EINDHOVEN UNIVERSITY OF TECHNOLOGY

Medical Electrical Engineering

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Medical Electrical Engineering

Biomedical and Health Care Technology
Eindhoven University of Technology

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Introduction

Health care is one of the domains in society where technological know-how and skills play an important and meaningful role. In about 20 research groups, from all departments of the Eindhoven University of Technology (EUT), there is an ongoing activity in research and education programs on Biomedical and Health Care Technology (BMT). The BMT profile of the EUT as a whole is supported by the contributions of all these research groups.

Biomedical and Health Care Technology is an interdisciplinary area located between medicine, health care and technology. It can be defined as: all activities for which know-how and skills from physics, mathematics and technological disciplines are applied, elaborated and directed towards problems in health care, medicine and biology. Examples are: research on fundamental materials aimed at the design of artificial organs or limbs, the development of new diagnostic, therapeutic or rehabilitation instruments as well as the conceptualization of new organizational models for health care institutions such as hospitals. This definition comprises many areas of interest for medical as well as technological disciplines.

The main part of the BMT research activities at the EUT is organized in three large research programs:

- Technology for Vital Functions
- Hospital Research Project
- Perceptive Information Processing in Interaction with Equipment and Software.

Students from all departments can choose one or more training courses out of the thirty BMT courses that are given each year by the different research groups of the university. Within each department it is also possible to complete the study with a master's thesis on a BMT subject or to specialize in biomedical engineering. The department of mechanical engineering has composed a special program that enables students to get a full master's degree in biomedical engineering.

The coordination of all BMT activities, as far as desired and possible, is embedded in the EUT BMT Center. This Center consists of a scientific committee with representatives from all departments of the university and a project office with a small staff. The task of the Center is twofold. Besides the coordination of all BMT activities in and between the departments there is also a continuous effort in tuning the BMT activities to the profile and policy of the EUT with regard to education and research programs.

For more than a decade there has been a mutual consultation concerning biomedical engineering on the national level between the three universities of technology and the Netherlands Organization for Applied Scientific Research (TNO). More recently this has been extended to the eight medical schools and university hospitals.

This bulletin presents the BMT activities in research and education of the Division of Medical Electrical Engineering.

Medical Electrical Engineering

At the end of the sixties, the Eindhoven University of Technology established a part-time chair in Medical Electrical Engineering within the Division of Measurement and Control of the Department of Electrical Engineering in order to strengthen the ongoing activities in the biomedical field. This was converted to a full-time chair in 1976.

The Division of Medical Electrical Engineering (EME) was founded in 1980. At that time it incorporated a large part of the teaching and research activities in biomedical engineering that earlier took place within the Division of Measurement and Control.

The Division EME now constitutes one of thirteen divisions of the Department of Electrical Engineering (EE) which together cover the vast area of electrical engineering. Teaching in the EE Department is subdivided into three main streams:

1. Information and Communication Engineering
2. Energy Systems
3. Control and Systems Engineering.

Medical Electrical Engineering belongs to the third stream although research activities are also closely related to the first stream.

The objective of the research and development in the Division of Medical Electrical Engineering is: 'The introduction into health and medical care of knowledge, methods and devices which will have a useful effect on the well-being of the patient, either directly or indirectly'. This area is so vast, that we limited it on the medical side to care and rehabilitation. This implies that inputs from clinical research are needed. The technological side of our multidisciplinary field relies on inputs from: physics and measurement theory, modeling and systems theory, instrumentation, electronics, communication and information theory, data processing and display and control theory. Ergonomics and man-machine interaction are important contributing areas too.

The research activities of the division cover a wide area:

- servo-anesthesia;
- ultrasound imaging techniques;
- instrumentation for the disabled.

Our problem solving approach consists of an initial assessment of the generality of the problem followed by the application using the disciplines and techniques mentioned above.
Most of the investigations take place in close collaboration with hospitals, rehabilitation centers and industry, both national and international. Several foreign investigators have spent some time with the Division EME; similarly, EME staff and students often go abroad for limited periods as part of the collaborations and to expand their experience.

The teaching activities of the Division EME are closely intertwined with its research. As a result of the diversity of research areas, the division offers both masters and doctoral students with different engineering backgrounds and interests an opportunity to test their abilities in applying their knowledge to medical engineering problems.
The exposure to multidisciplinary problems and experience with working in multidisciplinary teams is considered of the utmost importance.
The process of translating a problem from a non-electrical engineering area towards one's own area, working on the solution and then converting the solution to and applying it in the original area, should be mastered by most of the students and constitutes a **fundamental teaching objective** of the Division of Medical Electrical Engineering.
By the end of 1987, a total of 125 master students had graduated from the division.

