TRANSVERSE DIMENSIONAL CHANGES FOLLOWING RAPID MAXILLARY EXPANSION

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ABSTRACT

RAPID MAXILLARY EXPANSION has been advocated for the treatment of a narrow maxillary dental arch for over a hundred years. Early investigators found that the effects of maxillary expansion were not confined to the dental complex but also affected craniofacial morphology including the nasal cavity. The purpose of this study was to determine the effects of RME on skeletal, dental and nasal structures in a transverse plane and to relate these changes to nasal cavity function as determined by nasal airway resistance measurements. Twenty-five subjects exhibiting transverse maxillary dental deficiency were compared with 25 age and sex match controls. A number of skeletal, dental and nasal transverse widths and area measurements were selected and subjected to method error analysis. A nasal template was developed that allowed measurement of linear transverse widths and areas within the nasal cavity at different levels. As a result, six skeletal, five dental and seven nasal transverse widths and two nasal cavity area variables were measured and compared between the control group and the anomaly group before and after expansion with RME. Results indicate that there was little difference between the anomaly and control groups before treatment with the exception of maxillary skeletal and dental narrowness. Expansion using RME resulted in increased upper molar width, maxillary width, nasal cavity width and separation of the anterior nasal spine; however all patients did not respond uniformly. Whereas some patients demonstrated large increases in maxillary width, others experienced only moderate or little change. These differences may be related to the degree of ossification of the median palatine suture and to other aspects of maxillofacial maturity. Intranasal changes as a result of RME were restricted generally to the lower half of the nasal cavity and were highly variable, as were changes in nasal airway resistance. Ten patients experienced improvements in either anterior NAR, posterior NAR or both. Six patients had little or no change in either resistance and only three patients experienced increases in both anterior and posterior NAR. Maxillary dental transverse deficiency was successfully treated in all cases at the end of the retention period. Rapid maxillary expansion resulted in separation of the anterior nasal spine in all cases although the extent of separation of the median palatine suture was highly individual.

As a result of this study it would appear that rapid maxillary expansion is ideally suited to young patients with maxillary skeletal or dental narrowness who have increased anterior nasal airway resistance. Clinically it may be possible to identify those patients most likely to benefit from rapid maxillary expansion by utilising a simple clinical or cephalometric measurement.

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Declaration

I declare that this thesis has been composed by myself and that the work described is my own.

LIST OF ABBREVIATIONS

A	area
A50	cross-sectional area of the lower half of the nasal cavity
CRL	cranial reference line
CT	computed tomography
d	density of air
ERR	external root resorption
gm	grammes
k_1	laminar flow
k_2	turbulent flow
l	litre
lbs	pounds
m	month
mm	millimetres
MR_I	magnetic resonance imaging
MS_1	maxillary subgroup 1
MS_2	maxillary subgroup 2
NAI	nasal airway index
NAR	nasal airway resistance
ns	not significant
NS_1	nasal subgroup 1
NS_2	nasal subgroup 2

onp	open nasal passages
p	significance
Pa	pascals
PA	postero-anterior
po	partial obstruction of nasal passages
r	radius
RME	rapid maxillary expansion
s	second
s(i)	method error
s(i)%	percentage method error
sd	standard deviation
T	turbulent component
to	total obstruction of nasal passages
URTI	upper respiratory tract infection
$\dot{V}$	flow
y	year

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CHAPTER 1

LITERATURE REVIEW

1.1 GENERAL COMMENTS ON EXPANSION

There are a number of methods available to expand the maxillary dental arch. However there are two methods in current use which can expand the maxillary skeletal base which are distinguished by the speed or rate of expansion.

Slow Maxillary Expansion

A Quadhelix appliance can produce slow maxillary expansion over a period of 2-6 months (Rickets, 1975). Comparatively gentle forces are generated and can cause limited separation of the median palatine suture in deciduous and mixed dentitions. The rate of expansion using this technique has been estimated at 0.4-1.1mm per week and can result in an increase in intermolar width of up to 10mm (Bishara and Staley, 1987; Ladner and Muhl, 1995). Supporters of slow maxillary expansion believe that the gentler forces result in less post-expansion relapse compared with rapid maxillary expansion (Bell, 1982).

