogue or digital form it must be clear from the specifications that the equipment is capable of handling the captured information. This prerequisite also applies to equipment to produce hard copy.

STANDARDISATION OF METHOD It is clear from the experiments in this thesis that unless experimental parameters are fully specified, in particular those affecting amplitude and timebase, the evaluation and reproduction of work by different laboratories may well be flawed.

STANDARD SIGNAL Finally there is a need for a standard vibration generator to calibrate gnathosonic equipment. Gnathosonic recording systems should be capable of capturing and reproducing standard signals within stated limits and under specific conditions.

CHAPTER 10

CLINICAL GNATHOSONICS AND OTHER SIGNAL CAPTURE

INTRODUCTION

The major part of this thesis has been concerned with demonstrating the inadequacies of previous gnathosonic capture systems in the literature and the usefulness of *in vitro* modelling and experiments. A considerable amount of work still remains, but since the purpose of this thesis is to provide practitioners with a low cost gnathosonic facility, this chapter is intended to demonstrate the versatility of the developed apparatus with a number of clinical examples showing not only the quality but also the manner in which the signal may be manipulated by the associated software. Occlusal sounds were therefore recorded from volunteers, students and patients for these purposes.

FACILITIES AND DATA PROVIDED BY THE CAPTURE PROGRAM

Before examining captured clinical occlusal sounds in detail it is helpful to examine the ways in which the captured signals can be manipulated by the associated software. Figure 10 shows a typical computer screen dump of a gnathosonic signal. The component parts of the screen dump are numbered and are explained in the text which follows.

a) Displayed data: 'start' and 'end' indicate the first and last memory addresses of the points plotted in the displayed signal, numbering is in hexadecimal.

It will be shown later that any part of the captured signal may be expanded and therefore only certain sections of memory will be used in that display. The 'displayed data' shows the exact section of memory currently displayed.

b) Grid A grid with a centre zero middle line, may be superimposed to indicate the maximum and minimum excursions that a signal may make before 'clipping' takes place due to overload.

c) Trace The plotted trace of the captured signal.

d) Vector line A line divided into 10 segments. The two elongated vertical lines indicate the segment of the original trace which has now been expanded to the full length of the display.

This feature is helpful where a signal is complex or more than one signal has been captured. The trace displayed can be related to its position in the complete signal originally captured.

e) Information Line 1: Options available to manipulate the signal may be selected by a number on the computer keyboard.

zoom	Any part of the displayed signal can be expanded to fill the full width of the horizontal display. This process can be repeated until there are only two data points present.
all	To plot the 20224 data points takes time, therefore for speed and convenience of use the program defaults to plotting approximately 500 points, i.e. 1 in 40. 'all' is used to override this and plot every data point if required.
step	This is the opposite to 'all' and causes a return to the initial stepped plotting.
point	Used as a toggle to switch on or off marking of the data points which have been joined to make the trace.
grid	See b) above, acts as a toggle to switch the grid on or off.
mag	The trace displayed can be enlarged or reduced in either or both the X or the Y axes of the signal. This option is particularly useful in enlarging signals of low amplitude in the Y axis. For example, in the lower traces of figures 8.2.e and 8.2.f, where a residual 12.5KHz signal was clearly shown to be present by

a x10 enlargement in the Y axis.

plot A facility to use a plotter to plot the screen display instead of the usual screen dump method. The current program is specifically designed to use the Plotmate A4SM (Linear Graphics Ltd, UK).

save Stores the whole of the captured data on disk.

menu Returns the user to a master menu allowing a new signal to be captured.

dump Dumps the screen image to a printer.

f) Information Line 2: **SPC-notes** Notes added when captured data is saved to disc can be displayed by pressing the keyboard space (SPC) bar.

Range Records the setting of the input sensitivity and polarity of the external A-D converter.

Trigger Trigger setting is indicated, whether set or not, and if set the level at which capture is initiated on a scale of 0-127.

g) Information Line 3: **Pts=** Indicates the number of points plotted in the trace presently displayed.

Step Shows the points plotted, i.e. Step 40 indicates that every fortieth point has been plotted, whereas Step 1 indicates that every point has been plotted.

Delay Shows the time lapse in microseconds between each data point captured.

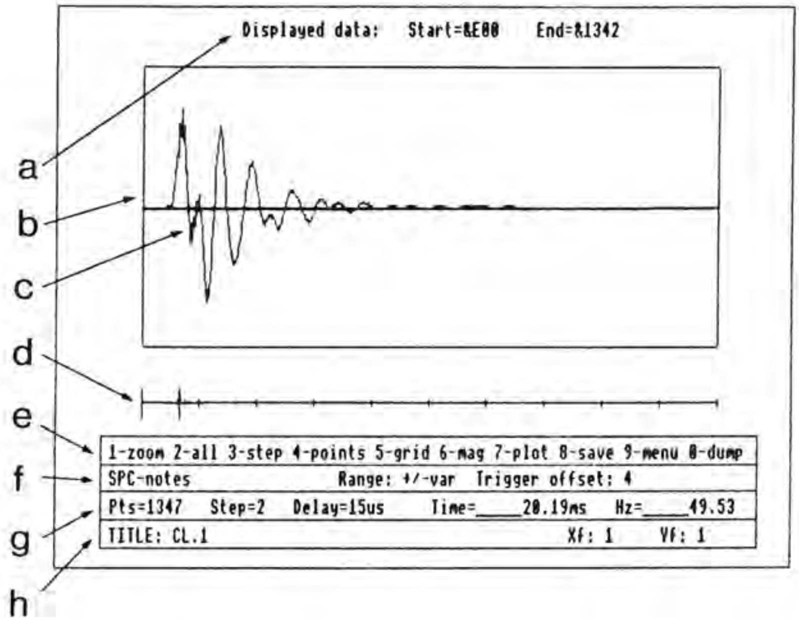
Time Indicates the time in milliseconds or microseconds for the full length of the current display.

Hz Shows the frequency of a signal if one cycle of that frequency fills the X axis of the display. If more than one cycle is present in the display then the figure at 'Hz' must be multiplied by the number of cycles shown to give the correct frequency. For example, if a signal has been manipulated to display 10 cycles, then the figure shown at 'Hz' must be raised by a factor of 10 to give the correct reading.

h) Information Line 4: **TITLE:** Before saving a captured signal and associated data to disc, a title may be added to the display for reference.

Xf: and Yf: The figures displayed indicate the factor by which the X or Y axis of the signal has been multiplied.

The experiments which follow illustrate the manipulation of signals captured by the program. All the



```
Displayed data:   Start=&E00    End=&1342

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                  Range: +/-var  Trigger offset: 4
Pts=1347   Step=2   Delay=15us     Time=_____20.19ms   Hz=_____49.53
TITLE: CL.1                                       Xf: 1     Yf: 1
```

Fig.10. Screen dump of a typical gnathosonic trace.

a) Memory data displayed.
b) Grid with centre zero middle line.
c) The gnathosonic trace.
d) Scale to show section of signal displayed.
e) Information Line 1.
f) Information Line 2.
g) Information Line 3.
h) Information Line 4.

manipulations are mathematical alterations of the stored data points and are not open to progressive distortion with amplification as is information stored in analogue form. Signal aliasing must always be avoided to prevent the generation of spurious waveforms.

EXPERIMENT 10.1.

A SIMPLE EXAMPLE OF SIGNAL ALIASING CAUSED BY INCORRECT SAMPLING

INTRODUCTION

A problem in clinical studies is the avoidance of aliasing. Although all the *in vitro* studies in this thesis have shown the frequency range of tooth impacts to be in the order of 0-6±1KHz, with loss of high frequency if the signal is sensed after travelling through soft tissues, this has not been demonstrated *in vivo*. To minimise the possibility of aliasing the initial signals were captured at the fastest sample time of 15us, which can reliably record frequencies up to 33KHz. This simple experiment demonstrates how sampling the signal too slowly leads to incorrect data being recorded by digital capture. To be consistent in clinical recordings the gain of the interface is always set at 5 unless otherwise stated.

METHOD

An accelerometer (BU1771 Knowles Laboratories UK) was attached to a small loudspeaker (40mm RS Components Ltd UK) as described in experiment 8.3, and a signal of approximately 5KHz was provided to the loudspeaker by a function generator (Thandar TG102 RS Components Ltd UK). The signals from the accelerometer caused by the vibrations of the loudspeaker cone were captured without triggering by the computer system, sampling the signal every 15us and the data saved to disc. The captured signal was displayed on screen through the software, in a series of steps from 40 to 1, each step representing 15us. Each screen was dumped to the printer to produce hard copy.

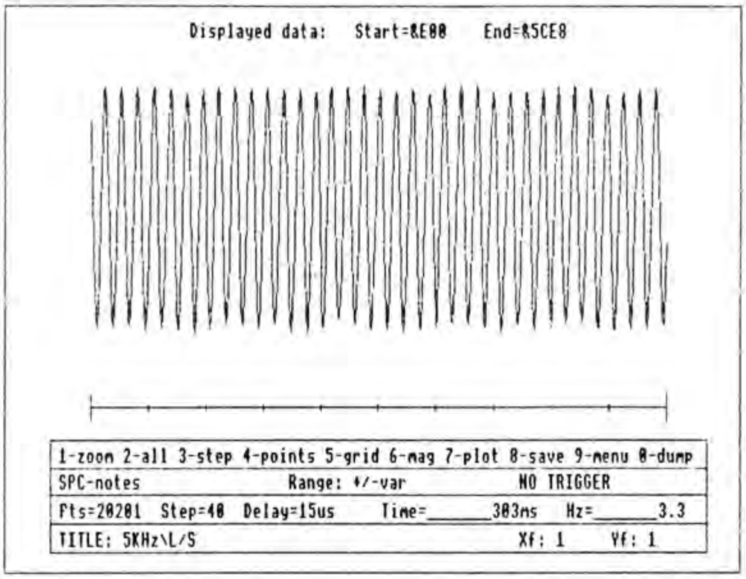
RESULTS

The results of experiment 10.1 are shown in figures 10.1.a-q

DISCUSSION

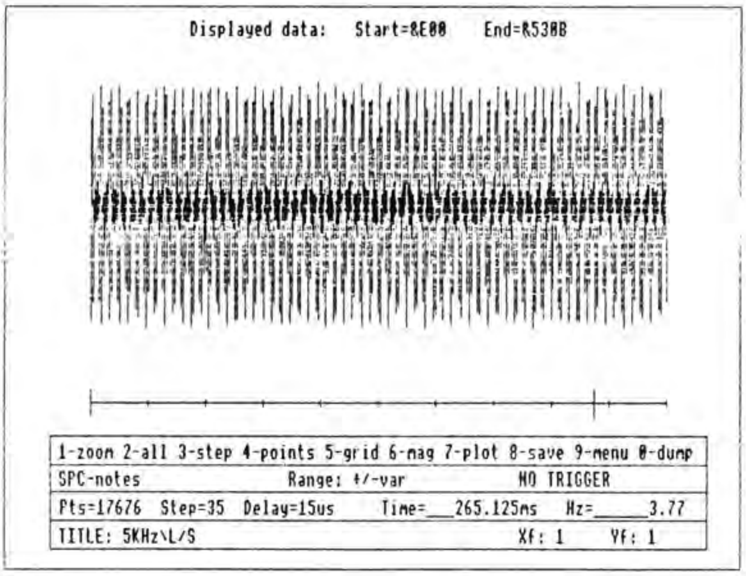
It can be seen from figures 10.1.a-q that the signal appears as differing frequencies, shown in figures 10.1.a-n, until the limit of two samples per cycle, shown in figures 10.1.o-q. A frequency of approximately 5KHz requires to be read at a minimum of 10K times per second i.e. every 100us to be properly captured. It can be seen from figures 10.1.a-n that various frequencies appear to be demonstrated as the sample time steps downwards from 600us. These spurious frequencies, where they can be read, are noted in the figure legends. The signal is unreadable at step 7 (105us sampling), whereas it is readable at its true value in figure 10.1.o, at step 5 (75us sampling). From these results it is clear that the signal must at minimum be sampled at twice its frequency to avoid spurious waveforms being created (see chapter 3). It is therefore necessary that the maximum frequencies liable to be present in a signal be known before a capture program is used so that the sampling of the signal can be adjusted to avoid aliasing.

Once the danger of aliasing is understood, it becomes clear that a high sampling rate should always be used in preliminary experiments to establish the true frequencies present. Once the highest frequency present has been established the sampling rate can be adjusted to, at minimum, twice that frequency.



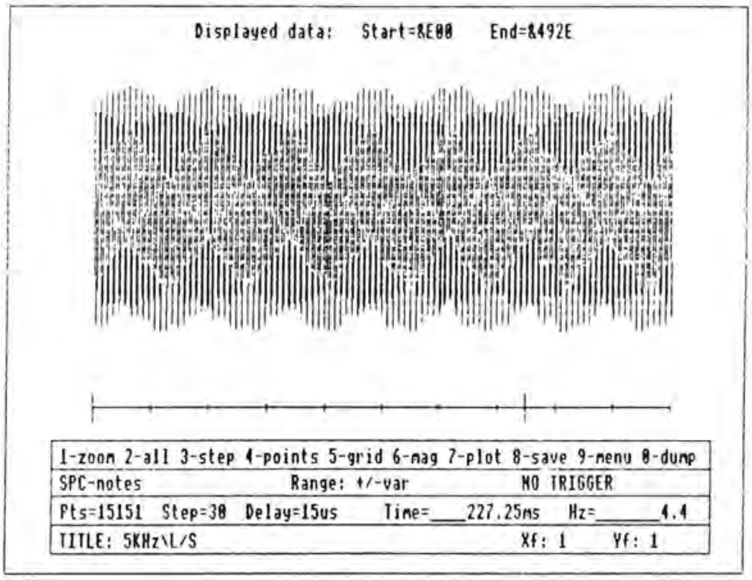
```
Displayed data:   Start=&E00   End=&5CE8
SPC-notes              Range: +/-var           NO TRIGGER
Pts=20201  Step=40  Delay=15us    Time=______303ms  Hz=______3.3
TITLE: 5KHz\L/S                                 Xf: 1    Yf: 1
```

Fig.10.1.a. 5KHz signal aliased. Sampled at Step 40 (every 600us).
Apparent frequency: 117Hz. (3.3x35.5).



```
Displayed data:   Start=&E00   End=&530B
SPC-notes              Range: +/-var           NO TRIGGER
Pts=17676  Step=35  Delay=15us    Time=___265.125ms  Hz=______3.77
TITLE: 5KHz\L/S                                 Xf: 1    Yf: 1
```

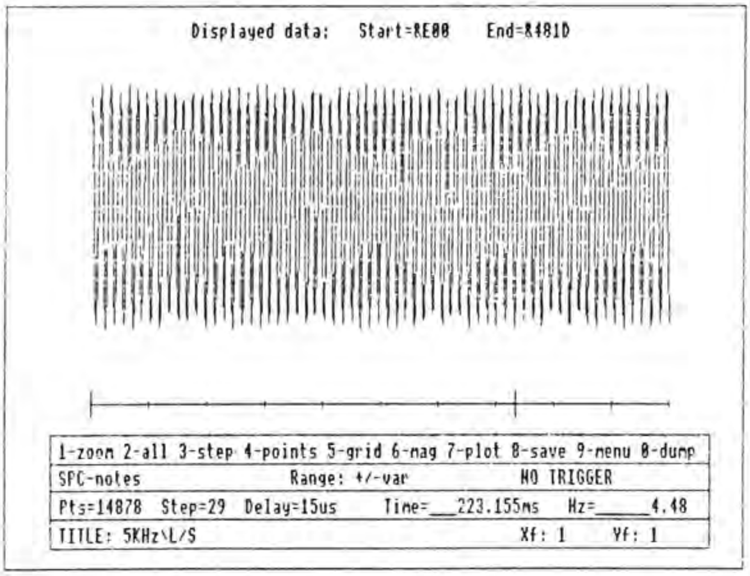
Fig.10.1.b. 5KHz signal aliased. Sampled at Step 35 (every 525us).
Apparent frequency: unreadable.



```
Displayed data:   Start=&E00    End=&492E

SPC-notes                  Range: +/-var            NO TRIGGER
Pts=15151  Step=30  Delay=15us    Time=___227.25ms   Hz=______4.4
TITLE: 5KHz\L/S                                     Xf: 1    Yf: 1
```

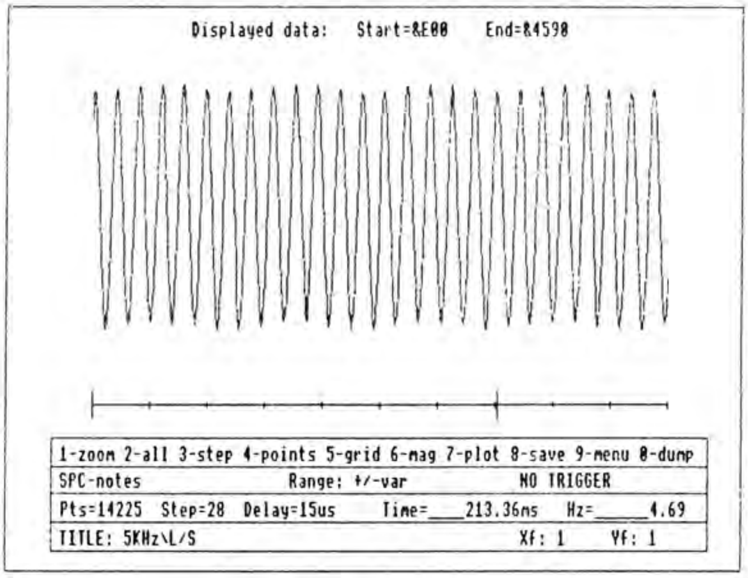
Fig.10.1.c. 5KHz signal aliased. Sampled at Step 30 (every 450us).
Apparent frequency: unreadable.



```
Displayed data:   Start=&E00    End=&481D

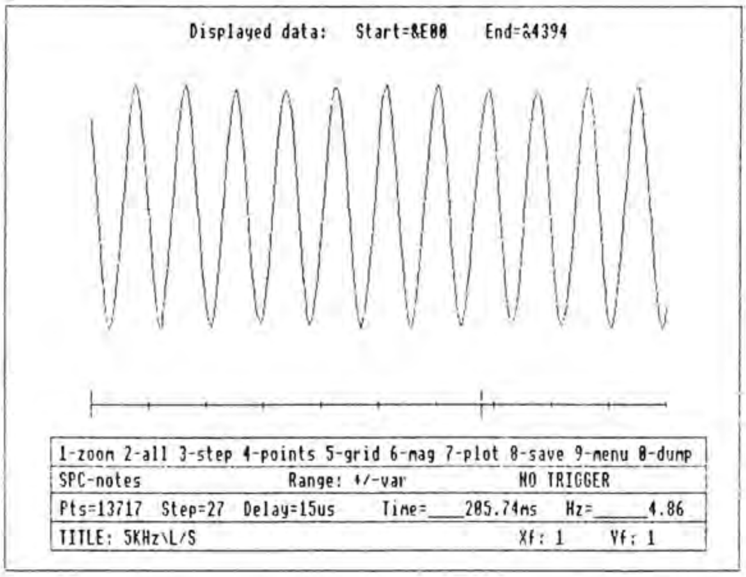
SPC-notes                  Range: +/-var            NO TRIGGER
Pts=14878  Step=29  Delay=15us    Time=__223.155ms   Hz=_____4.48
TITLE: 5KHz\L/S                                     Xf: 1    Yf: 1
```

Fig.10.1.d. 5KHz signal aliased. Sampled at Step 29 (every 435us).
Apparent frequency: 285Hz. (4.48x63.5).