Servo-anesthesia

During surgical procedures it is the anesthesiologist who ensures that the patient does not feel pain, is unconscious and does not move. This is done through drugs, which have side effects. Thus the condition of the patient needs to be monitored continuously and, if necessary, must be adjusted. In addition, all important patient data are recorded regularly, every 5 or 10 minutes. The complexity of the anesthesiologist's task depends of course on the type of operation and its progress; sometimes there are periods where so much needs to be done at the same time that the anesthesiologist becomes overloaded with work. The servo-anesthesia project is an investigation into possibilities to meaningfully decrease the anesthesiologist's workload through automation in order to:

- prevent accidents and critical incidents and thus ensure the patient's safety;
- automate routine tasks;
- assist therapy through prediction of optimal drug doses.

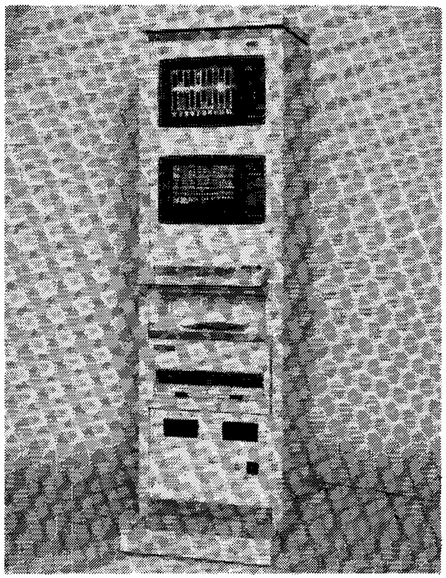
Monitoring and alarms
Analysis of the patient's condition in complex surgical procedures is possible only through the measurement of many physiological signals. Blood pressures measured at several sites, the electrocardiogram (ECG), several respiratory measurements and one or two temperatures are the main sources of information. Thus far, all these data are presented in an unordered way, by many different instruments, in different locations and with different types of display. Current alarm systems are very primitive and do not consider multiple sources of information. Therefore it can be very difficult to find the causes of sudden deviations from normality in the patient's condition, and the resulting loss of time may be life-threatening. Also, the many measurement data and the varying workload make it almost impossible to keep a complete and accurate anesthesia record. At critical moments, the anesthesiologist's attention is focused on the patient, but especially then a complete record is most important. Besides, the standard 5 minute interval is much too long to be able to accurately reconstruct the development of problems; an interval of 1 minute or less is necessary.

To solve some of these problems we designed a Data Acquisition and Display System (DADS), that:

- automatically acquires all important signals;
- alarms on all sudden deviations that persist too long;
- centrally displays all important data on two color displays;
- records those data in an automatically maintained anesthesia record, just like the 'black box' in an airplane; in addition, the anesthesiologist can manually enter extra data into this record, e.g. drug dosages.

The DADS system has been tested and used extensively at the Leyden University Hospital. A major research effort was to evaluate its features and to design general evaluation procedures for similar equipment. The results of this effort constitute a firm basis for the rémaining sub-projects.

Artificial intelligence
In the design of DADS we found,



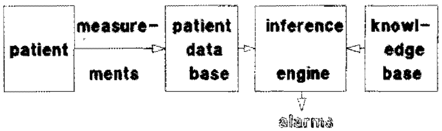
The Data Acquisition and Display System: all important data are presented together; alarms are given if abnormalities are detected.

that more and more medical knowledge needed to be incorporated into the software. In a research environment this knowledge changes (increases) frequently, and this makes software maintenance an enormous problem. Artificial intelligence research has developed 'expert systems', software especially designed to incorporate human knowledge and manipulate it, e.g. to derive conclusions and perform actions through 'reasoning' about elementary facts such as acquired measurements. Current expert systems are too slow and inefficient to handle all the data in patient monitoring, however. Our own newly designed real time expert systems tool SIMPLEXYS promises a much more efficient approach. It is used in two applications: a blood pressure controller and an improved 'intelligent alarms' software module.

Automatic control
During many surgical procedures the patient's state is controlled through the continuous infusion of drugs and fluids. In some cases the infusion flow rate has to be adjusted frequently to keep the patient in an optimal state. We expect that extra control modules inside a DADS will be able to take over the constant monitoring necessary to determine the effect of infusions and actually control the pumps that deliver the fluid. An example is induced hypotension through infusion of the drug sodium nitroprusside, which artificially lowers the blood pressure depending on the infusion flow rate.

This drug is potentially dangerous and its effect can vary a great deal; the infusion and its effect must therefore be carefully monitored and adjusted. Conventional control theory does not provide effective tools, but a new expert system based controller seems to be able to do the job.