Rapid Maxillary Expansion (RME)

Rapid Maxillary Expansion is normally completed within 1-4 weeks and uses relatively large forces over a short period of time to separate the median palatine suture. The appliance is secured to the posterior maxillary teeth and expansion is achieved by a midline expansion screw. The screw is turned between one and two turns a day and produces a rate of expansion of between 0.2-0.5 mm per day and can result in an increase of intermolar width of 10 mm or more (Bishara and Staley, 1987). Proponents of RME maintain that the high rate of expansion is necessary to limit tipping of anchor teeth and therefore maximise skeletal movements. This thesis is concerned with the effects of rapid maxillary expansion.

1.2 HISTORY OF RAPID MAXILLARY EXPANSION

RAPID MAXILLARY EXPANSION (RME) is a technique that utilises relatively large forces over a short period of time across the median palatine suture in order to cause separation of the maxillae. This technique has a long history and was first reported by E H Angell in 1860 who used a reciprocal jackscrew attached to premolars as a method of expanding the upper arch. However although the procedure and results described by Angell strongly suggest that RME had been carried out successfully and effectively the paper was reviewed with scepticism and disbelief (Bennett, 1914a; Haas, 1961). Despite this initial response the procedure was reported by a variety of workers with varying results in the late 1880s to 1910 (Haas, 1961). There were a number of appliance designs and screws available around this time for expansion of both the maxilla and mandible. For example the Coffin spring, Badcock screw, Reid screw, Highton device and Schelling's modification of the Coffin plate, in addition to the jackscrew used by Angell (Bennett, 1914b).

In 1886 Eysel advocated expansion of the dental arch as a means of improving nasal respiration, however it was not until the early years of this century that Brown described a case where nasal blockage was relieved by RME (Timms, 1974; 1986). In 1903 Brown claimed that opening the median palatine suture would increase nasal permeability by straightening a deviated septum and provide relief of hypertrophied nasal tissue (Wertz, 1968). This view was supported by Pfaff (1905) who said that expansion of the dental arch resulted in a lowering of the palatal vault and straightening of the nasal septum which in turn moved away from the turbinate bones and therefore permitted increased air volume.

However RME was not without its opponents. In 1904 Schroeder reported the results of a small clinical trial and did not observe improvement in nasal permeability due to maxillary expansion (Timms, 1986). Indeed early opponents to the technique were concerned that the nasal benefits were small or unproven and believed it to be either anatomically impossible to separate the maxillae or too dangerous to attempt (Haas, 1965). It would appear that the long-running debate by Orthodontists and Rhinologists on the benefits of RME at the early part of this century together with indifference to the technique from notable Orthodontists of the time contributed to its demise between 1910 and 1930 (Haas 1961, 1965).

In 1929 Mesnard reported that separation of the maxillae using fixed appliances was accompanied by lowering of the palatal vault and floor of the nose, straightening of the nasal septum and improvement in nasal permeability. Further to suture opening, new osteofibrous tissue was observed radiographically to appear between four and six weeks after expansion.

However, it was not until the 1950s that interest in RME was rekindled when a number of workers including Korkhaus (1953), Derichsweiler (1953) and Gerlach (1956) reported improvements in nasal respiration in addition to increases in maxillary apical base due to expansion (Wertz, 1968). Krebbs (1958) used metallic implants to demonstrate the rotation of the maxilla laterally and increased nasal cavity width following rapid maxillary expansion. In 1961 Haas described a fixed split plate appliance fabricated by a direct/indirect technique. The appliance was constructed with an acrylic baseplate and a midline expansion screw. Connecting bars were soldered to the buccal and palatal surface of each pair of bands. This appliance was later modified by Wertz in 1970 who left the connecting bars out of the appliance design. Haas (1961) reported the results from a small animal study and a clinical trial of rapid maxillary expansion. This paper provided evidence for changes in the maxilla and mandible in addition to expansion observed in the nasal cavity. This work was followed up by Haas in 1965 when he reported results from more completed cases and advised that close attention should be paid to appliance design, in particular a rigid appliance was regarded as essential for successful rapid maxillary expansion. Debbane (1958) reported the radiographic and histological changes at the median palatine suture due to expansion in an animal study of cats. While increases in intercuspal widths were found the maximum opening of the suture was only 0.7 mm. This seemed to confirm earlier findings that the hard palates of carnivorous animals are adapted to withstand lateral pressure and are generally not a suitable model in which to study effects of rapid maxillary expansion. In addition to Haas, a number of successful animal studies were reported in the 1960s. These studies used monkeys and were concerned with the histological events at the median palatine suture following separation (Starnbach and Cleall, 1964; Cleall *et al.*, 1965). In contrast to cats and dogs, pigs and monkeys appear to be good animal models with which to study rapid maxillary expansion.