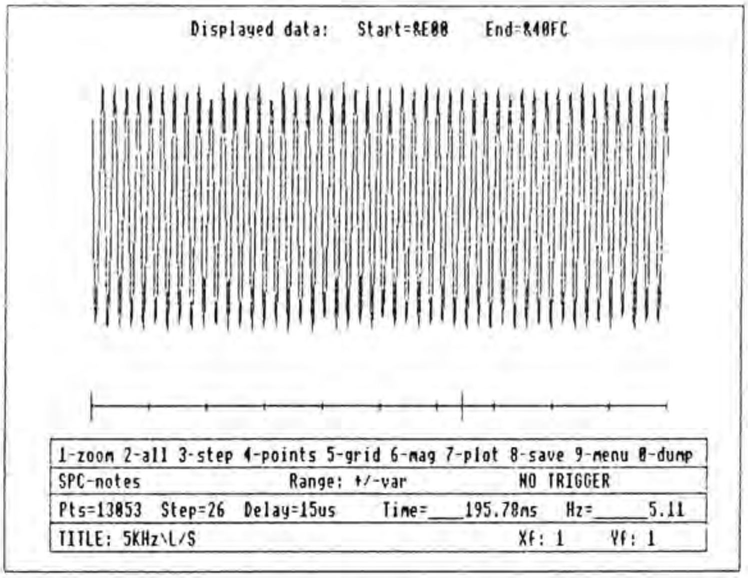
```
Displayed data:   Start=&E00   End=&4590
1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                 Range: +/-var              NO TRIGGER
Pts=14225  Step=28  Delay=15us     Time=___213.36ms   Hz=_____4.69
TITLE: 5KHz\L/S                                      Xf: 1    Yf: 1
```

Fig.10.1.e. 5KHz signal aliased. Sampled at Step 28 (every 420us).
Apparent frequency: 120Hz. (4.69x25.5).



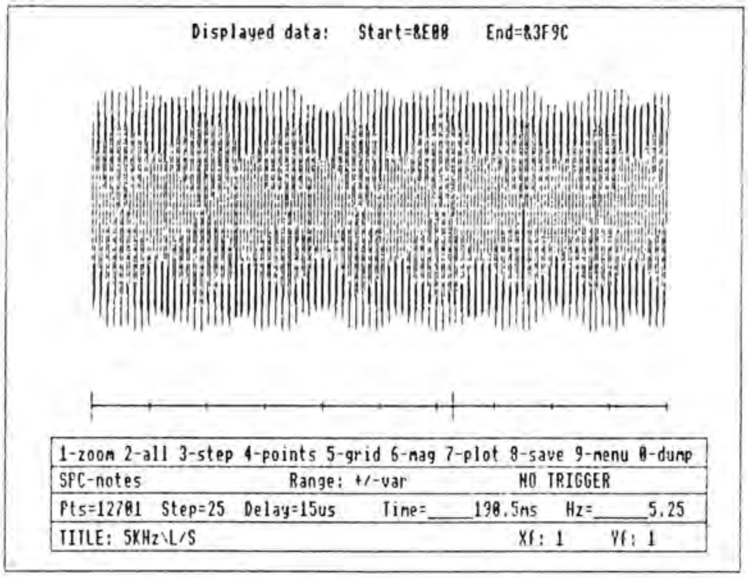
```
Displayed data:   Start=&E00   End=&4394
1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                 Range: +/-var              NO TRIGGER
Pts=13717  Step=27  Delay=15us     Time=___205.74ms   Hz=_____4.86
TITLE: 5KHz\L/S                                      Xf: 1    Yf: 1
```

Fig.10.1.f. 5KHz signal aliased. Sampled at Step 27 (every 405us).
Apparent frequency: 56Hz. (4.86x11.5).



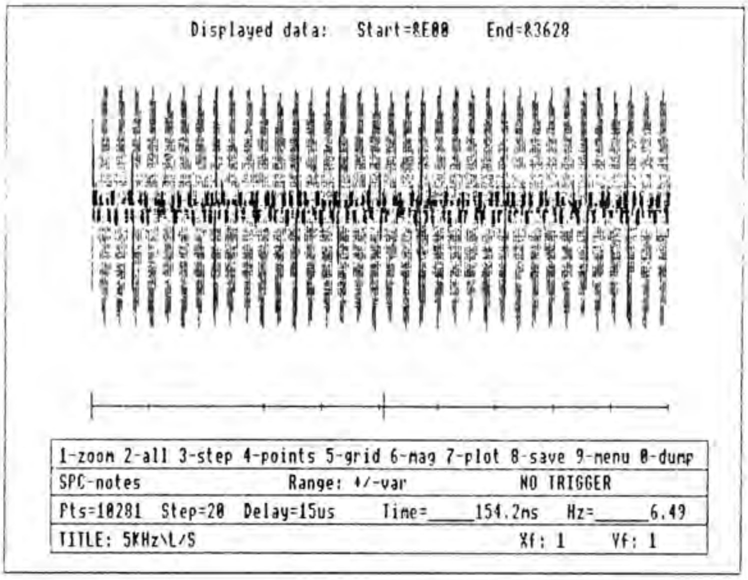
```
Displayed data:   Start=&E00    End=&40FC
SPC-notes                  Range: +/-var            NO TRIGGER
Pts=13053  Step=26  Delay=15us     Time=___195.78ms  Hz=_____5.11
TITLE: 5KHz\L/S                                     Xf: 1     Yf: 1
```

Fig.10.1.g. 5KHz signal aliased. Sampled at Step 26 (every 390us).
Apparent frequency: 245Hz. (5.11x48).



```
Displayed data:   Start=&E00    End=&3F9C
SPC-notes                  Range: +/-var            NO TRIGGER
Pts=12701  Step=25  Delay=15us     Time=____190.5ms  Hz=_____5.25
TITLE: 5KHz\L/S                                     Xf: 1     Yf: 1
```

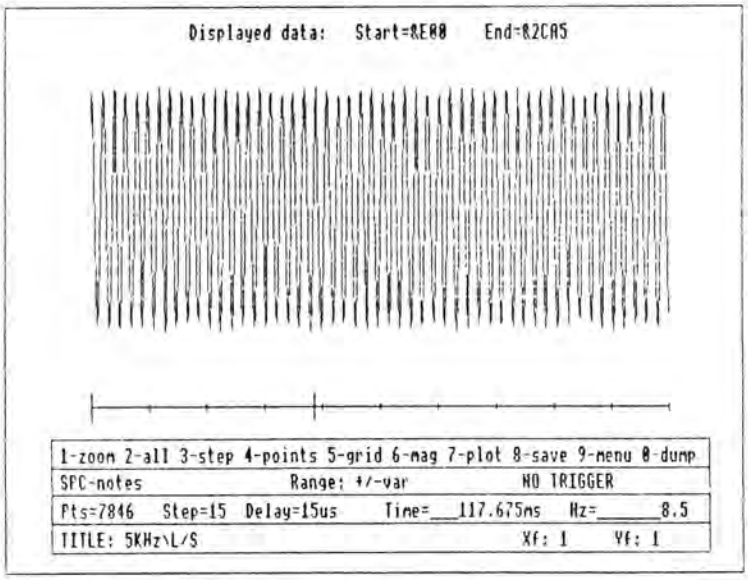
Fig.10.1.h. 5KHz signal aliased. Sampled at Step 25 (every 375us).
Apparent frequency: 452Hz. (5.25x86).



```
Displayed data:   Start=&E00    End=&3628

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                 Range: +/-var            NO TRIGGER
Pts=10281  Step=20  Delay=15us      Time=_____154.2ms   Hz=______6.49
TITLE: 5KHz\L/S                                    Xf: 1     Yf: 1
```

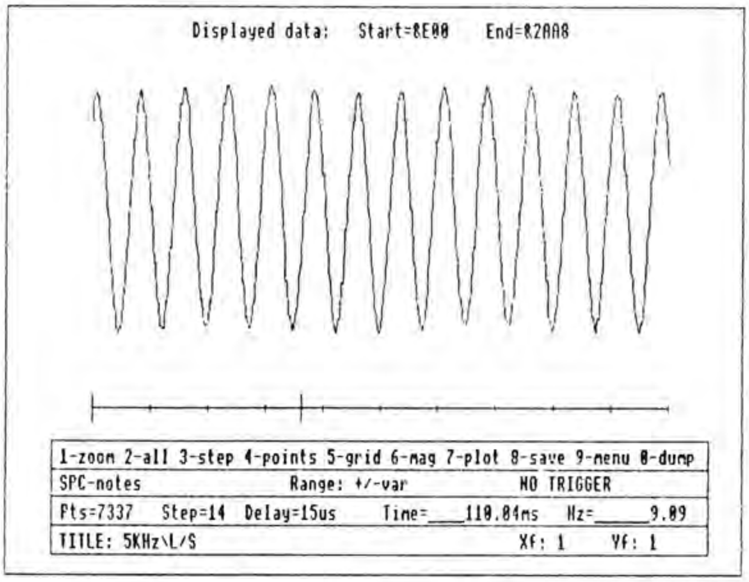
Fig.10.1.i. 5KHz signal aliased. Sampled at Step 20 (every 300us).
Apparent frequency: unreadable.



```
Displayed data:   Start=&E00    End=&2CA5

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                 Range: +/-var            NO TRIGGER
Pts=7846   Step=15  Delay=15us      Time=___117.675ms   Hz=_______8.5
TITLE: 5KHz\L/S                                    Xf: 1     Yf: 1
```

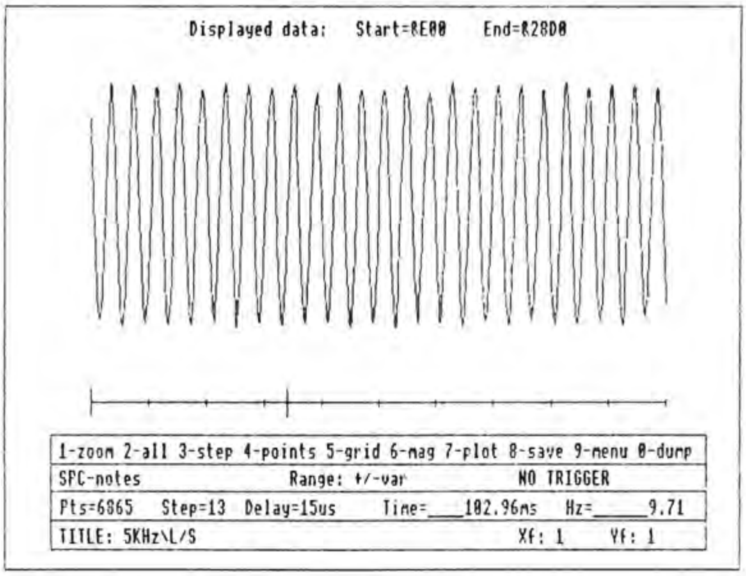
Fig.10.1.j. 5KHz signal aliased. Sampled at Step 15 (every 225us).
Apparent frequency: 438Hz. (8.5x21.5).



```
Displayed data:   Start=&E00   End=&2AA8

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                Range: +/-var          NO TRIGGER
Pts=7337   Step=14  Delay=15us    Time=___110.04ms   Hz=_____9.09
TITLE: 5KHz\L/S                                Xf: 1    Yf: 1
```

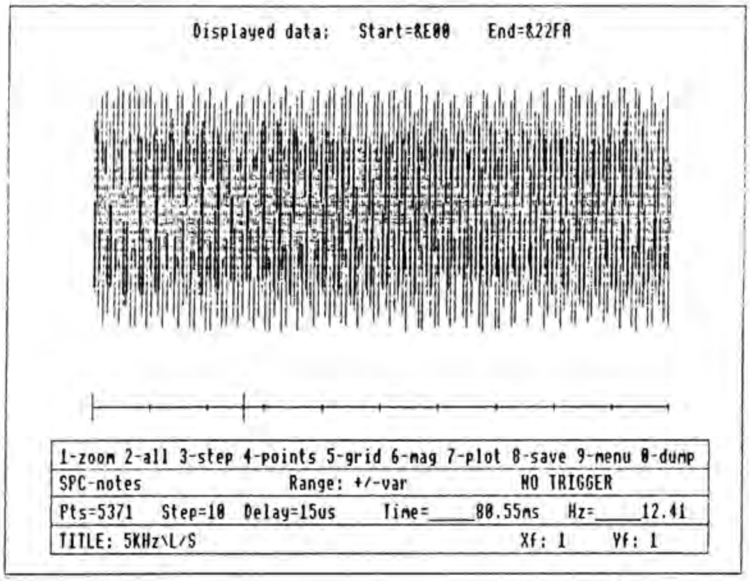
Fig.10.1.k. 5KHz signal aliased. Sampled at Step 14 (every 210us)
Apparent frequency: 120Hz. (9.09x13.3).



```
Displayed data:   Start=&E00   End=&28D0

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                Range: +/-var          NO TRIGGER
Pts=6865   Step=13  Delay=15us    Time=___102.96ms   Hz=_____9.71
TITLE: 5KHz\L/S                                Xf: 1    Yf: 1
```

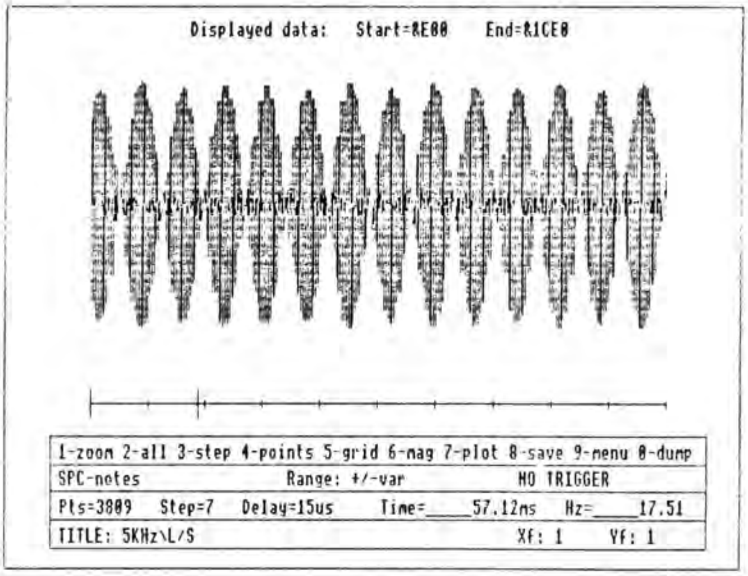
Fig.10.1.1. 5KHz signal aliased. Sampled at Step 13 (every 195us).
Apparent frequency: 248Hz. (9.71x25.5).



```
Displayed data:   Start=&E00    End=&22FA

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                  Range: +/-var              NO TRIGGER
Pts=5371   Step=10  Delay=15us     Time=_____80.55ms   Hz=_____12.41
TITLE: 5KHz\L/S                                       Xf: 1     Yf: 1
```

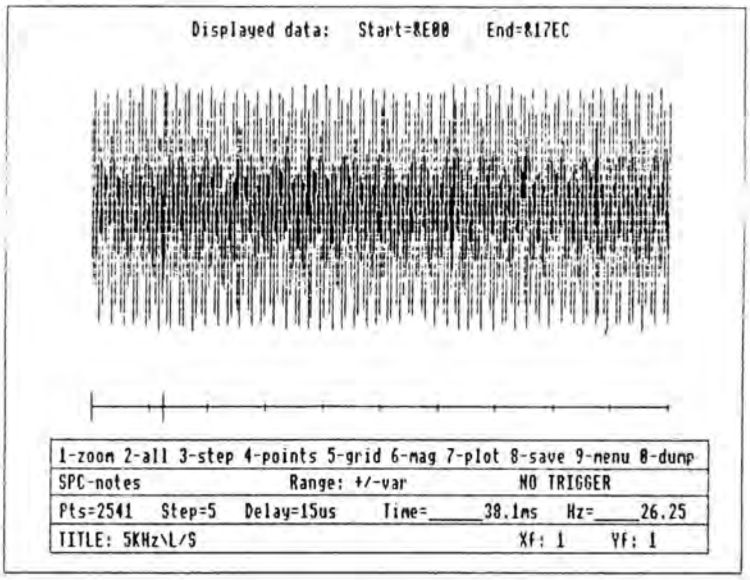
Fig.10.1.m. 5KHz signal aliased. Sampled at Step 10
(every 150us).
Apparent frequency: unreadable.



```
Displayed data:   Start=&E00    End=&1CE0

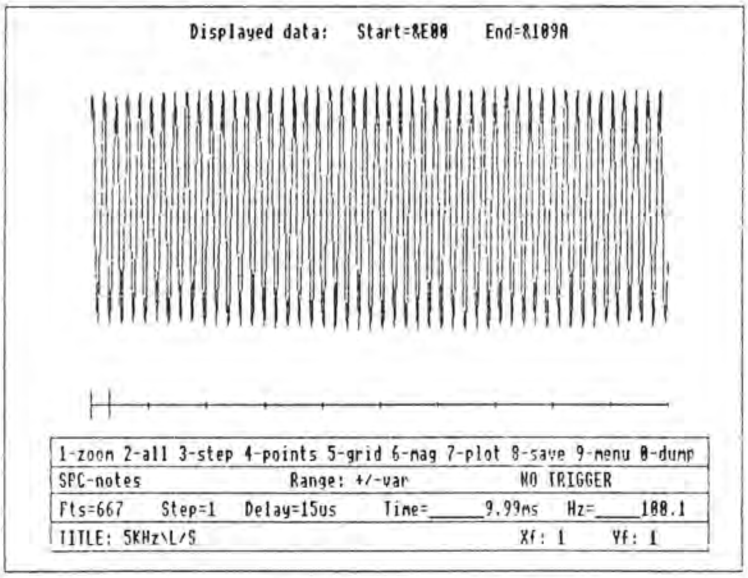
1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                  Range: +/-var              NO TRIGGER
Pts=3809   Step=7   Delay=15us     Time=_____57.12ms   Hz=_____17.51
TITLE: 5KHz\L/S                                       Xf: 1     Yf: 1
```

Fig.10.1.n. 5KHz signal aliased. Sampled at Step 7
(every 105us).
Apparent frequency: unreadable.



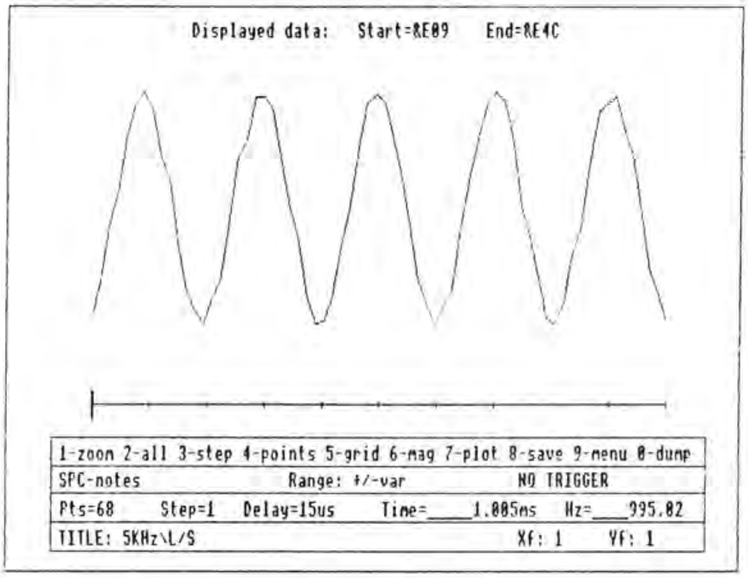
```
Displayed data:   Start=&E00    End=&17EC
SPC-notes                 Range: +/-var            NO TRIGGER
Pts=2541   Step=5   Delay=15us     Time=_____38.1ms   Hz=_____26.25
TITLE: 5KHz\L/S                                  Xf: 1     Yf: 1
```

Fig.10.1.o. 5KHz signal. Sampled at Step 5 (every 75us). NOT ALIASED. Frequency: 4.9KHz. (26.25x185).



```
Displayed data:   Start=&E00    End=&109A
SPC-notes                 Range: +/-var            NO TRIGGER
Pts=667    Step=1   Delay=15us     Time=_____9.99ms   Hz=_____100.1
TITLE: 5KHz\L/S                                  Xf: 1     Yf: 1
```

Fig.10.1.p. 5KHz signal. Sampled at Step 1. (every 15us). NOT ALIASED. Frequency: 4.9KHz. (100.1x48.7).



```
Displayed data:   Start=&E09    End=&E4C

SPC-notes                  Range: +/-var              NO TRIGGER
Pts=68     Step=1   Delay=15us     Time=____1.005ms   Hz=____995.02
TITLE: 5KHz\L/S                                       Xf: 1     Yf: 1
```

Fig.10.1.q. 5KHz signal. Sampled at Step 1
(every 15us). NOT ALIASED.
Frequency: 4.975KHz. (995.02x5).

EXPERIMENT 10.2.

DATA MANIPULATION OF A CAPTURED GNATHOSONIC SIGNAL AND PRELIMINARY EVALUATION OF ITS FREQUENCY

METHOD

A sensor (BU1771 Knowles Laboratories UK) was applied to the glabella of a volunteer using an elasticated fabric strap as described in experiment 9.1. The volunteer occluded the teeth sharply into centric occlusion and the gnathosonic signal was captured using triggering and a capture rate of 15us. The captured signal was manipulated by the various program functions.

RESULTS

The results of experiment 10.2 are shown in figures 10.2.a-f.