Intelligent Alarms
Most monitoring systems are based on simple threshold detection techniques for observing changes in the state of the patient. During the initial phases of anesthesia and during emergencies a cacophony of different alarms may occur. The goal of this sub-project is to develop methods that use the information available in the set of monitored signals. This should lead to suppression of alarms due to artifacts and known interceptions, earlier detection of relevant changes in patient and equipment and meaningful alarm messages. The implementation will make use of an expert system.



The Knowledge Base is continuously consulted to detect alarm conditions inherent in the measurements.

Depth of anesthesia
One of the greatest problems in anesthesia is the fact, that no good measurements are available about its most central aspect: depth of anesthesia. We currently study the feasibility of employing one or more features of the auditory 'evoked response' as an indicator of depth of anesthesia. The patient wears an ear phone and 'hears' clicks (even while he is unconscious). The clicks reach the brain and induce responses in the EEG that can be measured. If changes in these responses prove to correlate well with the clinical impression of the depth of anesthesia, a source of new information becomes available.

Integration of disciplines
The servo-anesthesia research is multi-disciplinary. The following scientific disciplines play a major role:

- human factors engineering (ergonomics): to determine the best way to present data, computed results and alarms for easy recognition;
- measurement theory: the patient data must be properly processed and disturbances must be detected and/or eliminated;
- control theory: for the design of automatic drug infusion control systems and control of respiration;
- computer (hardware) engineering: frequently a specially designed mi-

crocomputer performs better or at a lower cost;

- computer science (informatics): the computer programs, including the operating system, need to be specially designed;
- anesthesiology: of course.

Ultrasound imaging techniques

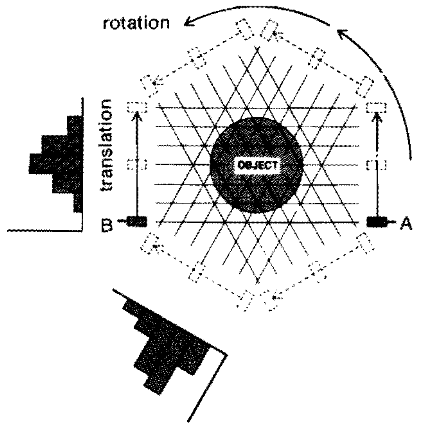
Ultrasound - that is sound with a frequency far beyond the limits of human auditory perception - is nowadays widely used in the medical field. It is used for diagnostic as well as for therapeutic purposes. An example of its therapeutic use can be found in e.g. diathermic therapy based on the internal heat dissipation by sound waves and lithotripsy. Examples of its diagnostic use are e.g. the measurements on the circulatory system based on the Doppler principle and also the different imaging techniques for making images of internal organs. Ultrasound imaging has, compared to X-ray imaging, the great advantage of being completely harmless to the patient. Of all the medical applications of ultrasound the research in the Division of Medical Electrical Engineering deals with the imaging techniques only.

Most applications of ultrasound in medical imaging make use of the echo principle: a short ultrasound pulse (fig. 3) is transmitted into the patient, the echoes of the different organs and tissues are received and then, somehow, mapped into an image. In this way, ultrasound imaging is analogous to radar imaging.

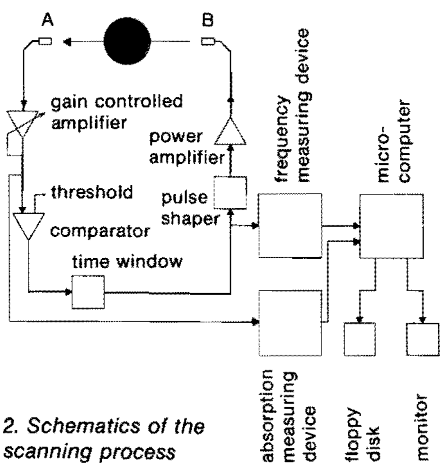
The research project of our group, however, makes use of the transmission principle. A transducer transmits a short ultrasound pulse into the patient and another transducer, placed at the opposite side of the patient, receives it. Then the time-of-flight of the pulse between the two transducers and the attenuation of the pulse during its travel are measured and subsequently mapped into an image. In this way, ultrasound imaging is analogous to X-ray imaging.

The aim of this research project is to make cross-sectional images of parts of the human body by means of the aforementioned principle. In these images the contrast producing variables are, as said, the local sound velocity and the local attenuation coefficient.