DISCUSSION

It can be seen from figure 10.2.a that the sound appears to be of very short duration, typical of a Watt Class A occlusion. However this is a rapid first plot using only every fortieth data, as indicated by 'step' in Information Line 1. Plotting every data point by selecting **all** shown in figure 10.2.b, produces a more detailed trace. This is not surprising as reading every fortieth data point can only resolve frequencies of up to 833Hz, whereas plotting every point at 15us intervals can resolve frequencies of up to 33KHz.

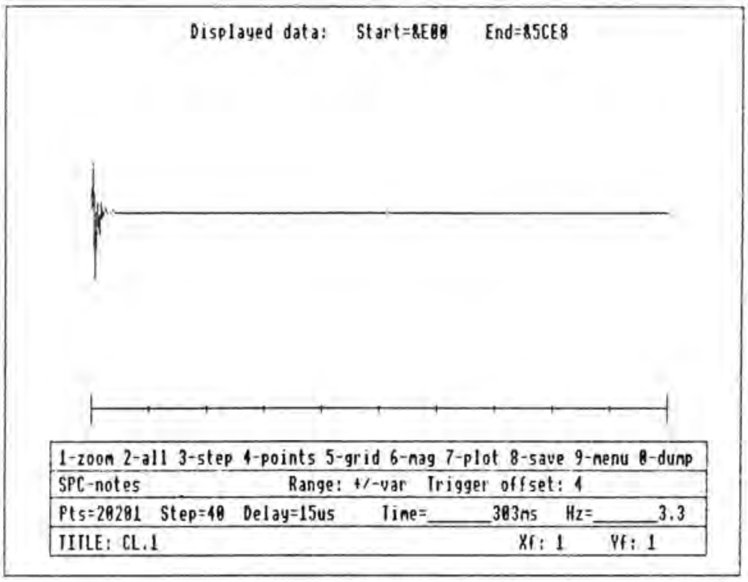
Using the **zoom** facility shown in figure 10.2.c, shows expansion of the trace in various stages until the components of the signal are clearly discernible. The screen dumps have been reduced for ease of comparison. The frequency of the signal is in the order of 1KHz which is in accord with the frequencies obtained in the *in vitro* studies when simulated soft tissues were used with a dry skull in experiments 5.9 and 5.10.

Selection of **pts** (points) figure 10.2.d, allows each point plotted to be marked on the trace. This is of use in the examination of expanded high frequencies to show that sufficient data points are present to properly demonstrate the signal.

Application of the **grid** seen in figure 10.2.e can establish the degree of saturation of the signal in amplitude and whether or not a signal has caused overload and been clipped. The centre line of the grid indicates zero voltage in the Y axis and therefore oscillations of the signal may be examined from a centre point. Further it will be seen if there should be any biasing voltage in the incoming signal.

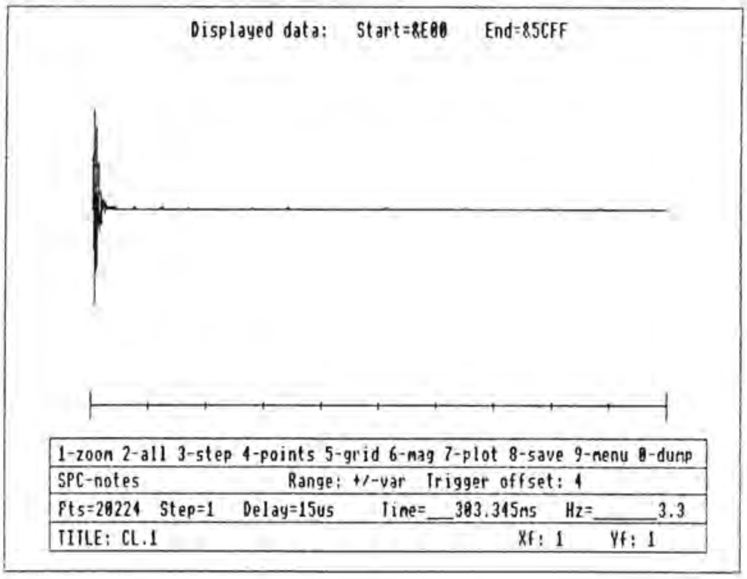
The **mag** or magnification factor, for example those shown in figure 10.2.f, allows enlargement or reduction of the plotted signal in both axes. The factor by which each axis is altered is shown in 'Information Line 4' as Xf and Yf. As the sample rate and the time in the X axis is shown in 'Information Line 3', the information in the trace can be interpreted even though the absolute length of the trace has been altered. Usually this option is used to enlarge signals of low amplitude, but for the purpose of demonstration using the signal under examination, the last part the trace can be seen more clearly by magnification in the Y axis, the first part of the trace has of course gone off-screen.

The models in chapter 4 and chapter 5 indicate a frequency range of 0-6±1KHz for enamel-enamel collisions, modified by high frequency loss due to tissue damping. The signals presently under examination are consistent with these findings, in fact no signal captured by this method has reached the upper limit, apart from the 12.5KHz resonance of the sensor which is of such low amplitude that it is not significant in relation to the amplitude of the whole signal and can be



```
Displayed data:   Start=&E00   End=&5CE8
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=20201  Step=40  Delay=15us    Time=______303ms   Hz=______3.3
TITLE: CL.1                                   Xf: 1    Yf: 1
```

Fig.10.2.a. Rapid first plot of every fortieth data point (Step 40, every 600us).



```
Displayed data:   Start=&E00   End=&5CFF
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=20224  Step=1   Delay=15us    Time=__303.345ms   Hz=______3.3
TITLE: CL.1                                   Xf: 1    Yf: 1
```

Fig.10.2.b. All data points plotted (Step1, every 15us).

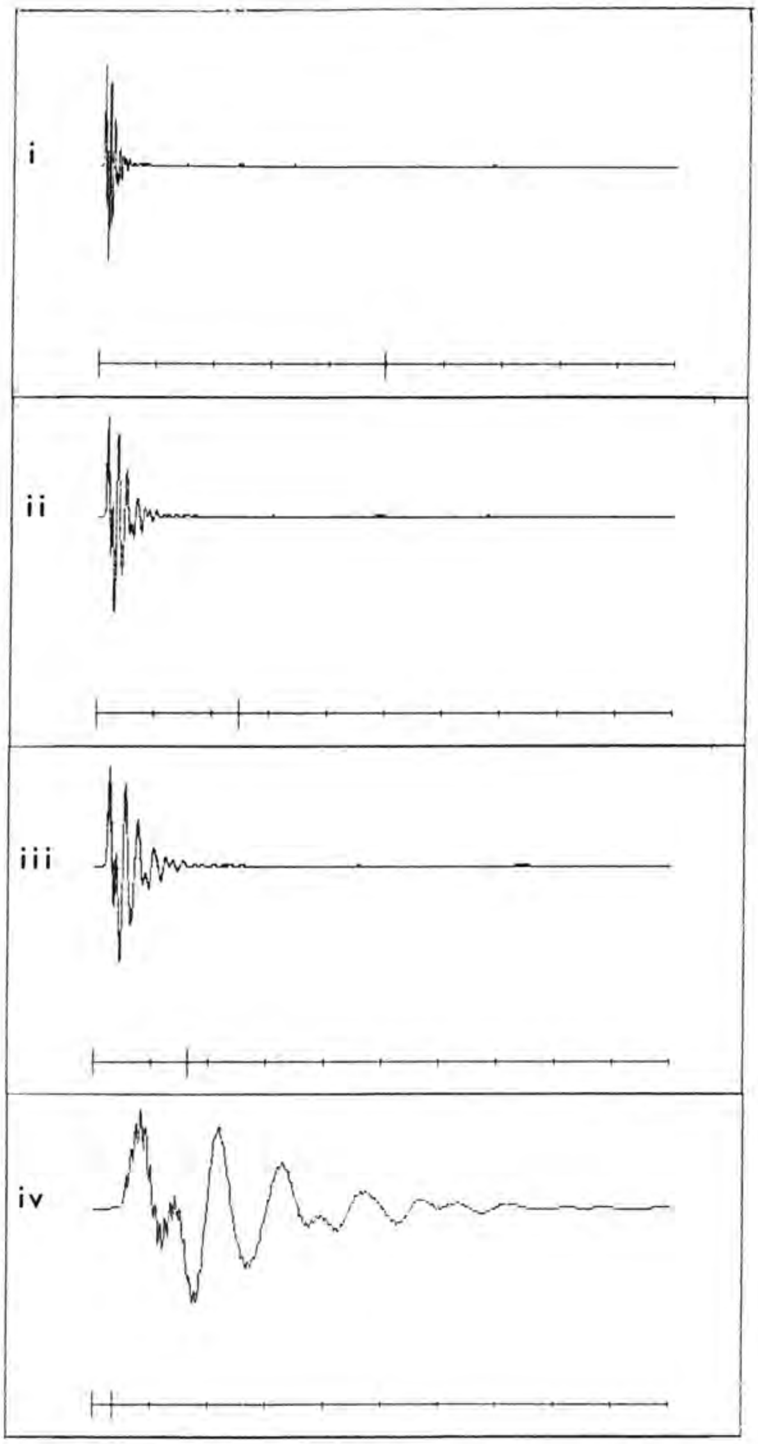
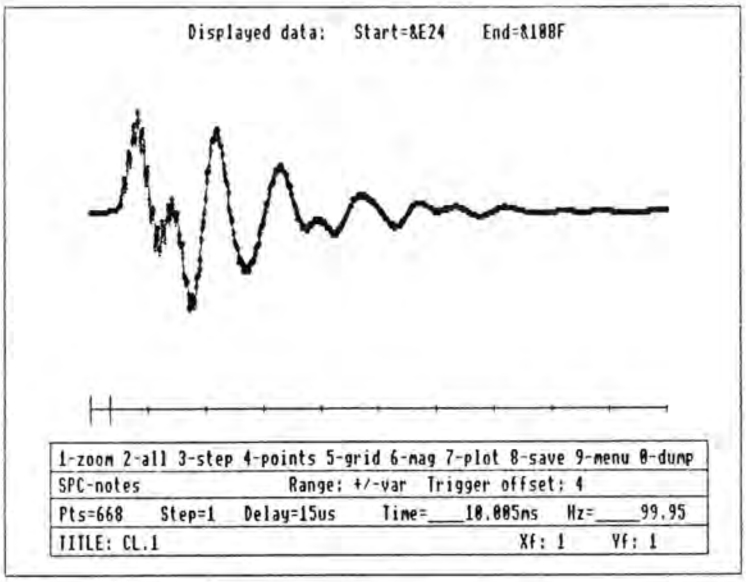


Fig.10.2.c. i. Timescale 151.665ms.
ii. Timescale 75.525ms.
iii. Timescale 50.040ms.
iv. Timescale 10.005ms.



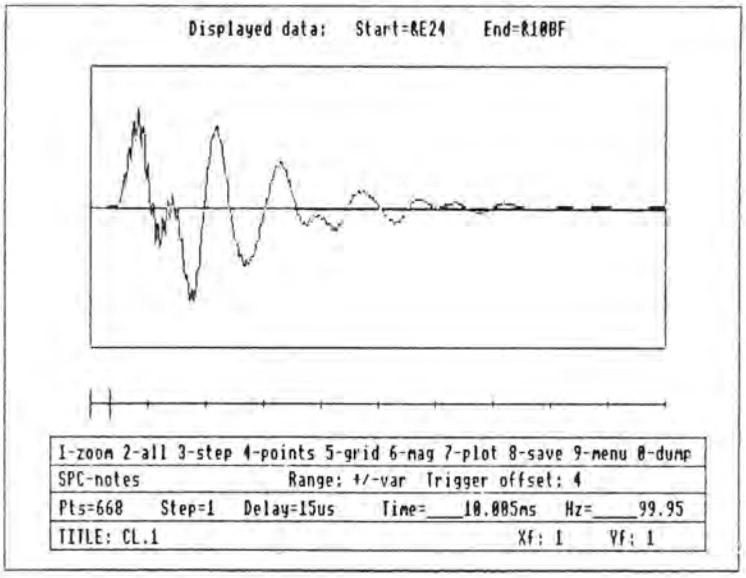
Displayed data: Start=&E24 End=&108F

SPC-notes Range: +/-var Trigger offset: 4

Pts=668 Step=1 Delay=15us Time=____10.005ms Hz=_____99.95

TITLE: CL.1 Xf: 1 Yf: 1

Fig.10.2.d. Points plotted marked.



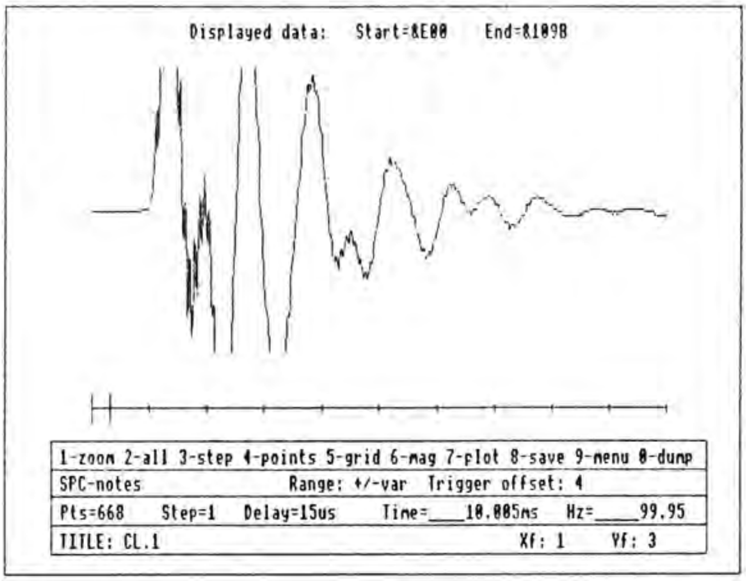
Displayed data: Start=&E24 End=&108F

SPC-notes Range: +/-var Trigger offset: 4

Pts=668 Step=1 Delay=15us Time=____10.005ms Hz=_____99.95

TITLE: CL.1 Xf: 1 Yf: 1

Fig.10.2.e. Grid applied to mark centre zero as well as upper and lower limits of amplitude recorded.



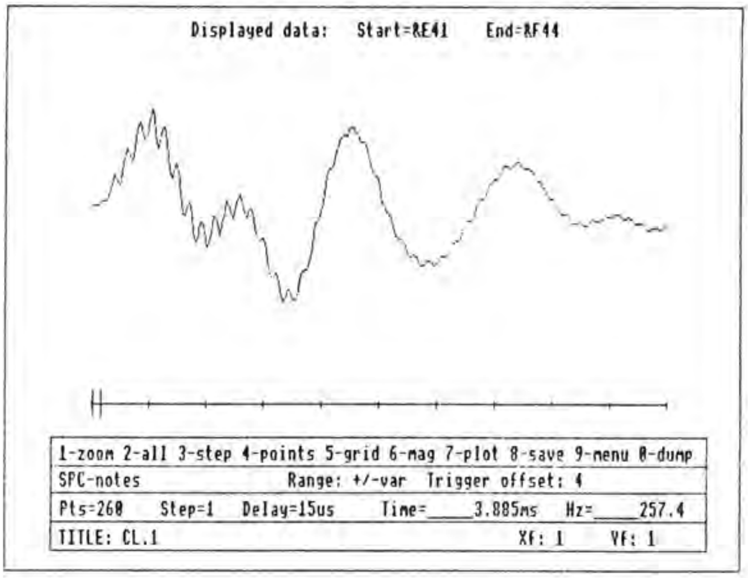
Displayed data: Start=&E00 End=&109B

SPC-notes Range: +/-var Trigger offset: 4

Pts=668 Step=1 Delay=15us Time=____10.005ms Hz=____99.95

TITLE: CL.1 Xf: 1 Yf: 3

Fig.10.2.f. Signal magnified x3 in the Y axis. The first part of the signal has gone off scale as the amplitude was already high.



Displayed data: Start=&E41 End=&F44

SPC-notes Range: +/-var Trigger offset: 4

Pts=260 Step=1 Delay=15us Time=_____3.885ms Hz=_____257.4

TITLE: CL.1 Xf: 1 Yf: 1

Fig.10.2.g. Timescale expanded to 3.885ms. Low amplitude 12.5KHz signal shown superimposed on the signal.

ignored. Figure 10.2.g shows this low amplitude frequency to be present in the signal under examination if it is sufficiently expanded. As the gnathosonic signal in the experiment was in the order of 1KHz it should be possible to capture such signals using a slower capture rate of, for example 150us, which can adequately capture a signal of 3KHz. The slower capture rate allows a longer time available to capture signals and therefore it is possible to capture more than one occlusal sound on a trace. A sampling time of 450us would adequately capture 1KHz but would allow no margin for the presence of a higher frequency which might be aliased.

EXPERIMENT 10.3.

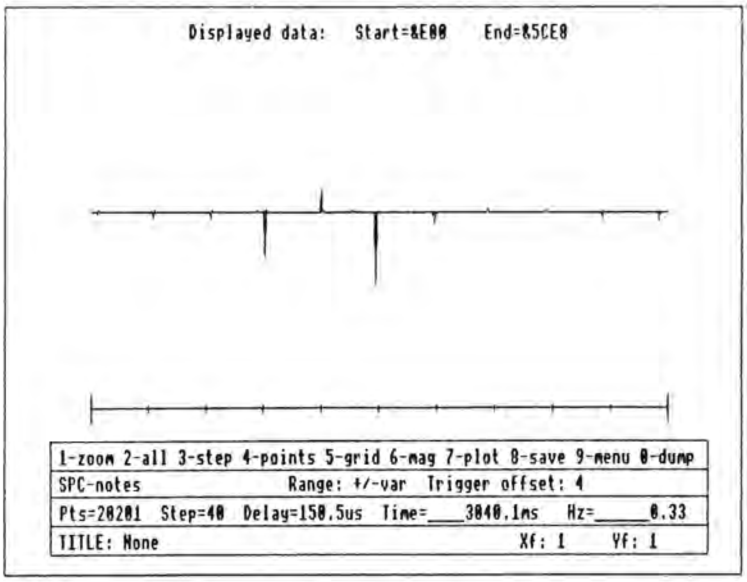
CAPTURE OF A GNATHOSONIC SIGNAL AT 150us SAMPLING RATE

METHOD

The experiment was carried out as described in experiment 10.2, except that the signal was sampled every 150us. The captured signal was replayed and manipulated by the program.

RESULTS

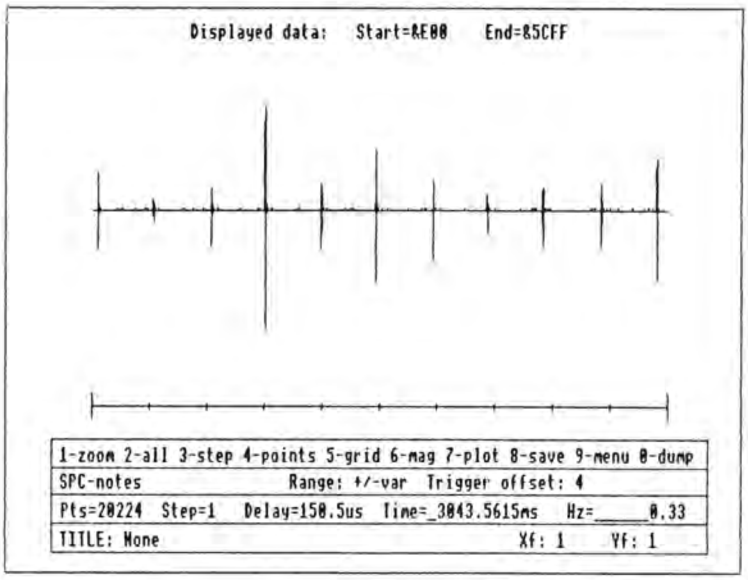
The results of experiment 10.3 can be seen in



```
Displayed data:   Start=&E00   End=&5CE0
```

```
SPC-notes                  Range: +/-var  Trigger offset: 4
Pts=20201  Step=40  Delay=150.5us  Time=___3040.1ms   Hz=_____0.33
TITLE: None                                   Xf: 1     Yf: 1
```

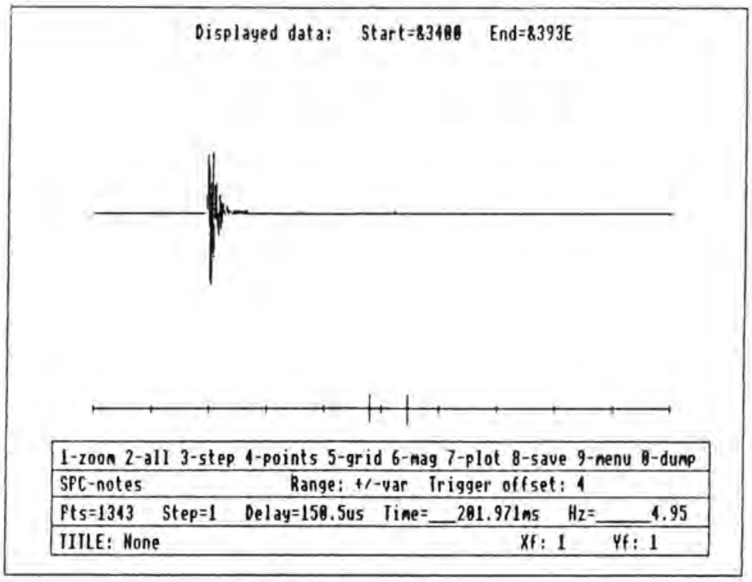
Fig.10.3.a. Rapid first plot, every fortieth data point (every 6020us).



```
Displayed data:   Start=&E00   End=&5CFF
```

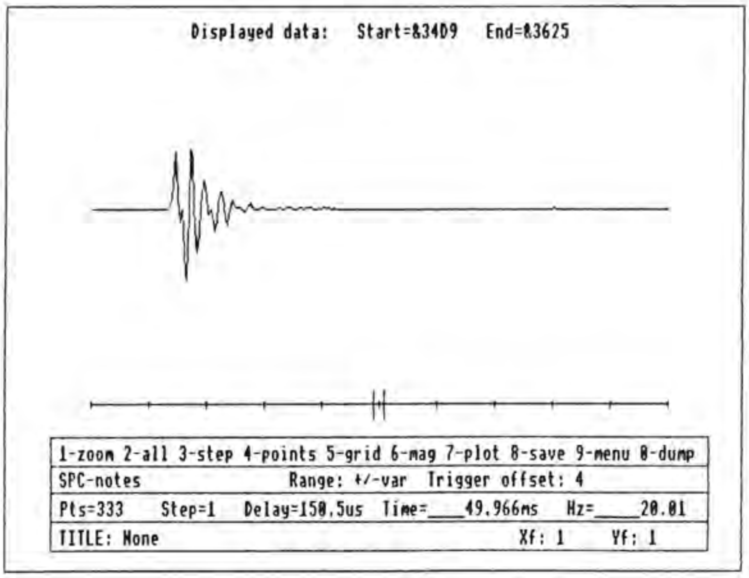
```
SPC-notes                  Range: +/-var  Trigger offset: 4
Pts=20224  Step=1   Delay=150.5us  Time=_3043.5615ms   Hz=_____0.33
TITLE: None                                   Xf: 1     Yf: 1
```

Fig.10.3.b. All points plotted.



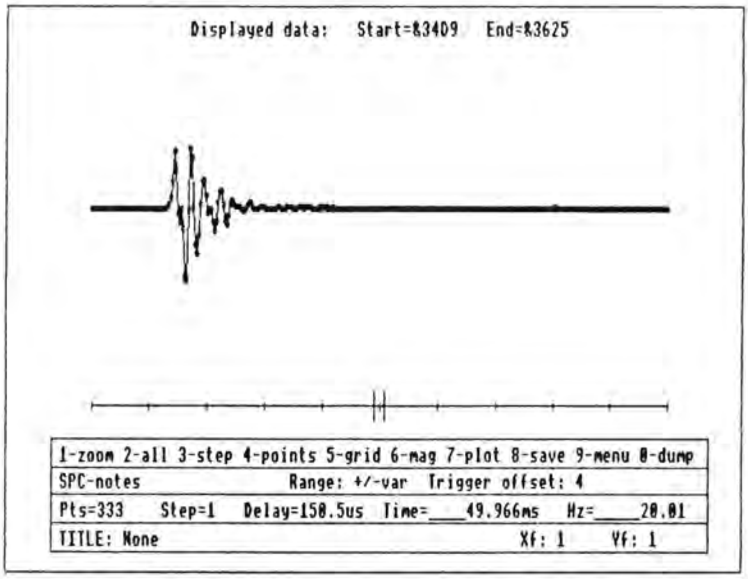
```
Displayed data:   Start=&3400   End=&393E
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=1343   Step=1   Delay=150.5us  Time=___201.971ms   Hz=_____4.95
TITLE: None                                   Xf: 1    Yf: 1
```

Fig.10.3.c. Timescale 201.971ms.



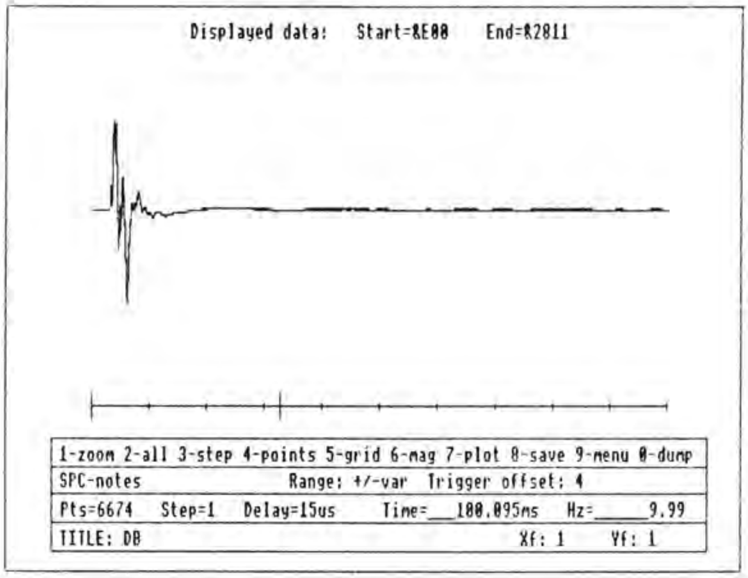
```
Displayed data:   Start=&34D9   End=&3625
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=333   Step=1   Delay=150.5us  Time=____49.966ms   Hz=____20.01
TITLE: None                                   Xf: 1    Yf: 1
```

Fig.10.3.d. Timescale 49.966ms.



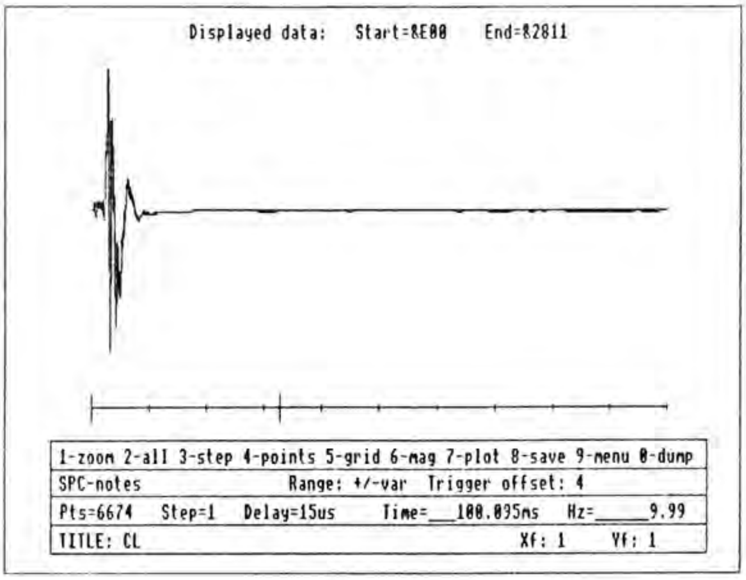
```
Displayed data:   Start=&3409   End=&3625
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=333    Step=1   Delay=150.5us  Time=____49.966ms   Hz=_____20.01
TITLE: None                                  Xf: 1     Yf: 1
```

Fig.10.3.e. Trace shown in fig.10.3.d with points plotted marked.



```
Displayed data:   Start=&E00    End=&2811
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=6674   Step=1   Delay=15us     Time=___100.095ms   Hz=______9.99
TITLE: DB                                    Xf: 1     Yf: 1
```

Fig.10.4.a. Volunteer 1 gnathosonic signal.



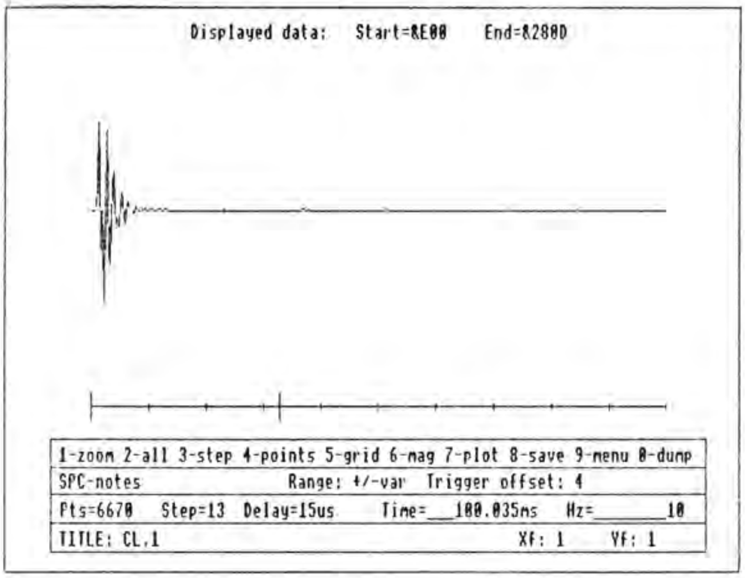
Displayed data: Start=&E00 End=&2811

SPC-notes Range: +/-var Trigger offset: 4

Pts=6674 Step=1 Delay=15us Time=__100.035ms Hz=______9.99

TITLE: CL Xf: 1 Yf: 1

Fig.10.4.b. Volunteer 4 gnathosonic signal.



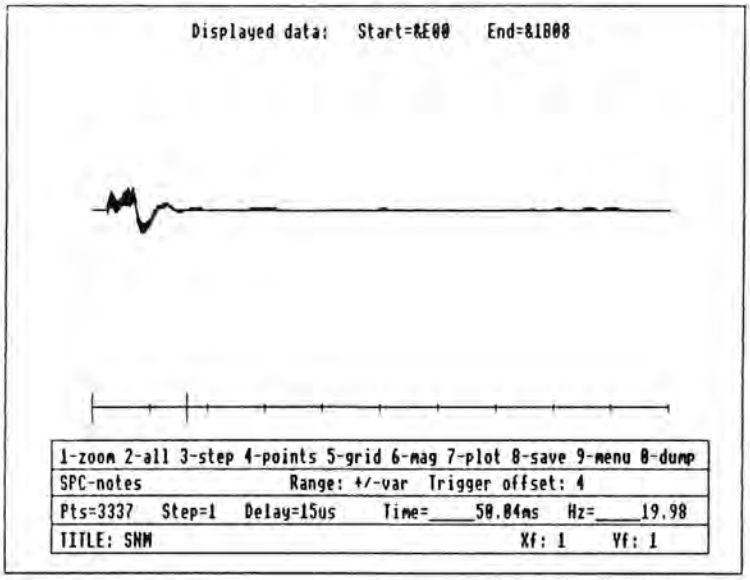
Displayed data: Start=&E00 End=&280D

SPC-notes Range: +/-var Trigger offset: 4

Pts=6670 Step=13 Delay=15us Time=__100.035ms Hz=_______10

TITLE: CL.1 Xf: 1 Yf: 1

Fig.10.4.c. Volunteer 18 gnathosonic signal.



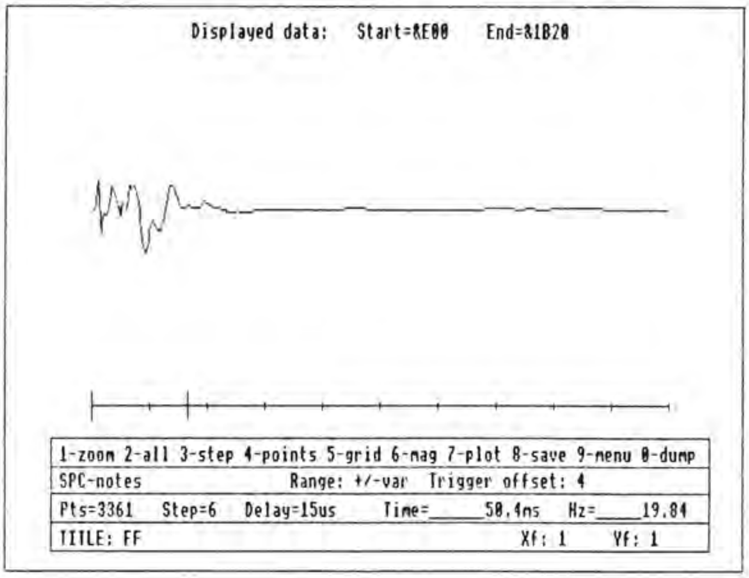
Displayed data: Start=&E00 End=&1B08

SPC-notes Range: +/-var Trigger offset: 4

Pts=3337 Step=1 Delay=15us Time=_____50.04ms Hz=_____19.98

TITLE: SNM Xf: 1 Yf: 1

Fig.10.4.d. Volunteer **S** gnathosonic signal.
Orthodontic patient.



Displayed data: Start=&E00 End=&1B20

SPC-notes Range: +/-var Trigger offset: 4

Pts=3361 Step=6 Delay=15us Time=______50.4ms Hz=_____19.84

TITLE: FF Xf: 1 Yf: 1

Fig.10.4.e. Volunteer **X** gnathosonic signal.
Orthodontic patient.

figure 10.3.a-e.

DISCUSSION

Comparison of figures 10.2.c.iii and 10.3.d shows a marked similarity of the traces, within the limits that might be expected of two signals generated by the same subject. Figure 10.3.e shows that there are sufficient points plotted on the trace to display all parts of the signal adequately.

These experiments are open to criticism as they are the results obtained from a single subject. Twenty students were therefore chosen at random for an experiment to evaluate the average and maximum frequencies which might be expected from such a group.

EXPERIMENT 10.4.

ESTIMATION OF THE AVERAGE FREQUENCY RANGE OF GNATHOSONIC SIGNALS *IN VIVO*

METHOD

Signals were captured directly from a sample of 20 students in the same manner as described in experiment 10.2 and each trace expanded so that the basic frequency could be estimated visually to within 100 cycles.

RESULTS

The results of experiment 10.4 are shown in Table 10.4, and samples of the traces are shown in figures 10.4.a-c expanded to 100ms full scale.

TABLE 10.4.

Estimated gnathosonic frequencies to ± 100 cycles.

STUDENT	FREQUENCY (Hz)	STUDENT	FREQUENCY (Hz)
1	700	11	700
2	800	12	500
3	900	13	500
4	1400	14	700
5	800	15	500
6	800	16	300
7	700	17	500
8	600	18	1100
9	300	19	800
10	500	20	600

Mean of 20 signals = 700±100Hz
to the nearest 100.

DISCUSSION

Frequency analysis of complex signals containing many frequencies requires Fast Fourier Transform. However the signals in this experiment were sufficient to allow a first approximation of the major frequencies present from an expansion of the signal, and the figures are shown in Table 10.4. It was in fact possible to be more accurate than the figures in Table 10.4, but in the absence of Fast Fourier Transform it was considered that a more conservative estimate to the nearest 100 cycles was appropriate.

Although it appears that sampling the signal every 150us is satisfactory for *in vivo* gnathosonic signals the capture rate in this experiment was kept at 15us in case there might be a possibility of some higher frequencies being present and open to aliasing.

All the signals in figures 10.4.a-c were expanded in a similar manner to experiment 10.2 and the frequencies present in the signals are in agreement with those predicted by the *in vitro* experiments in chapter 4 and chapter 5. The sample of 20 students showed a frequency range of 300Hz to 1.4KHz with a mean of approximately 700Hz. In a separate experiment traces from two students who were undergoing orthodontic treatment gave markedly atypical results which are shown in figures 10.4.d and 10.4.e, and were considered so unusual that such cases should be classified separately. Any low amplitude resonance of the sensor was ignored as this has already been shown in experiment 10.2 to be of little significance to the overall gnathosonic trace. As the estimated maximum frequency present was in the order of 1.4KHz, it was considered that the capture rate could be lowered to a delay of 150us, i.e. more than twice the maximum frequency present, without the problem of aliasing. Lowering the capture rate has the advantage that a greater total capture time is available allowing more than a single occlusion to be recorded, whereas sampling at 15us intervals provides an overall capture time of approximately 0.33sec. A delay of 150us allows a capture time of approximately 3.3 seconds, enough to capture 4-8 occlusal sounds depending on the patient.

Although the results indicate that a sampling rate of 150us is satisfactory for the capture of the sounds of occlusion of the teeth, it does not follow that the same will apply to other clinical situations.

Having taken account of the frequency ranges and possible duration of capture times of occlusal sounds sensed at the glabella, signal capture applied to dental implants was investigated. Percussion of mandibular implants, or percussion of mandibular teeth for that matter, cannot be properly sensed from the rest of the skull due to the profound loss of signal in the soft tissues of the temporomandibular joint.

EXPERIMENT 10.5.

ESTIMATION OF FREQUENCIES DERIVED FROM MANDIBULAR DENTAL IMPLANTS

METHOD

Signals were captured from a patient who had been fitted with mandibular dental implants of the osseointegrated type in the canine regions. The accelerometer (BU1771 Knowles Laboratories UK) was attached to a 21 gauge hypodermic needle as described in experiment 9.6. The point of the needle was passed through the mucosa and into firm contact with the alveolar bone within 10mm of the implant, the administration of local anaesthetic was not always necessary. The implants were percussed with a plastic hand held tapper. The accelerometer signals were recorded on magnetic tape (Philips D6350 Philips UK) for later replay and capture by computer.

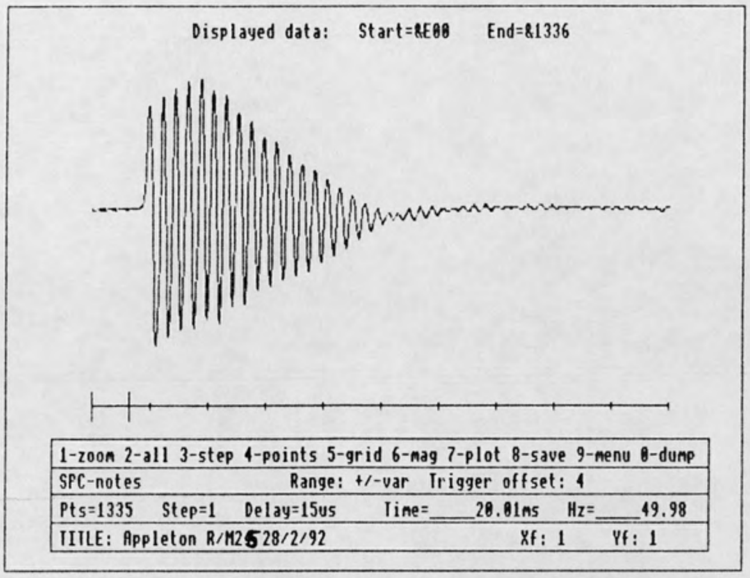
RESULTS

The results of experiment 10.5 can be seen in figures 10.5.a-c

DISCUSSION

It can be seen from figures 10.5.a-c that the frequency range from the percussion of mandibular osseointegrated dental implants sensed from the alveolar bone is greater than that sensed at the glabella from the occlusion of teeth. This is in agreement with the model experiments in chapter 4, i.e. there is little if any high frequency loss involved as the vibrations are not transmitted through soft tissues and so the shock waves cause resonance of the sensor beam.