In our project such a cross-sectional image is made as follows (fig. 2): An ultrasound pulse is transmitted through the region to be imaged from a transmitting transducer to a



1. Schematics of the experimental set-up receiving transducer and the time-of-flight of the pulse is measured. Then, by moving both transducers simultaneously in a direction perpendicular to the direction of the ultrasound beam, a linear scan is made along the object to be imaged. During this scan the time-of-flight is measured repeatedly, so that a sampled projection of the sound velocity distribution in the object is obtained. A number of such projections in different directions are obtained by rotating the platform carrying the transducers around the object and then repeating the measurement. From this set of projections the local sound velocity in each point of the object's cross-section is calculated by means of filtered back projection, a technique quite analogous to the technique used in X-ray CAT-scanning.



2. Schematics of the scanning process

In our experimental set-up (fig. 1) the object to be imaged is placed into a water tank. Over this tank is a platform carrying the transducers. The distance between the transmitting and the receiving transducers is 15 cm. Their resonance frequency is 1 MHz. They are mounted on carriages that permit lateral and rotational scanning movements. These movements are driven mechanically by stepper motors. One motor step corresponds to 0.1 mm of the lateral scan and to 0.1 degree of the rotational scan.

During each lateral scan the time-of-flight is measured repeatedly. This measurement is carried out by a reverberation method: each time the receiver detects the arrival of a pulse it will trigger the transmitter to send a new one. So the system will reverberate continuously; the reverberation frequency can be measured easily and accurately.
The transmitting transducer is excited with a rectangular electric pulse (width 0.5 /s). At the receiving transducer the received signal is amplified, rectified and then fed into a comparator to detect the moment of arrival of the pulse. As soon as this moment has been detected, a new rectangular electric pulse is formed, with which the transmitting transducer is excited. In this way the signal will reverberate forever. The reverberation frequency will be exclusively determined by the time-of-flight of the ultrasound pulse and by the electronic delay, the latter being a constant. This frequency can be measured accurately by simple means. For the amplification of the received signal a gain controlled amplifier is used. This makes the amplitude of the input signal of the comparator independent of the amplitude of the received acoustic signal (within a range of 60 dB).

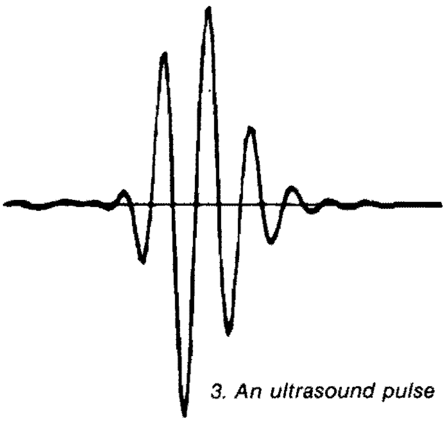
Measuring the time-of-flight by reverberation is simple, but it holds a large problem. Occasionally, spurious pulses may arrive at the receiving transducer. If such a pulse has an amplitude exceeding the threshold of the comparator, it will also trigger the transmitter and thus it will also reverberate. Therefore, any spurious pulse will spoil the measurement by drastically increasing the reverberation frequency. This problem has been overcome by adding a 'time window' to the circuitry. Every time a trigger pulse is detected by the receiver, this 'time window' will for a relatively long time block the passage from the comparator to the transmitter for all received pulses. It can easily be seen that, if this blocking signal lasts longer than half the expected time-of-flight, any spurious pulse will die out.

The reverberation frequency (which is about 10 kHz) is measured by means of a personal computer. All measured frequencies of all projections are stored on floppy disc. After completion of the fully automated measurement the computer retrieves the set of measured frequencies from the disc and then performs a reconstruction of the object in terms of sound velocity distribution. For this reconstruction a mathematical technique is used, the so called filtered back projection. This is a reconstruction technique widely used for reconstructing images in X-ray CAT scanning.

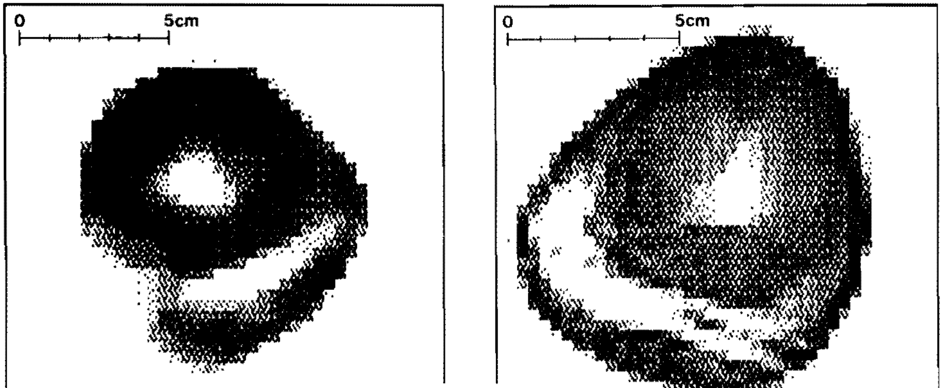
When during the scanning process not only the time-of-flight is measured but also the attenuation of the sound beam in between the two transducers, two different images can be reconstructed after completion of the measurement; one with the sound velocity, the other with the local absorption coefficient as the contrast producing variable.