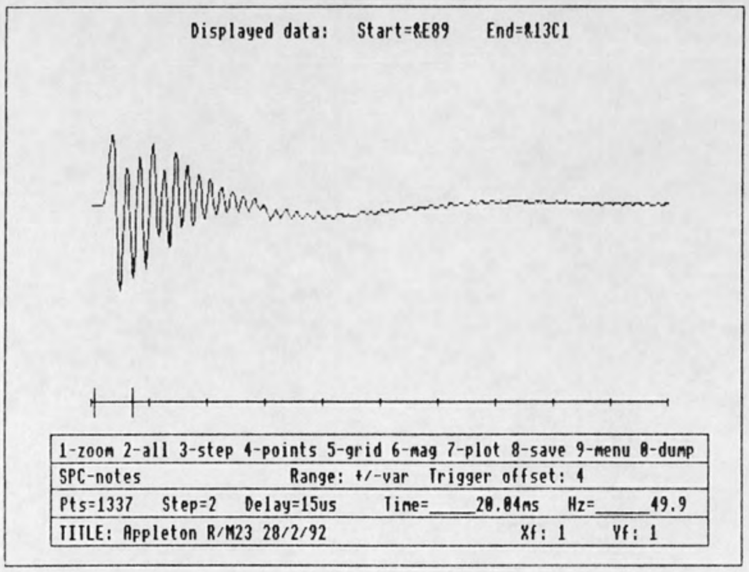
A signal captured from a failed implant in figure 10.5.d clearly shows that an implant which has failed to integrate does not provide such a clear sharp signal as one which has done so successfully. A similar picture to that of a failed implant emerges from preliminary experiments on teeth which have a poor periodontal condition shown in figure 10.5.e. From such signal variations it is clear that frequency ranges should always be established in the investigation of differing sources of vibration and differing methods of sensing. For instance if the sensor is applied to one side of the exposed part of an implant and the implant is struck on the opposite side, the results from preliminary studies of this method appear to be in accord with those



```
Displayed data:   Start=&E00    End=&1336

1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                  Range: +/-var  Trigger offset: 4
Pts=1335   Step=1   Delay=15us      Time=_____20.01ms  Hz=_____49.98
TITLE: Appleton R/M25 28/2/92                     Xf: 1     Yf: 1
```

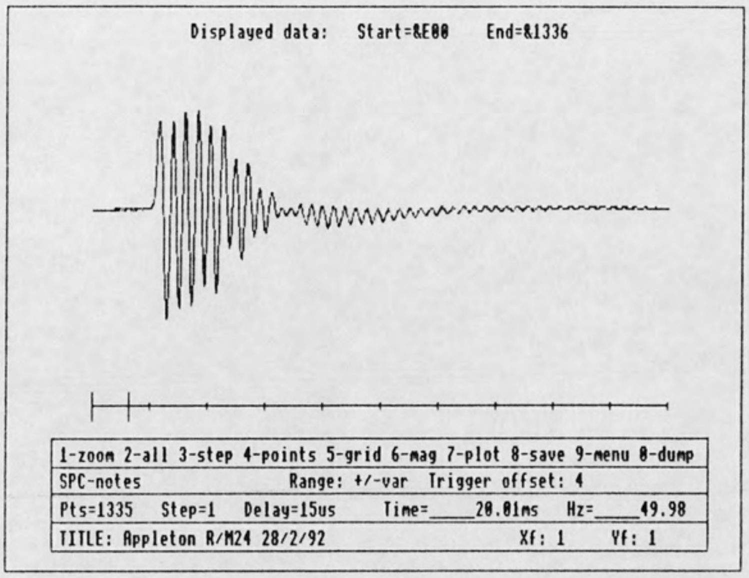
Fig.10.5.a. Successful mandibular implant.



```
Displayed data:   Start=&E89    End=&13C1

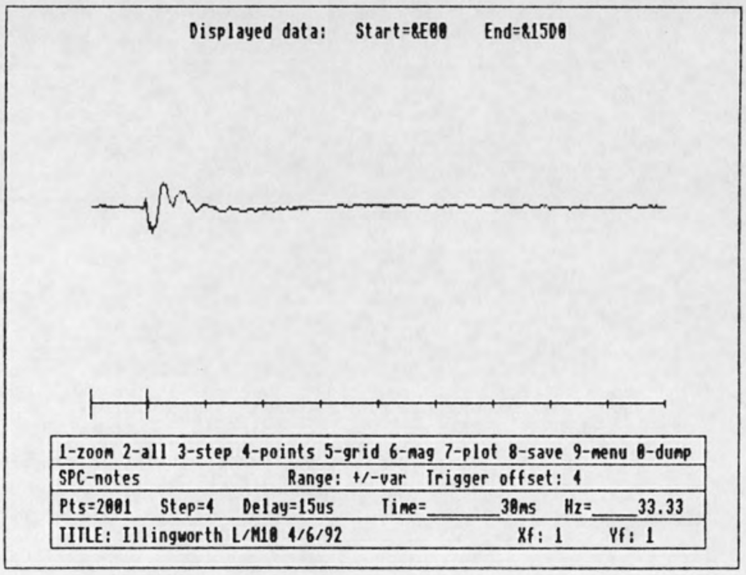
1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                  Range: +/-var  Trigger offset: 4
Pts=1337   Step=2   Delay=15us      Time=_____20.04ms  Hz=______49.9
TITLE: Appleton R/M23 28/2/92                     Xf: 1     Yf: 1
```

Fig.10.5.b. A second strike on the same implant.



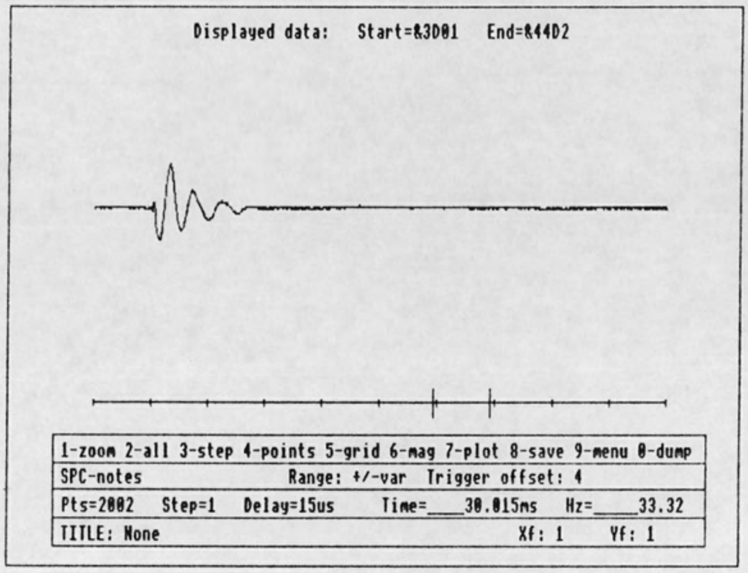
```
Displayed data:   Start=&E00   End=&1336
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=1335   Step=1   Delay=15us     Time=_____20.01ms  Hz=_____49.98
TITLE: Appleton R/M24 28/2/92                  Xf: 1    Yf: 1
```

Fig.10.5.c. A third strike on the same implant.



```
Displayed data:   Start=&E00   End=&15D0
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=2001   Step=4   Delay=15us     Time=________30ms  Hz=_____33.33
TITLE: Illingworth L/M10 4/6/92                Xf: 1    Yf: 1
```

Fig.10.5.d. A failed mandibular implant.



Displayed data: Start=&3D01 End=&44D2

SPC-notes Range: +/-var Trigger offset: 4

Pts=2002 Step=1 Delay=15us Time=____30.015ms Hz=____33.32

TITLE: None Xf: 1 Yf: 1

Fig.10.5.e. Percussion of a tooth with a poor periodontal condition.

obtained in the experiments on impacts in chapter 4 and require further investigation.

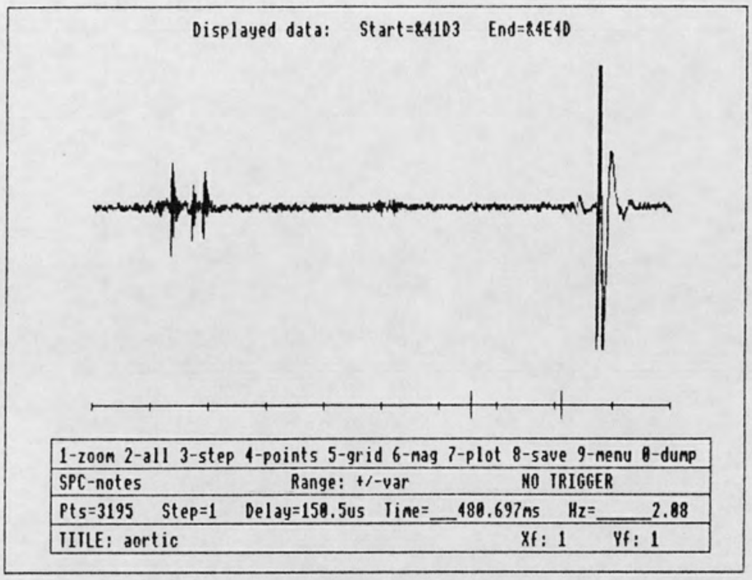
The same necessity to establish frequency patterns occurs when sounds generated by sources other than dental are investigated, such as vibrations produced by artificial heart valves or from joints such as the hip or knee.

EXPERIMENT 10.6.

SOUNDS CAPTURED FROM ARTIFICIAL HUMAN HEART VALVES

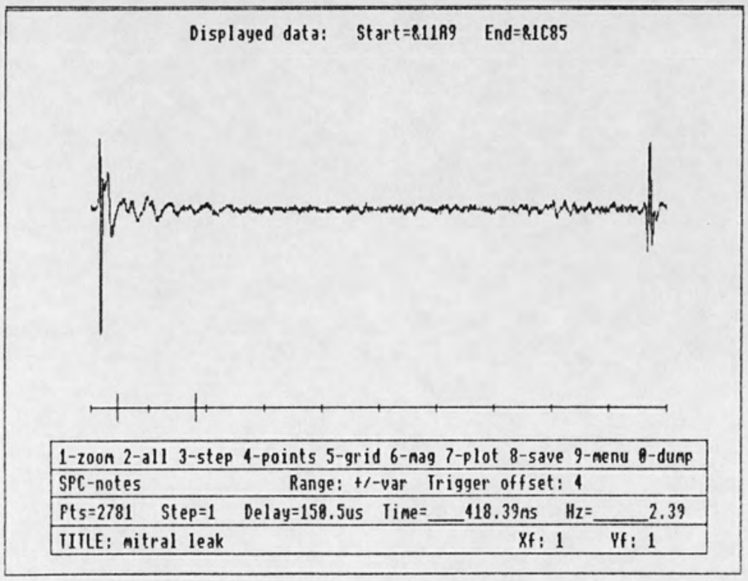
METHOD

The sensor (BU1771 Knowles Laboratories UK) was applied to the chest wall of a patient fitted with a Starr Edwards ball and cage aortic valve prosthesis. The sensor was held in place with adhesive tape in the region of the left sixth intercostal space. Heart sounds were recorded on magnetic tape (Philips D6350) which were later replayed and captured by the computer program. In the same manner records were made from another patient who had been fitted with a mitral prosthesis.



```
Displayed data:   Start=&41D3   End=&4E4D
SPC-notes                Range: +/-var            NO TRIGGER
Pts=3195   Step=1   Delay=150.5us  Time=___480.697ms   Hz=______2.08
TITLE: aortic                                      Xf: 1     Yf: 1
```

Fig.10.6.a. Patient with a prosthetic aortic valve. Valve produces the second sound.



```
Displayed data:   Start=&11A9   End=&1C85
SPC-notes                Range: +/-var  Trigger offset: 4
Pts=2781   Step=1   Delay=150.5us  Time=____418.39ms   Hz=______2.39
TITLE: mitral leak                                 Xf: 1     Yf: 1
```

Fig.10.6.b. Patient with a prosthetic mitral valve. Valve produces the first sound.

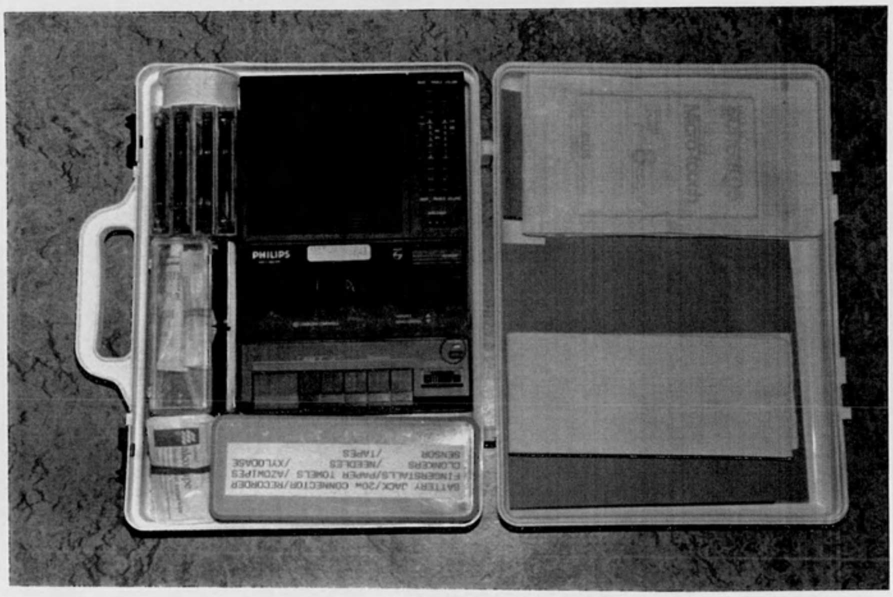


Plate 10 Brief case for home visits containing sensor, elasticated strap, tappers, recorder, tapes, gloves and any other items required.

RESULTS

The results of experiment 10.6 can be seen in figures 10.6.a and 10.6.b.

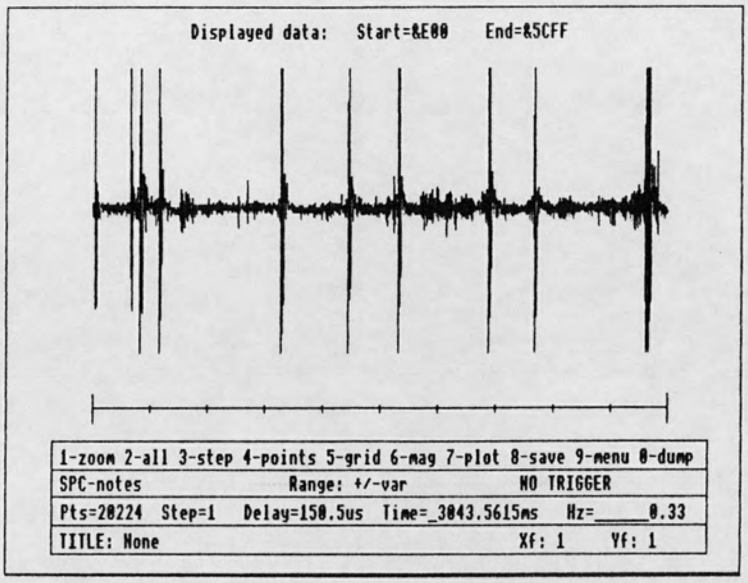
DISCUSSION

As might be expected the captured signals clearly show the first and second heart sounds. These sounds are less complex than the sounds produced by impact of the teeth. This implies that the capture rate might be slowed to the order of one sample every 450us, which would allow the capture of approximately 10 beats in a single record (at a resting heart rate of 60/min.). One of the patients was visited at home where tape recordings of the heart sounds were made using a brief case to carry the necessary equipment, shown in Plate 10.

It would be of interest to follow up such cases to see if any changes in the recorded signals predate any change in the condition of a prosthesis. The same suggestion applies to the sounds produced by the joints.

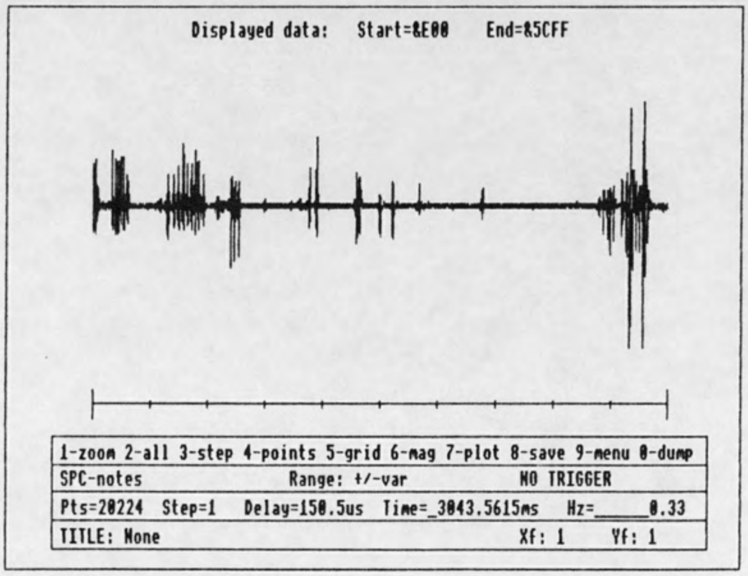
EXPERIMENT 10.7.

SOUNDS CAPTURED FROM HUMAN HIP AND KNEE JOINTS



```
Displayed data:   Start=&E00    End=&5CFF
1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                  Range: +/-var                 NO TRIGGER
Pts=20224  Step=1   Delay=150.5us  Time=_3043.5615ms   Hz=_____0.33
TITLE: None                                          Xf: 1      Yf: 1
```

Fig.10.7.a. Trace from the hip joint of a volunteer.



```
Displayed data:   Start=&E00    End=&5CFF
1-zoom 2-all 3-step 4-points 5-grid 6-mag 7-plot 8-save 9-menu 0-dump
SPC-notes                  Range: +/-var                 NO TRIGGER
Pts=20224  Step=1   Delay=150.5us  Time=_3043.5615ms   Hz=_____0.33
TITLE: None                                          Xf: 1      Yf: 1
```

Fig.10.7.b. Trace from the patella of a volunteer.

METHOD

The sensor (BU1771 Knowles Laboratories UK) was applied in separate experiments to the hip and then the patella of a volunteer. The sensor was held in place over the appropriate area with adhesive tape and the sounds captured and recorded in the manner described in experiment 10.6.

RESULTS

The results of experiment 10.7 can be seen in figures 10.7.a-b.

DISCUSSION

Examination of figure 10.7.b shows a trace similar to that published by Kernohan[53] recorded from a patella using considerably more expensive data gathering apparatus.

CONCLUSIONS FROM EXPERIMENTS 10.2 - 10.7.

1. Captured signal data can be easily manipulated to show various aspect of the signal which might not be apparent on display in real time.

2. The frequency range of gnathosonic signals sensed at the glabella with an accelerometer (BU1771 Knowles Laboratories UK) appear to be in the order of 0-1.3KHz, with 1.3KHz an absolute minimum.

3. Signals captured from clinically successful osseointegrated mandibular dental implants appear to be in the order of 0-12.5KHz, when sensed by an accelerometer (BU1771 Knowles Laboratories) attached to a 21 gauge hypodermic needle in firm contact with the associated alveolar bone.

4. By the differences apparent between successful and failed implants it would appear possible that signals recorded from the percussion of implants may be a useful technique in monitoring their status.

5. Capture of other sounds generated in the body may be a useful method of monitoring the condition of those parts and of their artificial replacements.

CHAPTER 11

SUMMARY OF FINDINGS

SUMMARY OF FINDINGS

The following is a summary of the major findings of the work reported in this thesis.

1) Simple collisions between solid materials can be used to model the impact of teeth.

2) In order to produce gnathosonic-type signals in laboratory models, damping appears to be required to simulate the presence of firstly the periodontal membrane and secondly the soft tissues beneath the sensor.

3) The frequency range of simple enamel-enamel collisions in laboratory models appears to be 0-6±1KHz. Additional damping reduces this to the order of 1KHz.

4) Both impact force and duration appear to be important parameters in determining the characteristics of the generated signal in laboratory models.

5) The dry skull may be used as a more complex in vitro model, and provides gnathosonic-type traces if careful attention is given to suitable damping.

6) Accelerometers make satisfactory sensors for gnathosonic studies.

7) The glabella appears to be the position of choice for placement of the sensor. Other positions can give rise to problems in signal analysis.

8) Signal aliasing is a critical problem which must be addressed in all gnathosonic research and publications, particularly where digital sampling is used.

9) A low cost computer together with a similarly low cost interface and sensor is capable of capturing the whole range of gnathosonic frequencies without aliasing. Gnathosonic facilities should therefore be within the capability of the general dental surgery without recourse to expensive purpose designed equipment.

10) The apparatus designed for gnathosonic studies is equally applicable to the study other sounds of both medical and other origin.

11) A standard domestic cassette tape recorder can reliably capture gnathosonic signals without significant distortion and provide simple data

storage at the chairside.

12) Analysis of the literature suggests that there has been little previous use of control experiments in gnathosonic studies, and that therefore almost all the previous publications must be regarded as unreliable.

13) The following parameters must be controlled and specified in reported work for gnathosonic research to be reproducible.

    Sensor type, characteristics, specifications, place and method of application.

    Record/replay apparatus, specifications and settings.

    Method of capture, and in the case of digital sampling the capture rate.

    Timebase and units of measurement in the Y axis.

14) The beta wave reported by Brenman[16] and cited by other workers appears to be an artifact created by residual tissue or sensor movement.

15) The classification by Watt which has formed a basis for many gnathosonic studies should be revised.

16) The signal envelope, or overall shape, rather than

the fine structure of the frequencies within it provide the significant data for gnathosonic study.

17) The use of a portable cassette recorder allows gnathosonic or other recordings to be made anywhere by carrying the equipment in a brief case. The recordings are analysed later.

CHAPTER 12

RECOMMENDATIONS FOR FURTHER RESEARCH

RECOMMENDATIONS FOR FURTHER RESEARCH

As a result of the work carried out in this thesis it is possible to suggest some areas for further gnathosonic research as follows.

1) Model experiments in the laboratory should be the cornerstone of all future gnathosonic research. For example, models developed in this thesis could be modified in order to represent the clinical situation more closely.

2) Investigation of the difference in vibration transmission when a tooth is struck axially or transversely might yield useful information.

3) Modelling might lead to a better understanding of how vibrations are propagated throughout the teeth and jaws on occlusion of the teeth.

4) It might be appropriate to repeat with controlled equipment some of the previous studies by workers such as Brenman and Watt.

5) Useful studies using a dry skull could be followed up especially with simulated soft tissues. Synthetic soft tissues with known mechanical characteristics

would be an improvement upon animal tissue.

6) Models might be developed to show pathological states such as periodontal disease, and to act as controls for workers in that field who are using vibrations to assess the condition of the periodontium.

7) An area which must be investigated in detail is the interface between the sensor and the skin surface.

8) Research into sensing bilaterally has not been investigated in depth. With the development in recent times of highly sophisticated signal processing equipment it might be possible to gain additional information on the gnathic system.

9) Investigation of power spectra using Fast Fourier Transform is an obvious area for research but from the work in this thesis it is clear that as far as gnathosonics is concerned the frequency is not critical, only the envelope delineated by the waveforms.

10) The developed capture system could be used as a research or data logging tool in any field of dentistry or medicine where vibrations are a product or byproduct of investigation or treatment.

11) It is important that a simple system be developed to calibrate gnathosonic equipment so that workers could have common parameters for the comparison of research.

12) It would be useful for ways of recording sounds generated by the mandibular teeth to be investigated in addition to the method applied to implants in this thesis.

13) Dental implants should be a productive field of investigation, in both the maxilla and mandible.

14) Investigation of the effect of compromised mandibular teeth occluding with sound maxillary teeth (or the reverse) does not appear to have been considered as sensing of sounds is normally from the maxillary teeth.

15) Good occlusions should be investigated to determine how nearly all the teeth occlude at the same instant, this might give some insight into the greater detail of the vibrations produced be the occlusion of the teeth.

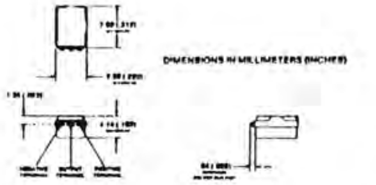
APPENDIX

SPECIFICATIONS

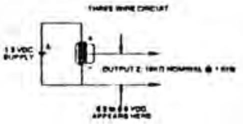
- SENSOR - TRANSDUCER
- BBC MASTER128 MICROCOMPUTER
- UNILAB INTERFACE
- MICROPHONE
- FUNCTION GENERATOR
- OSCILLOSCOPE
- CASSETTE RECORDER
- DSA524 STORAGE ADAPTOR
- CASSETTE TAPES

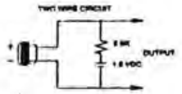
Knowles.
SUBMINIATURE TRANSDUCERS

BU-1771
VIBRATION TRANSDUCER
DATA SHEET



MODEL BU PATENTED UNDER U.S. 3,512,100; JAPAN 1,021,806; SWITZERLAND 490,786; CANADA 868,383; FRANCE 1,597,239; GERMANY 1,916,703; GREAT BRITAIN 1,219,299; DENMARK 138,349; HOLLAND 144,167. OTHER PATENTS PENDING.



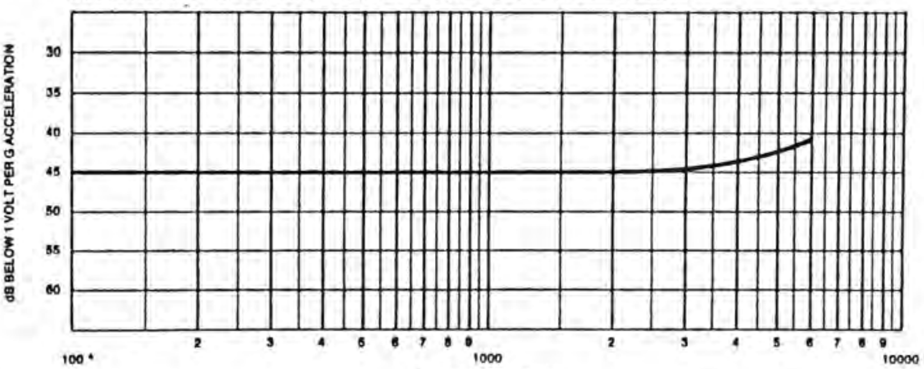


Subminiature ceramic vibration transducer which can be used as an accelerometer. Contains an FET amplifier stage and is designed for a wide variety of applications requiring high vibration sensitivity, wide frequency range, small size, and high mechanical durability.

Battery Voltage Range: 1.5 to 20 VDC
Battery Drain: 0.05 mA DC (Max.)
(In two wire circuit with 1.5 VDC)
Weight: 0.28 grams (Nominal)
Output Impedance @ 1K Hz:
5,200 Ohms (Nominal) In two wire circuit
DC Resistance between case and negative terminal: 100 Ohms (Max.)

NOTE: BU-1771 is specified in a two wire circuit. Device can also be used in a three wire hook-up with approximately 10 dB increase in sensitivity.

Open circuit vibration sensitivity (1.5 VDC Supply) tested with 1g acceleration.



* Frequency Response remains flat to 20 Hz.

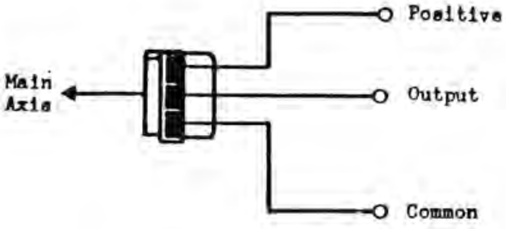
BU SERIES

Knowles.
Working with you toward finer sound reproduction

KNOWLES ELECTRONICS, INC.
3100 North Mannheim Road
Franklin Park, Illinois 60131-2397, U.S.A.
Phone: (312) 455-3600
Cable: Knolec Chicago
Telex: 72-8397

KNOWLES ELECTRONICS CO.
Victoria Road, Burgess Hill
West Sussex RH15 9LP, England
Phone 044 46 5432
Cable: Elcknol Burhill
Telex 87460

4.2 **3-Wire Mode** - typical performance



N.B. g = 981 cm/sec^2

1. Supply voltage : 1.5V DC (range 1.1 to 20V)
2. Standing Current : 30 µA DC (range 20 - 50 µA)
3. Output Impedance : 13KΩ (range 8 - 22KΩ)
4. Response : See Section 6.
5. Sensitivity at 1KHz : -30 dB re 1V/g, i.e. 30 mV/g.
6. Typical Minimum g : at 1KHz for 6 dB signal to noise .003 g or 3 cm/sec^2
7. Typical Maximum g (peak) : limited by electrical "clipping".

The maximum negative electrical excursion of the output may be typically 0.3V (range 0.2 to 0.9V and governed by production tolerances).

The signal will begin to 'clip' on a negative going acceleration of $\frac{0.3V}{\text{sensitivity}}$ which is typically 10g.

At resonance the sensitivity is 40 dB higher so clipping occurs (in this instance) at 0.10g.

The FET will cease operation when the voltage across it is reduced below nominally 0.2V.

The maximum positive excursion is therefore

$$V_{supply} - (0.3 + 0.2) = 1V$$

8. Phase Acceleration directed to the arrowed direction of the main axis results in a positive output.

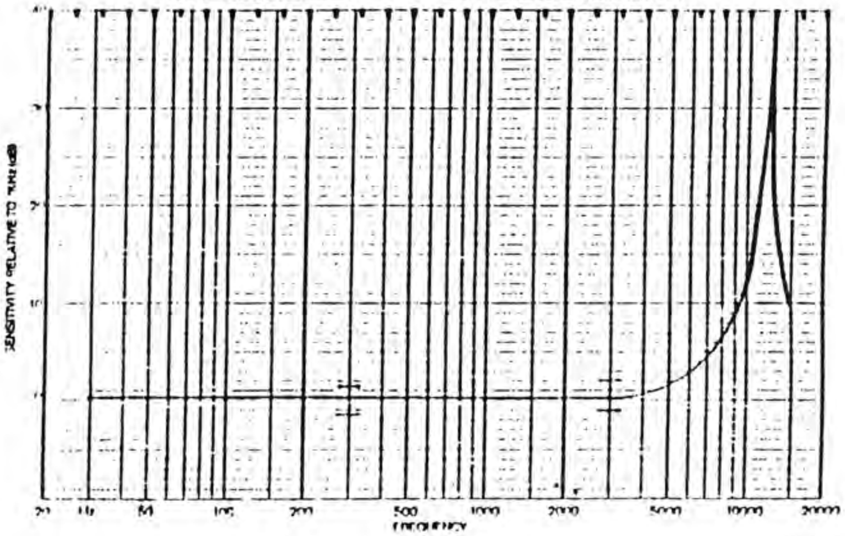
With the transducer wired in this mode a voltage appears on the output which does not match with the requirements of the Unilab interface. An input transformer removes this problem. In this work a 6:1 matching transformer was used (wearite Ltd UK).

6.0 RESPONSE

Device Conformity

Frequency (Hz)	Range of Deviation from 1KHz(dB)	
300	- 1.5	+ 1.5
1000	0	0
3000	- 1.0	+ 2.0

RESPONSE OF BU 1771 RELATIVE TO 1KHz



BBC MASTER128 MICROCOMPUTER

8 bit microcomputer
64K normal memory
20K shadow memory
6502 central processor
    operating at 2MHz
1MHz bus port

SECTION 7
INFORMATION

7.1 SPECIFICATION

Analogue Inputs
Input resistance 1 Megohm
Conversion rate of 125,000 per second.

Sensitivity	0 to +10 volts
	0 to + 1 volt
	0 to 100 millivolts
variable	25 mV to 2.5 volts f.s.d.
	−5 to +5 volts
	−0.5 to +0.5 volts
	−50 to +50 millivolts
variable	−12.5 to +12.5 mV up to −1.25 to +1.25 volts

Analogue Output
0 to +2.55 volts through 2.45 Kohms to give 0 - 1 mA into a 100Ω load.
Setting time of 1 μs

Digital Inputs
Up to 8 digital inputs of TTL type.

Digital Outputs
Up to 8 digital outputs of TTL type.

Relay Outputs
Four single pole changeover relays with contacts rated at 1 amp, 24 volts.

Trigger
Linked to the analogue input system can be used to initiate action on a rising or a falling analogue input.

7.2 ELECTRICAL PROTECTION

It is very important that a computer interface provides protection for itself and for the computer to which it is connected. There is always a danger that a user may overload an input or try to input a signal into an output terminal. The Unilab Interface is protected on all its front panel input and output connections against accidental misuse. There are, of course, limits to this protection and care must be taken to avoid exceeding these limits. Ideally, of course, the user would ensure that inputs were never overloaded.

Connection of a power supply of up to 10V AC to any front panel terminal should not cause damage. Analogue inputs can tolerate up to +/− 100 volts and up to +/− 35 volts can be tolerated by the analogue output. The digital inputs/outputs are the most sensitive to damage and connection of a high current source of greater than +/− 10 volts for an appreciable time will result in damage to input protection resistors in the Interface. If the overload is sufficiently great to burn these out, further damage will be avoided as the input source will be disconnected from internal electronic circuitry.

ALTAI

EM-100

ELECTRET CONDENSER MICROPHONE

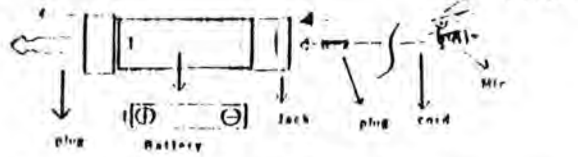
FEATURES:

- The Super mini microphone with tie clip is suitable for application on school teaching, public speaking, and recording
- High sensitivity and wide frequency response

SPECIFICATIONS:

① Directionality	: Omni directional
② Frequency Response	: 50-18K HZ
③ Impedance	: 1000Ω
④ Sensitivity	: -65db at 1000HZ
⑤ Power supply	: UM-3 (1.5V) ×1
⑥ Weight	: 115g (With plug)
⑦ Dimensions	: 13⌀×23㎜
⑧ Cord	: 4M

To amplifier:



① Insert one UM-3 Battery into the battery room

② Connect the plug on the cord of Mic to the jack on the end of the battery room

5 120 F001

TG 102 FUNCTION GENERATOR

SPECIFICATION

OPERATING RANGE

Frequency range:	<0·2Hz to 2MHz in 6 overlapping decade ranges with fine adjustment by a calibrated vernier.
Internal Mode	
Vernier range:	>1000:1 on each range, except 10Hz range: >100:1
Vernier accuracy:	Better than ±5% of full scale 1k to 1M ranges; better than ±8% on 10 and 100 ranges.
External (Sweep) Mode	
Sweep range:	>1000:1 within each range, except 10Hz range: >100:1
Input impedance:	10kΩ
Input sensitivity:	
Input for 10:1 sweep	~ 4·5V peak-to peak
Input for 100:1 sweep	~ 4·95V peak-to peak
Input for 1000:1 sweep	~ 5V peak-to peak
Maximum allowable input voltage:	±10V
Sweep linearity:	Better than 1%
Maximum slew rate of sweep voltage:	0·1V/μs

OPERATING MODES

(Specifications apply for vernier between 0·2 and 2·0 and output 10V peak-to peak into 50Ω termination).

Sine	
Distortion:	Less than 0·5% on 100, 1k and 10k ranges; less than 1% on 10 and 100k ranges; all harmonics >25dB below fundamental on 1M range.
Amplitude flatness:	±0·2dB to 200kHz; ±1dB to 2MHz
Triangle	
Linearity:	Better than 99% to 200kHz
Square Wave	
Rise and fall times:	<80ns
Mark : Space ratio:	1:1 ±1% to 100kHz
DC	
Range:	±10V from 50Ω

OUTPUTS

50Ω:	Two switch-selectable ranges with >30dB vernier control within each range.
0dB:	0·6V to 20V peak-to peak from 50Ω (0·3V to 10V into 50Ω).
−20dB:	60mV to 2V peak-to peak from 50Ω (30mV to 1V into 50Ω).
DC offset control range:	±10V from 50Ω. DC offset plus signal peak limited to ±10V (±5V into 50Ω). DC offset plus waveform attenuated proportionally in −20dB position.
TTL	Capable of driving 20 standard TTL loads.

GENERAL

Power Requirements	
Input voltage:	110/120 volts AC nominal 50/60Hz or 220/240 volts AC nominal 50/60Hz adjustable internally. The TG102 will operate safely and meet specification within normal AC supply variations viz. 100-130 volts AC and 200-260 volts AC respectively.
Power consumption:	Typically 15VA.

THE 2205 OSCILLOSCOPE

The TEKTRONIX 2205 Oscilloscope is a rugged, lightweight, dual channel, 20 MHz instrument that features a bright, sharply defined trace on an 80 by 100 mm cathode-ray tube (crt).

Its low-noise vertical system supplies calibrated deflection factors from 5 mV to 5 V per division at full bandwidth.

Stable triggering is achieved over the full bandwidth of the vertical system. The flexibility and high sensitivity of the trigger system provides a range of conveniences such as hands-free triggering with the peak-to-peak automatic mode, normal trigger mode, independent selection of TV line and TV field triggering at any sweep speed, and single-sweep triggering. The trigger signal is dc coupled. An external triggering signal or an external Z-axis modulation signal can be applied via a front-panel connector and the source-selector switches.

The horizontal system provides calibrated sweep speeds from 0.5 s to 100 ns per division. For greater measurement accuracy, a X10 magnifier circuit extends the maximum sweep speed to 10 ns per division.

Accessories

The instrument is shipped with the following accessories: operator's manual, two signal adapters, a power cord, and a power-cord clamp. Part numbers for these standard accessories, as well as for other optional accessories, are located in Section 6, *Options and Accessories*. The voltage sensing signal adapters were designed specifically to complement the performance of your 2205.

PHILIPS Cassette recorder D6350/00/05

SPECIFICATIONS

⊣⊢ : 9 V (6xR14)

🔌 : 220/240 V, 50/60 Hz

Frequency response: 100-8000 Hz within 8 dB

Tape speed : 4.76 cm/sec

Wow and flutter : ≤ 0.35%

Input sensitivities

BU3	ext. mic	0.25 mV/ 2 kΩ
BU4	tape in	200 mV/50 kΩ

Output

BU5	tape out	500 mV/8 Ω ◁
BU8	Ext. L.S.	

S1. DSA524 TECHNICAL SPECIFICATIONS

VERTICAL INPUT AMPLIFIERS

Number of channels	2.
Bandwidth	DC to 35MHz (10V/div to 20mV/div). DC to 20MHz (10mV/div). DC to 10MHz (5mV/div). DC to 5MHz (2mV/div).
Accuracy	±3%.
Input Protection	400V DC or ACpk.

DIGITAL RECORDING SYSTEM

Vertical Resolution	8 bits (0.4%).
Recording Memory Size	4096 words per channel.
Max. Sampling Rate (single event signal)	20MS/s (single channel). 20MS/s (dual alternate). 5MS/s (dual chop).
Max. Storage Bandwidth (single event signal)	5MHz (4 samples/cycle) using sine inter-interpolation.
Max. Equiv. Sample Rate (repetitive signal)	2GS/s.
Max. Storage Bandwidth (repetitive signal)	35MHz.

TIMEBASE MODES

Normal	100ms/div to 5us/div.
Repeat (repetitive signal)	2us/div to 50ns/div.
Roll	200mins/div to 200msecs/div.

ACQUISITION MODES

Run	Acquisitions are repeated automatically.
Hold	Acquisition memory contents are frozen.
Single	Acquisition memories are updated once and then frozen.

TRIGGER MODES

Triggered	Acquisitions are only taken in synchronism with a trigger signal.
Auto	As triggered but acquisitions free run when there is no trigger signal.
Line	Acquisitions are taken in synchronism with AC line frequency.
Pre-trigger delay	The acquisition is stopped such that data prior to the trigger event is captured.
Post-trigger delay	The acquisition is stopped such that data after the trigger event is captured.

TRIGGER CONTROL SYSTEM

Source	CH1, CH2 or External.
Level	Variable ± 4.25 divisions or fixed (zero).
Sensitivity	Internal < 0.8 divisions, External < 300mV (DC to 5MHz). Internal < 3 divisions, External < 1V (5MHz to 20MHz).
Slope	Selectable as positive or negative.
Coupling	Selectable as AC, DC or HF reject.
Time Delay	0 to 40 divs pre-trigger, 0 to 10,000 divs post-trigger (10 seconds max.).
Events Delay	Selectable 1 to 16 trigger events before acquisition.

OSCILLOSCOPE DISPLAY SYSTEM

Trace A	Displays 1024 words from either CH1 or any indexed waveform storage memory.
Trace B	Displays 1024 words from either CH2 or any indexed waveform storage memory.
Line Type	Selectable as individual levels (dots) or joined to form a smooth line.
Update Rate (Run Mode)	Selectable between 50 per second and one every 3 seconds (continuous in roll mode).

OSCILLOSCOPE DISPLAY VERTICAL CONTROL

Position	Continuously variable for each trace ± 4.25 divisions.
Gain Variable	Continuously variable for each trace between X1 and X0.2.
Invert	Displays trace B inverted.
Add	Adds trace B (normal or inverted) to trace A.
Multiply	Multiplies trace A by trace B.
Average	Displays the average of between 2 and 256 acquisitions.

OSCILLOSCOPE DISPLAY HORIZONTAL CONTROL

Compress	Compresses the whole 4096 words of the acquisition memory into the 1024 words of the trace memory.
Scan	Selects which block of 1024 words from 4096 is displayed.
Magnify (x10)	Expands any 102 word section of the memory ten times to fill the screen using digital liner interpolation.
Sine Interpolation	Re-constructs sinusoidal waveforms in magnify mode.