The measurement of the sound attenuation consists of measuring the mean frequency down shift of the ultrasound pulse. This can be explained as follows: All human tissues absorb ultrasound, and each tissue has its own specific absorption coefficient. The tissues have in common that their absorption coefficient is frequency dependent: the higher the frequency, the more the absorption. So, when a broadband pulse travels through the human body, the higher frequency components of its spectrum will be attenuated more strongly than the lower frequency components. As a result the mean frequency of the received pulse will be lower than the mean frequency of the transmitted pulse: the mean frequency has been shifted down by the relative disappearance of the higher frequency components. And the more the attenuation, the larger the frequency down shift.

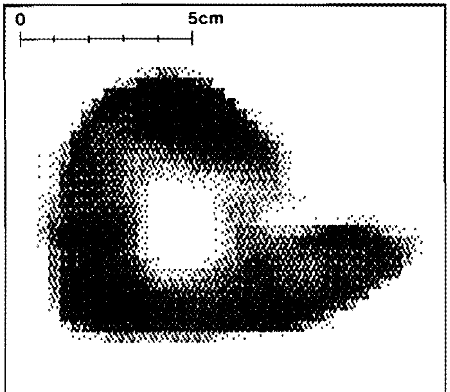
This frequency down shift can be obtained from the time interval between two successive zero crossings within each received sound pulse. This measurement is done together with measuring the time-of-flight of the pulses and the obtained zero



3. An ultrasound pulse



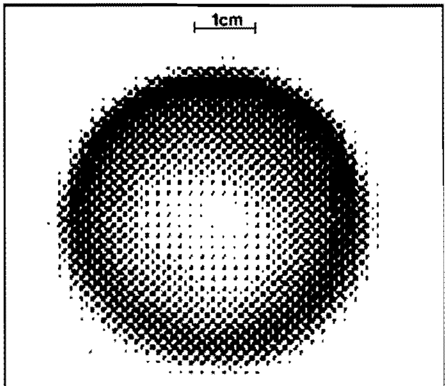
4. Image of the heart of a pig



5. Image of a pig's kidney

crossing intervals are also stored on floppy disc. The reconstruction program then retrieves both sets of data in order to reconstruct two images.

Since the time-of-flight is measured as the mean value of at least 200 periods of the reverberation, the time-of-flight can be measured with

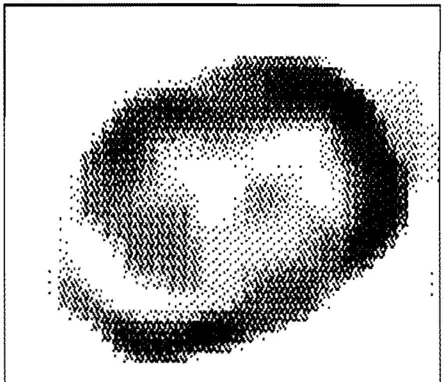


6. Image of a soft-boiled egg

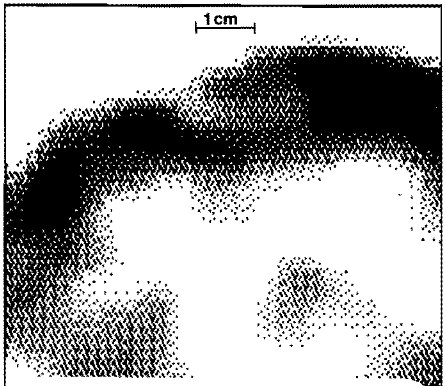
a relative accuracy of 0.01% (that is 10 ns on a mean time-of-flight of 100 μs).
The differential accuracy in the frequency down shift, which is measured over the same 200 periods, is about 300 Hz.
As far as the spatial resolution is concerned, the axial resolution is about 1 mm, the lateral resolution depends on the beam diameter and is actually 3 to 4 mm. By the reconstruction process these resolutions are transformed into an isotropic over-all resolution of about 2 mm.

Till now, measurements with this apparatus have been carried out on organs in vitro, such as pig's hearts, kidneys and livers and on a phantom (figs. 4 to 9). This phantom is a cylinder made of agar-agar with cylindrical holes of different diameters, into which narrowly fitting inserts can be put. These inserts are made of agar-agar to which propanol has been added to change the sound velocity. As the relation between the propanol concentration and the sound velocity is accurately known, the use of this phantom enables quantitative measurements.
Fig. 9 shows an ultrasound image of the phantom. The smallest insert visible is 2 mm wide. Fig. 7 and 8 show images of a pig's heart. In these images the ventricles can clearly be recognized. In Fig. 5 a pig's kidney image shows the pelvis and the ureter.