WAVEFORM STORAGE (NON-VOLATILE)

Digitising Memories	2 of 4096 words each.
Indexed Memories	16 of 1024 words each.
Storage Period	Potentially infinite, supported by trickle charged batteries, hold-up period 1 month when un-powered.

PROGRAM STORAGE (NON-VOLATILE)

System	All controls are fully programmable and front-panel settings can be stored and recalled individually or in sequence. Maximum number of stored settings 50.

RS-423 INTERFACE (RS-232 COMPATIBLE)

Baud Rate	Selectable between 300 baud and 38,400 baud in 8 steps.
Write Functions	All front panel controls are fully programmable and can be set via the interface. The trace memories and indexed waveform memories can all have data written to them.
Read Functions	The front panel status can be read via the interface. Data can be read from the trace memories and the indexed waveform memories.

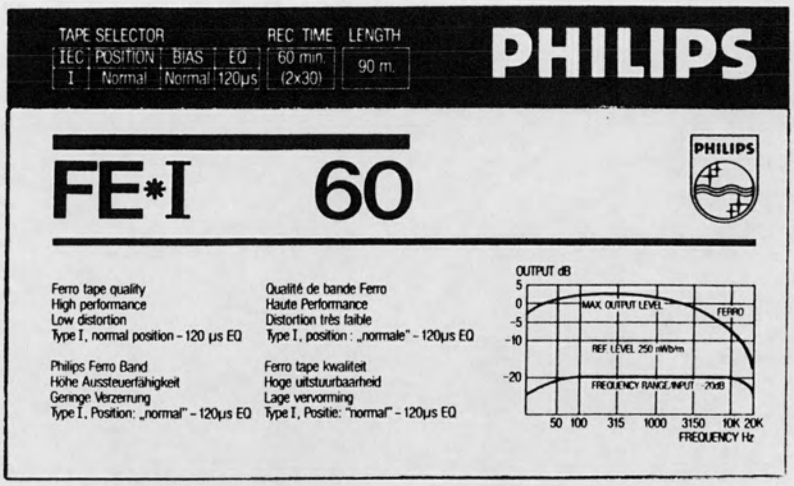
HARDCOPY OUTPUT FACILITIES

Printer Interface	Links to dot-matrix printer (Epson quad density graphics compatible) via RS-423 interface. Prints stored waveforms plus annotation.
Digital Plotter Interface	Links to digital X-Y plotter (HP-GL compatible) via RS-423 interface. Plots stored waveforms plus annotation.
Analogue Plotter Interface	Provides simultaneous output of A and B traces for analogue chart recorder plus X output for X-Y plotter. Output 100mV/div. Speed 1,2,5 or 10 seconds per division. Pen lift/chart feed output 0 to 5V.

POWER REQUIREMENTS	110, 120, 220 or 240V ± 10% at 50/60Hz. 30VA max.

OPTIONS

GP-IB (IEEE-488) Interface	Provides all of the functions of the RS-423 interface via the General Purpose Interface Bus.
DS-PC Link	Software and firmware package which links the instrument to an IBM-PC compatible personal computer for waveform display and control.



TAPE SELECTOR				REC TIME	LENGTH
IEC	POSITION	BIAS	EQ	60 min. (2x30)	90 m.
I	Normal	Normal	120µs		

PHILIPS

FE*I 60

Ferro tape quality
High performance
Low distortion
Type I, normal position - 120 µs EQ

Qualité de bande Ferro
Haute Performance
Distortion très faible
Type I, position : „normale" - 120µs EQ

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Geringe Verzerrung
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Ferro tape kwaliteit
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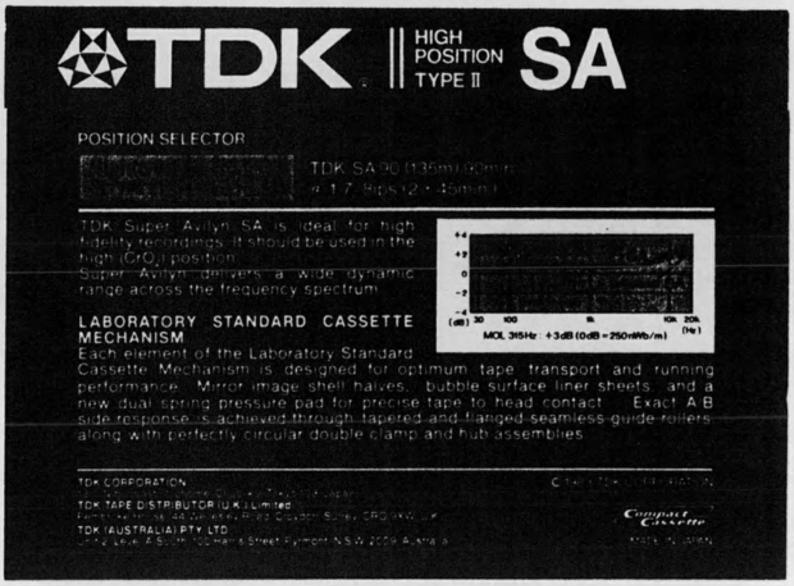
Lage vervorming
Type I, Positie: "normal" - 120µs EQ



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Super Avilyn delivers a wide dynamic range across the frequency spectrum.

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REFERENCES

1 The Shorter Oxford English Dictionary. 3rd ed, p 133, Oxford: Clarendon Press, 1990.

2 Laennec R T H. Traite de l'auscultation mediate et des maladies des poumones et du coeur. 4th ed, Chapter 1, p 10, Paris: J S Claude 1837. (First published 1819)

3 Williams C J B. Memoirs of life and work. p 41 London; Elder and Co, 1884.

4 Alison S. On the differential stethosphone and some new phenomina observed by it. Proceedings of the Royal Society 1858; 196-209.

5 Nicolai L. Uber das "Stereostethoskop"". Klinische Wochenschrift 1936; 15: 91.

6 Watt D M, Hedegard B. The stereostethoscope - an instrument for clinical gnathosonics. J. Pros. Dent. 1987; 18: 458-464.

7 Kerr W. Stethoscope and symballophone. In Medical Physics(Ed.) Glasser,O. Volume 1 pp. 1473-1490. Chicago: Year Book Publishers, 1944.

8 Ekensten B. Phonograms of anomalies of the temporomandibular joint in motion. Odont T 1952; 60: 235-242.

9 Brenman H S. Millsap J S, A "sound" approach to occlusion. Bulletin of the Philadelphia Country Dental Society 1959; 24: 4-8.

10 von Bekesy G. Vibration of the head in a sound field and its role in hearing by bone conduction. J Acoust Soc Amer 1948; 20: 749-760.

11 Brenman H S, Hattler A B. Myograms and occlusograms. Dental Progress 1963; 3(4): 253-261

12 Watt D M. Preliminary report on the auscultation of the masticatory mechanism. Dent Prac Dent Rec 1963; 14: 27

13 Rodriques A A, Oestler V T. Electromyograph. In Electrodiagnosis and electromyography, pp 191-232, New Haven, Conn.: Elizabeth Licht, 1956.

14 Watt D M. Gnathosonics - a study of sounds produced

by the masticatory mechanism. J Pros Dent 1966a; 16: 73-82

15 Watt D M. Clinical applications of gnathosonics. J Pros Dent 1966b; 16: 83-95

16 Brenman H S, Weiss R C, Black M. Sound as a diagnostic aid in the detection of occlusal discrepancies. Penn Dental Journal 1966; 69(2): 33-39.

17 Watt D M. A gnathosonic study of tooth impact. Dent Prac Dent Rec 1967; 17(9): 317-24.

18 von Gierke H E, Oestreicher H L, Franke E K. Parrack H O, von Wittern W W. Physics of vibrations in living tissues. Journal of Applied Physiology 1952; 4: 886-900.

19 Watt D M. Gnathosonics in occlusal evaluation. J Pros Dent 1968; 19(2): 133-143.

20 Watt D M. Recording the sounds of tooth contact: a diagnostic technique for evaluation of occlusal disturbances. Int Dent J 1969; 19(2): 221-238.

21 Watt D M. Classification of occlusion. Dent Practit 1970; 20: 305-308.

22 Brenman H S. Gnathosonics and occlusion. In Kawamura Y (ed) Frontiers of Oral Physiology. Volume 1. pp 238-256. Basel: Karger, 1974.

23 Stallard R E, Ravins H E. The use of sound in adjusting dental occlusion. Quintessence International 1976; 61-66.

24 Watt D M, Wakabayashi Y. Study of a classification of occlusion. J Oral Rehabil 1978; 5(2): 101-10.

25 Takamiya S. A study on bone conduction of occlusal sound. Shika Gakuho 1979; 79:(7): 1317-1359.

26 Watt D M. Gnathosonic diagnosis and occlusal dynamics. New York: Praeger, 1981.

27 Watt D M. Temporomandibular joint sounds. J Dent 1980; 8(2): 58-70.

28 Watt D M, McPhee P M. An analysis of temporomandibular joint sounds. J Dent 1983; 11: 346-355.

29 Tanaka Y. The occlusal sound-wave detector. J

Gnathol 1984; 3(1): 29-41.

30 Watt D M, McPhee P M. Gnathosonic monitoring of occlusion of complete and partial dentures. J Oral Rehab 1985; 12: 107-112.

31 Nakazawa A. A study of shock acceleration and characteristic frequency of occluding teeth. Shika Gakuho 1986; 86: 187-216.

32 Fuller D J. The tooth contact sound as an analogue of the "quality of occlusion". J Pros Dent 1987; 57(2): 236-243.

33 Tyson K W, Geissler P R. Practical gnathosonics using accelerometers. J Dent 1987; 15(4): 181-2.

34 Tyson K W, Bagnall R D. Chairside gnathosonics using a home computer. Dent Pract 1987; 25: 5-7.

35 Teodorescu H N, Burlui V, Leca P D. Gnathosonic Analyser. Med Biol Eng Comput 1988; 26(4): 428-31.

36 Freer T J, Smith A. The reproducibility of gnathosonic recordings over time. Aust Dent J 1989; 34(3): 245-53.

37 Muramoto T, Taguchi S, Asazuma Y, Kifune R, Honma S, Tsuchida K, Hara K. Relative influence of plaque control, scaling and root planing on occlusal sounds. J Oral Rehab 1989; 16: 575-580.

38 Taguchi S, Sugita N, Asazuma Y, Hara K. Duration patterns of percussion sound in healthy and periodontally affected teeth. J Oral Rehab 1990; 17: 579-585.

39 Schulte W, d'Hoedt B, Scholz F, et al. Periotest neues messverfahren der funktion des parodontiums. Zahnartl Mitt 1983; 73: 1229-1240.

40 Schulte W. The new Periotest method. Compendium of Continuing Education in Dentistry 1988; 12: 410-417.

41 Schulte W, Lukas D, Ernst E. Periotest values and tooth mobility in periodontal disease: a comparative study. Quintessence International 1990; 21(4): 289-293

42 Muhlemann H R. 10 years of tooth mobility measurements. J Periodontol 1960; 31: 110-122.

43 Kato H. Measurement of resonance frequency of normal

and pathalogical periodontium - new method of periodontal examination. J stomatological Soc 1968; 35: 58.

44 Noyes D H, Clark J W, Watson C E. Mechanical input impedence of human teeth in vivo. Med Biol Eng 1968; 6: 487-492.

45 Noyes D H, Solt C W. Measurement of mechanical mobility of human incisors with sinusoidal forces. J Biomechanics 1973; 6: 439-442.

46 Korber K H. Electronic registration of tooth movements. Int Dent J 1971; 21(4): 466-477.

47 Yankell S L. Review of methods for measuring tooth mobility. Continuing Education in Dentistry 1988; 12: 428-432.

48 Oullette P L. TMJ sound prints: electronic auscultation and sonagraphic audiospectral analysis of the temporomanbdibular joint. Journal of the American Dental Association 1974; 89: 623-628.

49 Shi C S, Guan O Y, Guo T W. Power spectral analysis of occlusal sounds of natural dentition subjects. J Oral Rehabil 1991; 18(3): 273-7.

50 Kernohan W G. Microcomputer analysis of joint vibrations. Orthopaedic Review 1982; 5: 287-296.

51 Cowie G H, et al. Vibration emission in detecting congenital dislocation of the hip. Orthopaedic Review 1984; 13: 30-35.

52 Shaw S N, Kernohan W G. The development of a screening aid for congenital dislocation of the hip. In Byford G H (ed) Technology in health and care, Biological Engineering Soc, pp 107-108, London: 1985.

53 Kernohan W G, Beverland D E, McCoy G F, Mollan R. Oscillatory movement of the human pattella: description and explanation. In Measurement in clinical medicine the institute of measurement control. pp297-301, London: 1986.

54 Kernohan W G, Beverland D E, McCoy G F, Shaw S N, Wallace R G, McCullach G C, Mollan R A. The diagnostic potential of vibration arthrography. Clin Orthop 1986; 210: 106-112.

55 Kernohan W G, Beverland D E, McCoy G F, Hamilton A, Watson P and Mollan R. Vibration arthrometry. Acta

Orthop Scand 1990; 61(1): 70-79.

56 Kernohan W G, Cowie G H and Molla, R. Vibration arthrometry in congenital dislocation of the hip. Clin Orthop and Related Res 1991; 272: 167-174.

57 Harris C M, Crede C E. Shock and vibration handbook. 2nd ed, New York: McGraw-Hill, 1976.

58 von Gierke H E. Transmission of vibratory energy through human tissue. In Glasser O (ed) Medical Physics. volume 3, pp 661-669 Chicago: Year Book Publishers, 1960.

59 Newland D E. An introduction to random vibrations and spectral analysis. 5th impression, London and New York: Longman, 1983. (First published 1975)

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Short Communication

Practical gnathosonics using accelerometers

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KEY WORDS: Gnathosonics, Accelerometers

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ABSTRACT

Gnathosonics, using sound as an analogue of the occlusion, has mainly been confined to specialist institutions as, apart from the use of a strethoscope, the cost of instrumentation is prohibitive. By using accelerometers in place of microphones, the requirement for an anechoic chamber to make recordings becomes unnecessary. Permanent records of the sounds of occlusion can be made inexpensively. Gnathosonics can become an instrument in the general dental surgery to monitor the occlusion.

A basic harmony exists between the temporomandibular joints, the muscles of mastication and the teeth of the opposing jaws. Any malrelation of the opposing occlusal surfaces of the teeth, from whatever cause, affects the contact of the cusps of these teeth on closure. Watt (1966, 1970, 1981) demonstrated that the sounds of tooth impact provide analogues of occlusion of the teeth and that the sounds can be detected using a stereostethoscope. Twin microphones are placed over the zygomata to detect the sounds and record them on tape to provide permanent and comparable records. The tapes are then replayed at one-quarter speed through a sensitive ink recorder to produce a visible record for reference. When records are made it is necessary for the patient to be enclosed in an anechoic chamber (acoustic box) so that background noise is not picked up by the microphones. The advantage of having a visible record of this analogue of dynamic occlusion is that the records can be compared. In addition, the technique enables the drawing of large samples of occlusal activity for analysis.

Sounds and vibrations

While microphones are sensitivie to the sound vibrations induced in the skull by occlusal impact, these same vibrations can be detected using accelerometers, which are not sensitive to air-borne sounds. As both systems, microphones and accelerometers, use the vibration of the skin surface to activate them, it is not unreasonable to expect that the output of both transducers should be similar (*Fig. 1*). Accelerometers have the particular advantage that they are not vulnerable to extraneous noises, so that the anechoic chamber becomes redundant.

For general use, a single accelerometer is held firmly in place on the forehead by a band above the glabella. Experience has shown this to be the most satisfactory position as it is centrally placed, close to bone and sound is carried directly up the frontomaxillary butresses.

Freed of the anechoic chamber, recorded gnathosonics becomes a chairside tool. An inexpensive tape-recorder, with a minimum of two speeds, can be used to record and to listen to the occlusal sounds. The permanent record is available for future comparison. When listened to at half speed interpretation of the sounds is much easier. The use of an ink jet graph writer to produce a graphic record is ideal.

Sounds and occlusion

Stable occlusal impacts without interferences are heard as single short sounds as the patient snaps the teeth together. On the other hand, occlusal interferences result in the sounds of tooth contact being extended, often with double or complex components (*Fig. 2*).

Alterations to the occlusion may be caused by the interference of a poorly placed restoration, crown, bridge or partial denture, and this can be monitored. When the introduced abnormality is corrected the sounds return to normal.

Auscultation of the sounds of occlusion, and its recording, is a useful diagnostic aid in the treatment of

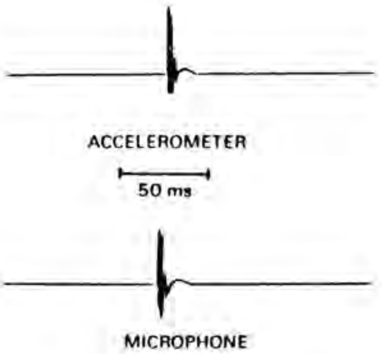

Fig. 1. Traces produced of similar tooth impacts recorded by accelerometer and microphone.

gnathic disorders. A computer program that will allow a home computer to be used as an oscilloscope to display the sounds, and store them on tape or disc, is presently under development.

Mandibular dysfunction syndrome

Many factors have been considered to initiate or contribute to mandibular dysfunction. When investigating occlusal interferences and abnormal tooth contacts using articulator methods, the reproduced movements may not represent the patient's normal or abnormal functional activities (Craddock, 1949; Trapozzano and Lazzari, 1967; Watt, 1969).

Greater insight into the condition is to be gained from investigation of the occlusal dynamics using gnathosonic techniques. The manner in which the patient occludes, deflective contacts, faceting and the quality of the sound produced as the teeth occlude can all lead to a better understanding, and so to a more accurate diagnosis of gnathic dysfunction. Auscultation, recording and interpretation of temporomandibular joint sounds can also play a part in the overall assessment of the gnathic system.

Using the apparatus

The transducer presently in use is BU1771 (Knowles Electronics, Burgess Hill, UK) which is inexpensive. The actual frequencies shown on the traces are not of great significance, largely being a function of the physical properties of the tissues and transducer. It is the overall shape of the envelope produced by the trace that indicates the quality of occlusal contact. To this end small accelerometers are ideally suited as their fundamental frequency is well outside the frequency band involved in the tracings.

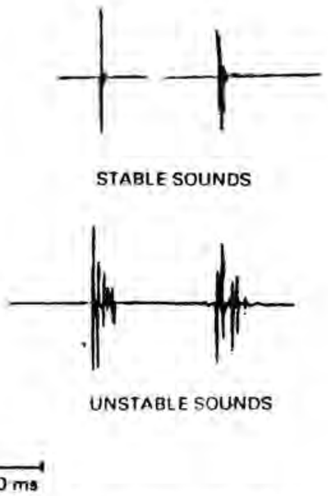

Fig. 2. Accelerometer traces produced by stable and unstable occlusions.

CONCLUSION

Gnathosonics can be looked on as a multipurpose facility, from the simple to the complex: checking that an occlusion is stable, that any kind of restorative procedures have not caused interferences, that the occlusion has returned to stability after orthodontic treatment, to diagnosis and treatment of difficult dysfunction syndromes. Sounds made by complete or partial dentures are also open to monitoring and interpretation. Gnathosonics is just as 'at home' in the general practitioner's surgery as it is in the hospital.

References

Craddock F. W. (1949) The accuracy and practical value of records of condylar path inclination. *J. Am. Dent. Assoc.* **38**, 697–710.

Trapozzano V. R. and Lazzari J. R. (1967) The physiology of the terminal rotational position of the condyles in the temporomandibular joints. *J. Prosthet. Dent.* **17**, 122–133.

Watt D. M. (1966) Gnathosonics—a study of sounds produced by the masticatory mechanism. *J. Prosthet. Dent.* **16**, 73–82.

Watt D. M. (1969) Recording the sounds of tooth contact: a diagnostic technique for evaluation of occlusal disturbances. *Int. Dent. J.* **19**, 221–238.

Watt D. M. (1970) Classification of occlusion. *Dent. Pract.* **20**, 305–308.

Watt D. M. (1981) *Gnathosonic Diagnosis and Occlusal Dynamics.* New York, Praeger, pp. 127–149.

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CHAIRSIDE GNATHOSONICS USING A HOME COMPUTER

ABSTRACT
A low-cost computer method for capturing and displaying gnathosonic data has been developed, offering the possibility of gnathosonic study in general dental practice rather than in specialist institutes. Particular features of the technique are the relatively simple equipment involved, and the ability to expand captured sound envelopes well beyond that achieved by existing methods.