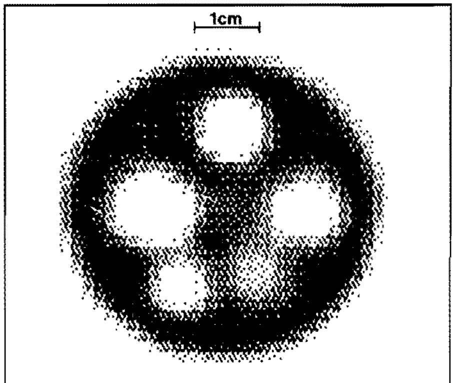
The results obtained so far are promising. The calculated limits of the resolution can be approached rather closely and the set-up is indeed very simple and consists of relatively few components. The results show that a personal computer



7. Another image of a pig's heart



8. Close-up image of a pig's heart



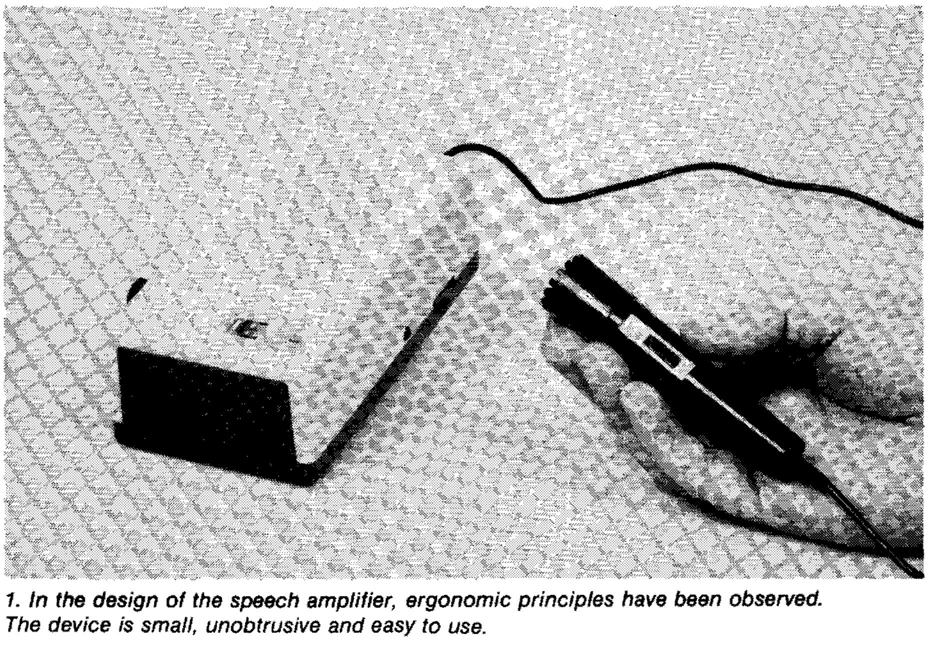
9. Ultrasound image of the phantom

can readily be used to perform both the measurements and the image reconstruction in a accurate way and in a reasonable period of time. The results also demonstrate the feasibility of this set-up to be developed into a clinically useful and low-cost apparatus. This apparatus may be especially useful in mammography because of the high velocity contrast of malignant breast tumors.

A problem that is presently being studied is the imaging of specimens containing bone, in view of imaging pathological structures in the extremities. Bone is a difficult material to image because of its high absorption and its high reflectivity.
Another actual problem is whether filtered back projection - within the constraints imposed by the demand for simplicity - indeed is the best method for performing the reconstruction.

Instrumentation for the disabled

The design and development of equipment for the disabled in the Department of Electrical Engineering was started in 1968. The aim is the development of special new appliances and the adaptation of existing electrical and electronic equipment in order to facilitate communication between the disabled and their environment; communication is to be understood in a wide sense, as the examples will show. This type of research often depends highly on the application. The request that leads to the start of a project usually originates from a disabled person himself or from the nursing staff that cares for such persons, from the physician who treats such patients, or from a rehabilitation center. Such an individual request often serves as a pointer to a problem of a more general nature in need of a solution. When a project has reached the stage at which a well defined solution is obtained, every effort is made to rouse industrial interests, so that as many disabled persons as possible can profit from the research results. This means that usually solutions in the form of a prototype are required, on the basis of which a trial production run can be scheduled for evaluation purposes.
The specialization of the project