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GNATHOSONICS, the sounds made by the teeth on closure, is a recognised method for studying mandibular function and the state of the occlusion (Watt 1966, 1981), but is unattractive to the general practitioner because of the complex and expensive equipment involved.

The technique reveals details of occlusal dynamics; for example, stable occlusion produces short sharp sounds while unstable occlusion produces sounds which are longer and more complex due to both hitting and sliding.

In principle, the sounds of the teeth on contact can be examined either directly or from a recording, and the sound envelope analysed for the number and duration of contacts. In practice the sounds have always been recorded on tape and analysed later, and have required an anechoic chamber to avoid external noises being picked up by the microphone. Recently, however, Tyson and Geissler (1987) have overcome this problem using vibration transducers, instead of microphones, placed directly over the hard bone of the forehead so that the only sounds captured are those made by the patient.

In spite of this, the technique is still not attractive to the general practitioner because it has required a variable speed recorder so that sounds can be captured at high speed and replayed into a chart recorder at low speed to "slow" the sound down. Even so, special inkjet chart recorders capable of fast response are required to fully expand the sound envelope, and this is beyond the resources of the average dental practice. Gnathosonics has therefore been limited to specialist institutes such as dental hospitals.

However, home computers could solve all of these problems since, with suitable programming, they can store, display and expand data quite readily. We have therefore developed such a technique which involves nothing more complicated than a suitable home computer, an accelerometer, a tape recorder if required, and a fast analogue-digital converter, all of which are within the means of most dentists.

Equipment

Our technique uses the popular BBC range of computers, and the analogue-digital converter is part of a multipurpose low-cost interface (Unilab, UK) which simply plugs into the 1 MHz bus port of the computer. The interface has in fact four analogue input sockets, and can be connected to four different signal sources simultaneously if required. Sounds are captured either directly or on tape using a vibration transducer of the type described by Tyson and Geissler (Type BU1771, Knowles Electronics UK), and a typical set-up is shown in Fig 1.

FIG 1 Apparatus for computerised gnathosonics. Sounds are captured by an accelerometer retained by a headband (shown here worn by a technician). The analogue-digital interface is the orange-coloured box at bottom right, and the small cream-coloured box beyond the computer is a disc drive

```
GNATHOSONIC CAPTURE BY COMPUTER

Which input (A/B/C/D)?.... A

Sensitivity?

(1) 10  volts f.s.d.
(2)  1  volt  f.s.d.
(3) 0.1 volts f.s.d.
(4) 25mV-2.5V f.s.d.

                              Y

Trigger (Y/N)? Y

Rise or Fall (R/F)?

2304 samples will be taken.

Delay (40-60000 microsec)?  40
```

FIG 2 Actual screen display of set-up procedure for the analogue interface

Software

We have developed a sampling program which takes approximately 2,000 readings at any interval between 40 microseconds and 16 seconds, with a high resolution screen display of the captured sound envelope and a zoom facility to enlarge selected parts for detailed analysis. The program also includes a printer driver routine currently written f Silver Reed EB50 p but since the langu Basic this could be a readily for other p The program is fully driven, and the u required to have limited knowledg computers.

Typical method

In a typical pro the computer progra prompts the user for of how the interface is set up, as shown in Fig particular interest is th

Continued on

HAIRSIDE GNATHOSONICS

From page 5

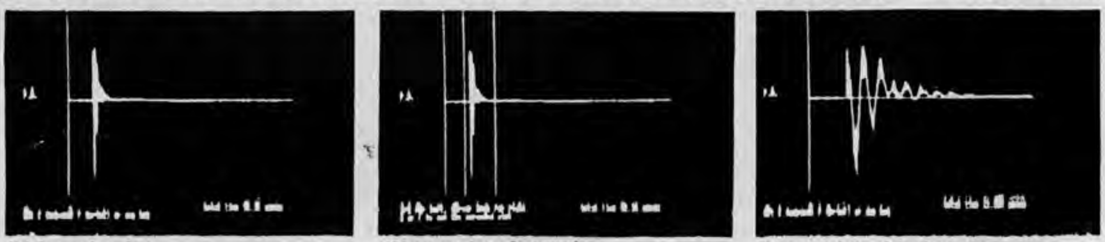
```
Plot data    (G)
Fast plot    (F)
Save data    (S)
New data     (N)
Reset delay  (D)
Reset all    (R)
Exit         (E)
_
```

IG 3 Actual screen display of ptions once a sound has been ptured

an optional trigger built to the interface, which llows the program to pause ring sampling until a nal is detected. Normally e use this trigger, and the rogram takes a limited number of background readings before pausing. The patient is then instructed to make the required sound, and the program automatically captures the sound envelope as a series of discrete readings stored in the computer's memory. Alternatively, the sound can be recorded on tape from the vibration transducer and played at normal speed into the interface later.

Various options are then presented to the user in the form of a menu, as shown in Fig 3. For example, the whole set of readings can be saved on disc by pressing "S". The first two options are the most important however, since they allow the data to be displayed graphically on screen. Option "G" uses every reading and takes several seconds, whereas option "F" only uses every fourth reading and is therefore much faster although the display is not as detailed.

A typical "G" plot is shown in **Fig 4** for a stable occlusal sound. **Fig 4a** is the normal sound envelope, and has options "E" and "P" at bottom left for expanding or printing the screen display. In **Fig 4b**, the expansion option "E" has been selected and vertical bars have been positioned via the keyboard to denote the area for expansion. **Fig 4c** then shows the chosen section expanded to full screen width. This process is extremely rapid, allowing the sound to be readily expanded to any desired degree. Finally, a printout of the expanded envelope can be obtained for further study by pressing "P", as indicated at bottom left in **Fig 4c.**



4(a) the sound envelope

4(b) an area chosen for expansion

4(c) expanded plot of the chosen area

FIG 4 Actual screen display of stable occlusal sound captured by computer (potential difference vs time).

Comparison with current technique

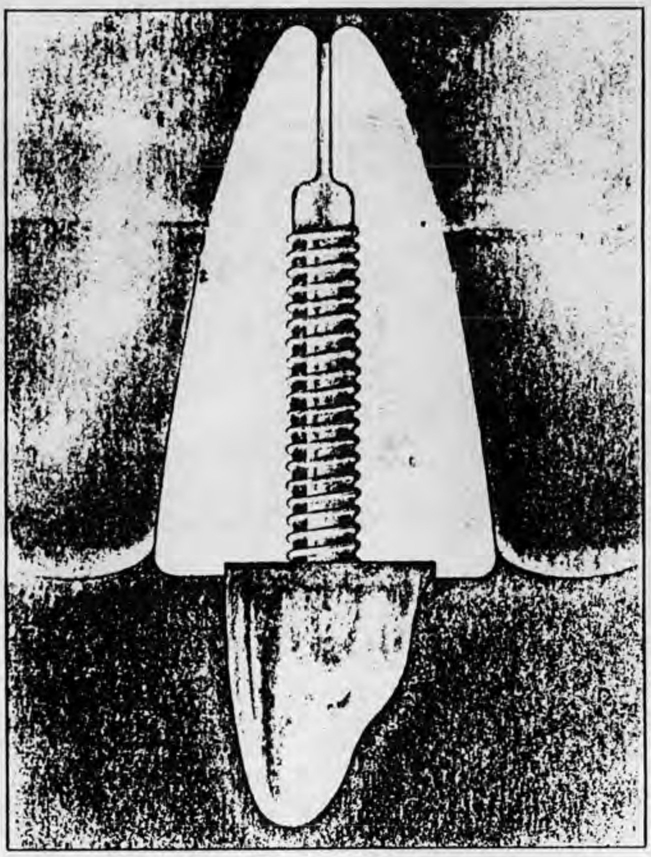
In our work to date, we have compared the classical capture technique with the new low-cost computer method, and have found that the computer is both easier and provides much more detailed information. In particular, since the user can choose the degree of expansion of the recording from screen prompts, and since the computer simply transfers a stored image to the plotter, there is no need for high-speed plotting. In fact, since the program will store each captured sound on disc for easy viewing later, there may be no need for a plotter at all.

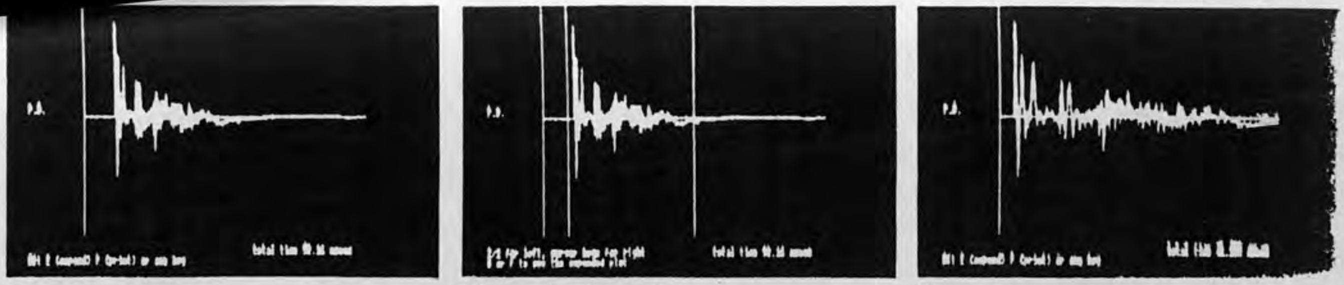
Other dental sounds

As already indicated, **Fig 4** shows a stable occlusal sound captured by the new technique. As our studies progress, we are now examining a variety of dental sounds to refine the procedure and provide a more detailed analysis of sound envelopes. This is illustrated in **Figs 5 and 6**, where other dental sounds have been readily expanded beyond the point normally expected of conventional equipment, revealing details of the sound envelope hitherto hidden. So simple is this procedure and so detailed the result that it may lead to a significant step forward in the use of gnathosonics in dental diagnosis.

Frequency limitation

There are two limitations to the capture of higher frequency sounds by this method. First, at least two readings for each cycle are required or the observed frequency will be less than the true frequency. The software has a minimum sampling delay of 40 microseconds, which translates into two readings for each cycle at 12.5 KHz. Below this, the overall frequency pattern will be captured although detail will be lost as the frequency approaches this value, but above it the captured "frequency" will appear to





5(a) the sound envelope
5(b) an area chosen for expansion
5(c) expanded plot of the chosen area
FIG 5 Actual screen display of unstable occlusal sound captured by computer (potential difference vs time)

6(a) the sound envelope
6(b) an area chosen for expansion
6(c) expanded plot of the chosen area
FIG 6 Actual screen display of multiple sound from plastic rod striking teeth, captured by computer (potential difference vs time).

decrease. At the same time, the vibration transducer has a resonant frequency of 10-12 KHz, so that frequency patterns in this region are somewhat confused. For both these reasons, the technique described here has an upper frequency limit of about 12.5 KHz.

Summary

A low-cost computer method of capturing and manipulating gnathosonic data has been developed, offering the possibility of gnathosonic study in general dental practice. Work is currently in hand to further refine the technique and provide a means for a clinician to properly analyse the detailed sound envelopes obtained.

Further information

Interested clinicians can obtain further details and a copy of the software from the authors.

References

Tyson K W, Geissler P R. Practical gnathosonics using accelerometers. *J Dentistry* 1987 (submitted).

Watt D M. Gnathosonics — a study of sounds produced by the masticatory mechanism. *J Prosthet Dent* 1966; 16: 73-82.

Watt D M. *Gnathosonic Diagnostics and Occlusal Dynamics*. New York: Praeger, 1981.

PROPOSED CHANGES TO FIRST AID GUIDANCE

A DRAFT revised first aid guidance has been published by the Health and Safety Commission. Changes to the existing guidance recommend a stronger emphasis on linking the level of first aid provision to hazards at work rather than the numbers of employees.

The guidance recommends that first-aiders take extra training which focuses on specific hazards instead of the routine occupational first aid training. Guidance has been expanded on the provision of first aid in small businesses; on the experience necessary for trainers and examiners in first aid at work; on the selection of first aiders; and the training of lay instructors.

Surveys have been carried out by HSE's medical division to investigate knowledge of and compliance with the regulations. These identified a lack of understanding in two main areas — appropriate first aid materials and the lack of training for specific hazards.

A revised leaflet on first aid at work has also been published, giving general information on first aid priorities, such as the procedure for burns and scalds, eye injuries, electric shock and gassing. The leaflet, illustrated with photographs on methods of resuscitation, is issued for inclusion in first aid boxes.

Copies of the leaflet (ISBN 0 11 883958 6) are available from HMSO: £3.50 for 25; £13 for 100; and £60 for 500. The draft guidance, also available from HMSO, is £7.50.

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Letters to the Editor

Sources of error in gnathosonics

Dear Sir,

As part of our research we have investigated the sources of error in gnathosonics, and have become concerned at the number of published papers which do not properly address the inherent practical problems.

We believe that there are at least the following four major problems in developing a clinically acceptable gnathosonic system:

- Hardware assembly.
- Complete sound capture with no spurious signal components.
- *In vitro* and *in vivo* testing.
- Meaningful data analysis.

Unfortunately, many literature reports in the field of gnathosonics deal mainly with analysis and clinical significance of the captured sounds. Often there are no control experiments, and all the captured sound is assumed to have come from the patient, particularly where commercial apparatus is used.

We have made no such assumptions, and have begun to address the first two problems using our own hardware. As a result we have identified a number of causes of possible error which may be present in work by others. One effect in particular, called aliasing, is well known in other fields of signal capture and can lead to a totally false captured sound. However we have been unable to find a mention of it in the dental literature. We should like to highlight some of the precautions which must be taken by researchers in this field.

The following problems have been found by us to affect the captured sound envelope:

- Aliasing caused by incorrect capture rate.
- Mass and contact area of the sound-receiving device.
- Resonance in the sound-receiving device.
- Position of sensor on the head.
- Estimation of signal duration.
- Earth loops.
- Attenuation of signal by automatic gain control.
- Frequency response of recording/replay systems.

The most worrying problem is aliasing, which occurs in digital signal capture when the sampling rate is too slow, so that more than one wave passes between readings. The apparent frequency is then low, and the slower the sample rate the worse this becomes. A similar effect in analogue capture would result from a chart recorder with a slow pen response.

The problem is illustrated in *Fig. 1* for a decaying sine wave of frequency *f*, where a digital sampling rate of approximately 1.1. *f* results in an apparent wave of only about 0.1 *f*. At least two samples per cycle are required to record the true frequency, and this sets a lower limit for sampling frequency at 2 *f*. For complex real signals in gnathosonics, the sampling rate should therefore be at least twice the highest frequency present. For example, if sounds up to 1 KHz are to be studied, the signal sampling frequency *must* be at least 2 KHz, and the signal *must not* contain frequencies greater than 1 KHz. One routine way of ensuring this in general signal capture is an electronic filter to limit the upper signal frequency, but of course important information may then be lost. The alternative is to sample at such a high rate that all frequencies present are captured without aliasing. However, we have not been able to find general mention of such precautions in the gnathosonics literature.

The inertia of the sensor can in fact act as a mechanical filter for higher frequencies. In our work the sensor is a miniature vibration transducer (accelerometer), and in a series of experiments in which it was mounted on metal blocks of increasing mass, we have found that as the inertia increases there is a corresponding decrease in highest recorded frequency. Again however, no dental paper appears to have addressed the problem. The effect could of course help to combat aliasing, but important higher frequency components could be lost in this way unless the characteristics of a given sensor are known *and* reported. Without such sensor data in research papers, we believe that any reported signals and their interpretation should be treated with caution.

During investigations into the frequency response of our own system, unusual 'noise' was also observed when test signals in the region of 12 KHz were sampled, due to

Fig. 1. Aliasing—the effect of too low a sample rate. A signal of frequency *f* is sampled at approximately 1.1 *f*, individual samples being shown by vertical lines. The resulting apparent 'frequency' is only about 0.1 *f*, as shown by the heavy line.

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transducer resonance. Other sensors such as microphones may have similar problems, and unless the sampling rate is at least twice this resonant frequency, high frequency 'noise' will be aliased and will appear in the captured envelope as a spurious low frequency signal. If suitable precautions are not taken against this, or are not stated in published work, low frequency components in captured sounds may again be open to doubt.

In addition, we have investigated the effect of changing the sensor position, and have found the most satisfactory place to be at the glabella, just above and between the eyes, where the sounds of occlusion are carried up the maxillary buttresses with least interference from other routes of sound conduction.

We have also considered the interpretation of gnathosonic data. Prolonged sliding contact between teeth should produce a correspondingly long signal, and signal length has been used by various researchers as a diagnostic index. There is a basic problem, however, in that long but quiet signals will appear to decay to background in a relatively short time. They might then be mistaken for short signals. For example, gnathosonics has historically used analogue equipment such as chart recorders, where signal attenuation can be adjusted so that quiet and loud noises have similar amplitudes for 'comparison'. However, an enlarged quiet recording from a patient in pain might then appear to have a long duration. A subsequent reduced loud signal when the patient is pain free might in the same way appear to be of short duration. This would give the expected appearance of the tooth sound becoming crisper as treatment progressed, whereas this might not be the case at all. We have not yet properly solved this problem, even for digitized waveforms, and other workers should be aware of this capacity for inadvertent signal manipulation.

On occasions we have also observed that inadvertent earth loops, which arise when the chassis potential of different components of electronic equipment are not the same, can introduce spurious extra components into a captured signal. These are usually of low frequency, further complicating what may already be an aliased signal with false low frequencies.

Further, we have examined gnathosonic sounds by recording them on cassette tape, and have encountered a problem with automatic gain control which attenuates any high signal amplitude. The problem for gnathosonics is that the initial signal is indeed of high amplitude which then decays. Attenuation of the initial peak has been found to give a false shape to the sound envelope, not least because the attenuation persists into subsequent vibrations. The simple answer is to keep the signal below the age threshold, and users of such recorders should be aware of the problem.

A second problem with tape recorders, and indeed hard copy devices such as chart recorders, is that the frequency response must be uniform across the desired frequency range. Workers should therefore check that sound envelopes have not been distorted in this way.

We believe that these sources of error are sufficiently serious as to cast doubt on gnathosonic data unless a research report includes the means of their control. What appears to be lacking from gnathosonics is an agreed standard against which all work can be judged, and it is our opinion that the most pressing need at present is the setting of such a standard. This therefore is a major goal of our current research.

In the meantime, researchers in this field should be aware of the pitfalls, particularly aliasing, and ensure that any research publications include full specifications of the apparatus used and the methods by which the problems highlighted here have been addressed.

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Periodontics: A Practical Approach

Dear Sir,

While wishing to extend my thanks to Dr Caffesse for reviewing my book *Periodontics: A Practical Approach (J. Dent.* 1991; **19**, 368), I cannot let some of his comments pass unchallenged.

I am surprised that the innovative separation of the treatment philosophy, principles and methods, comprising Part II, from that of the corroborative research findings presented in Part III, should have come across so adversely and moreover, stated to have led to minor inconsistencies. The purpose of this format was to facilitate an unimpeded examination and understanding of the practical aspects of periodontics, whilst maintaining a close link with the readily accessible documentary support for this approach in the separate review of the scientific basis of therapy, as stated clearly in the preface, and reinforced by Sture Nyman in the foreword to the book. A further and closer examination of the book will, I am confident, make the merits of this layout more evident and in turn clarify any apparent inconsistencies. Should however any such inconsistencies still persist, a note thereof for rectification in subsequent editions would be appreciated.

The statements that the author's 'personal views comprise approximately 75 per cent of the book' and 'are unsupported by references or resources for further reading' are astonishing and cannot be sustained and, indeed, are countermanded by the later statements that 'Part III presents a review of current research findings to support the clinical approach recommended... and that these chapters present extensive reviews of pertinent topics and are supported by excellent citations'. Furthermore, the fact that the major part of the book does, by design, not incorporate the supportive references in their conventional juxtapositioning to the text, cannot be construed as rendering the content as unsubstantiated personal opinion. These statements are therefore not considered to be justified.

Finally, the classification and nomenclature of surgical procedures is viewed somewhat critically. The purpose of this simplified approach to surgery of only three basic techniques is to avoid the conventional treatment planning difficulties in which, as stated in the preface, the appropriate techniques must be selected from the bewildering array currently available to cater for the varying degrees of breakdown present in any one case. In addition, the terms given are, with the exception of 'surgical reattachment', not unique and describe precisely and unequivocally the objective of the exercise, unlike that of, for example, the 'Modified Widman flap' used elsewhere. It is of further interest in this context, that no