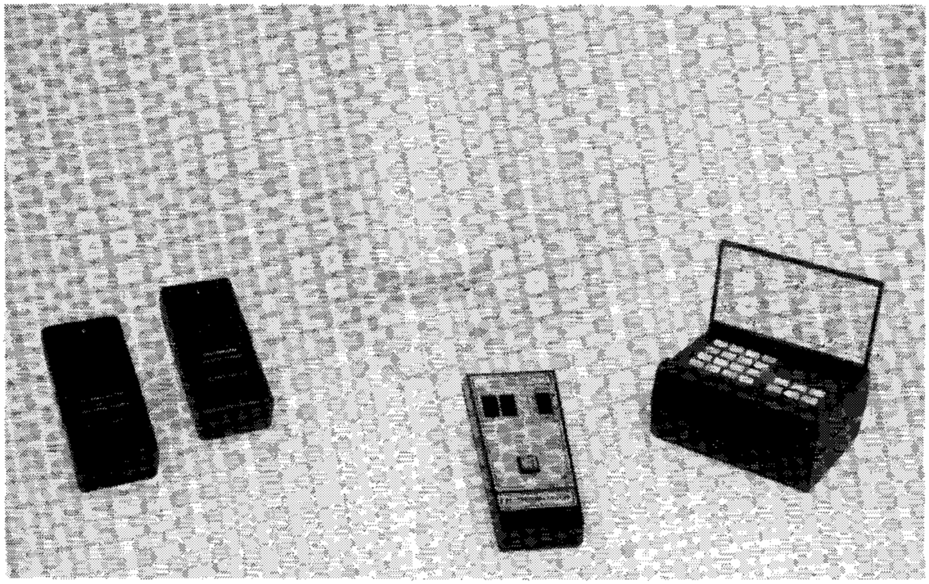


1. In the design of the speech amplifier, ergonomic principles have been observed. The device is small, unobtrusive and easy to use.

group 'Instrumentation for the Disabled' in equipment with communication aspects, has initiated a cooperation with the Institute for Perception Research (IPO), resulting, in 1984, in the interdepartmental working group 'Communication Aids for the Disabled'. We also participate in the working group 'Rehabilitation of Persons with Motor Disabilities' of the Ministry of Health, in two user committees of the Technical Science Foundation and in a concerted action of the European Community.

A number of earlier and current projects of both our group and the interdepartmental working group are described below.

Speech amplifier
A laryngectomee, a person whose larynx has been surgically removed, can only 'talk' to people by first swallowing some air and then again expelling it while moving his oesophagus, as an imitation of the normal speech process. After a lengthy period of training this can be fairly successful in a quiet environment. Problems arise when such people need more 'voice volume'. Their air reserves are then quickly exhausted and they soon tire, with the frequent result that they stop trying to talk and lapse into isolation. A small speech amplifier was produced for a patient in Eindhoven and it worked well, as the enthusiastic reactions of doctors treating such patients indicate. It is a simple, relatively cheap device, which is now commercially produced and has been selling well for some time.



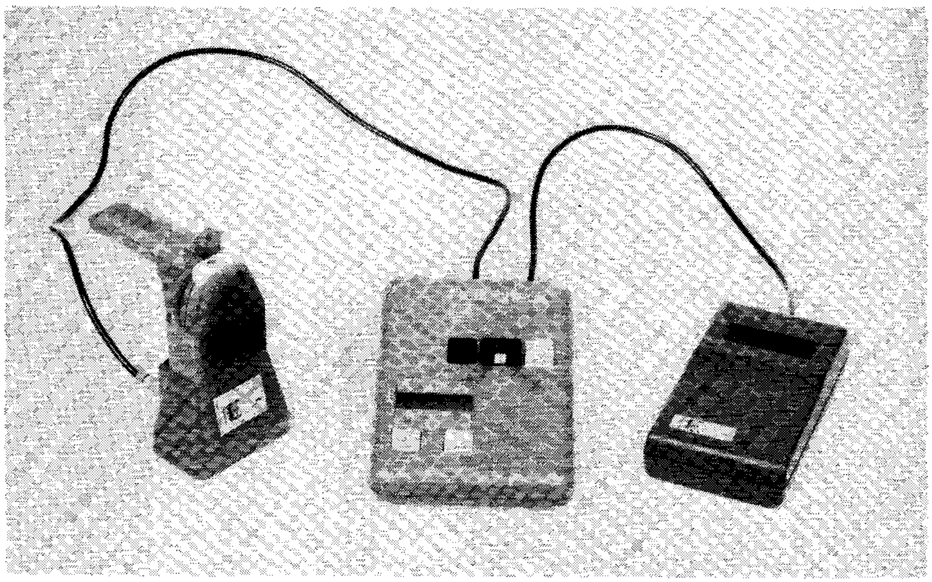
2. The monoselector remote control system can be used to operate a total of 16 devices, such as bidirectional motors, switches and dimmers.

Monoselector
This is an adapted, highly flexible, wireless remote control system that allows the severely physically disabled to operate a total of 16 appliances with a single button, the type of which can be chosen depending on the disability. Actions such as opening and closing curtains, operating radio and TV receivers, dimming lamps or switching them on and off, can be performed without the help of others, even by patients confined to bed. The monoselector has been successfully marketed since its introduction at the Hannover Trade Fair in 1987.

Reflotalk
Blindness is one of the most dreaded late complications of diabetes. In the Netherlands there are half a million diabetics, 100,000 of whom are insulin-dependent. Of these, 10,000 are visually disabled. The Reflotalk has been developed to enable them to determine their blood-glucose content and thus their required dose of insulin by themselves. A drop of blood is

drawn by means of a specially adapted device and placed on a strip, which is introduced into a glucose meter. The Reflotalk pronounces all relevant calibration information and the blood glucose values using a speech chip.

Speaking elevator indicator
The speaking elevator indicator for the blind, also called the 'micro-piccolo', consists of a microprocessor and a speech chip. When the elevator buttons are operated, it tells whether the elevator is out of order, what floor one is going to, and, when the doors open, on which floor one has just arrived.



3. The adapted blood-glucose meter consists of three parts: a hypodermic syringe device (left), the glucose meter (center) and the speech part (right).

Speech recognition
Research into the possibility of producing a cheap speech recognizer has started. The incorporation of such a device into aids for those disabled who are deprived of most of their motor functions but still are able to speak, would allow speech to operate any type of electrical equipment in the patient's environment. Earlier research has shown that this is both possible and worthwhile. Price and bulk of existing speech-recognition systems have thus far prevented their application in this field.

Pocket Voice
This is a user-friendly communication device for persons suffering from temporary or permanent loss of speech. With this aid, the user can have the device pronounce any one of 28 messages of his or her own choice at the press of a button. Five Pocket Voice prototypes have recently been evaluated in practical situations, so that the effectiveness and acceptance of its synthetic speech can be determined.

Speaking Kitchen Scales
Research has started on the applicability of synthetic speech to electronic kitchen scales for the blind and those with very poor eyesight. In our laboratory, such scales have already been designed and tested; efforts are made to develop a production prototype for evaluation by potential users.

Typophone
This device, for blind and severely visually disabled typists, pronounces the characters after operation of the corresponding typewriter keys. It also has a memory for a few lines of text. The design of the typophone is now being finalized and adapted for production. Negotiations with a number of manufacturers have started.

Relations and Collaborations

The Division of Medical Electrical Engineering (EME) maintains contacts with a number of universities, research institutes and industries, as a fundamental necessity for its activities. In addition, this offers some students the opportunity to do their research projects outside the division.
The Division EME participates in the Biomedical and Health Care Technology (BMT) Committee of the EUT which initiates and coordinates many biomedical engineering activities.
A very close collaboration exists with the Department of Anesthesiology of the College of Medicine, University of Florida, Gainesville; dr. Beneken is also Adjunct Professor in this Department. Mutual exchanges of coworkers and students occur regularly.
In cooperation between the Catholic University Brabant (Tilburg) and the Eindhoven University of Technology, a study is being performed on 'the elimination of eye movement artifacts from the electroencephalogram'. This study is a Ph.D. project.
Further academic contacts are maintained with the State University of Limburg at Maastricht, the Catholic University at Nijmegen, the Erasmus University at Rotterdam, the University Hospital at Antwerp, Belgium and the Institute for Rehabilitation Research at Hoensbroek.
The position of dr. Beneken as chairman of the Concerted Actions Committee on Biomedical Engineering of the European Community yields a wide view of the field and provides easy access to various research institutes.

Lectures

Measurements in Medicine I
This series of lectures explains some of the measurements that are commonly used in medical practice as well as their underlying physiological mechanisms. Only those measurements are dealt with that are related to bio-electrical phenomena. Topics: physiology and properties of the cell; excitation of membranes of nerve and muscle cells; nerves as information channels; the receptor mechanism; transmission of impulses; volume conductor fields; electrodes; electrocardiogram, electroencephalogram, electromyogram; electro-medical safety.

Measurements in Medicine II
This series of lectures also explains some measurements that are commonly used in medical practice as well as their underlying physiological mechanisms. Now those measurements that are not directly connected with bio-electrical phenomena are dealt with. Topics: physiology and measurements of the respiratory system: pulmonary mechanics, tests of pulmonary function, respiratory gas analysis; physiology and measurements of the circulatory system: blood pressure, blood volume and blood velocity; medical imaging systems: theory and applications; patient monitoring: measurements and measuring systems, decision making, therapeutic devices, applications.

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