In a series of papers in the 1960s Isaacson and coworkers studied the forces produced in rapid opening of the suture (Isaacson *et al.*, 1964; Zimring and Isaacson, 1965). They estimated that the force produced by a single turn of the jackscrew in a Haas type of appliance were between 3 and 10 lbs. Grossman (1963) advocated the use of silver copper alloy cast cap splints for rapid maxillary expansion. In 1974 Timms endorsed the use of these as a rigid high anchorage appliance which consisted of cast cap splints extending from the molars to cover as far forward as the lateral incisors. The base of the appliance was composed of acrylic and a Glenross Mark VI screw used for expansion. Bonded full coverage appliances have been described (Mondro, 1977; Howe, 1982; Spolyar, 1984). Recently Sarver and Johnston (1989) advocated the use of bonded rapid palatal expansion appliances. These were constructed mainly of acrylic and bonded to the occlusal surface of the maxillary premolars and molars. These authors claim that the 2-3 mm of coverage of the maxillary posterior teeth results in intrusive force on the maxilla and mandible to limit vertical changes seen in other RME appliances. This view is supported by Asanza *et al.* (1997) who compared Hyrax and bonded expansion appliances and found that interocclusal acrylic on bonded appliances help control vertical relationships.

There have been attempts recently to construct an RME appliance of a similar design to the cast cap splint but fabricated in clear acrylic. This appliance covers the occlusal surface of the maxillary molars and premolars and is connected by an expansion screw in the midline. There are obvious aesthetics advantages however full evaluation of this appliance is ongoing at present (McDonald, unpublished).

1.2.1 Alternative Appliances Advocated for Maxillary Expansion

Removal Expansion Plates

As stated above there have been a large number of expansion plates advocated for both maxillary and mandibular expansion. The most common appliance used for orthodontic expansion of the maxillary dental arch today is an upper removable appliance with a midline expansion screw. Although limited separation of the median palatine suture has been recorded with removable appliances (Skieller, 1964; Ivanovski, 1985) these are generally not effective for RME because of the lack of rigidity (Zimring and Isaacson, 1965). These appliances offer little resistance to rotation of the maxillary teeth which tilt buccally and limit any skeletal effect.

Quadhelix

In 1975 Ricketts described the quadhelix appliance which was a modification of an earlier expansion design. This is less rigid than a typical RME design and works more slowly using forces estimated to be between 0.5 and 2.5 lbs (221 - 1149 gm). This is used mainly to expand the maxillary dental arch although there are some reports of separation of the median palatine suture (Ladner and Muhl, 1995). However expansion across the maxillary molars is thought to result mainly from buccal tipping and rotation of molar teeth (Herold, 1989). Indeed Hicks (1978) has reported maxillary molar tipping between 1.5° and 24° using this slow expansion technique.

Biederman, Derichsweiler and Hyrax appliances

These appliances are attached by bands to the first permanent molars and premolars and are connected in the midline by an expansion screw. The Biederman and Hyrax appliances have no acrylic baseplate contacting the palate and therefore cause less irritation to the palatal tissues. Biederman RME appliances have been connected with marked buccal root resorption of the first premolars during expansion (Barber and Sim, 1981; Langford, 1982; Odenrich *et al.*, 1982). When active expansion is discontinued these defects are thought to undergo repair.

Jackscrew

Gray (1977) reported a large number of cases treated with a simple jackscrew soldered to bands on the posterior teeth. A total of 310 cases were presented aged between 4 and 24 years. He advocated the technique for a wide range of nasal and respiratory complaints.

Minne-Expander

The Minne-expander is available from Ormco and is soldered to bands on the abuttment teeth. This is a heavy caliber coil spring expanded by turning a central nut which compresses the coil producing a continuous force for expansion. Forces are kept low, typically in the region of 2 lbs to produce slow maxillary expansion.

Magnetic Expansion Device

Darendalilier *et al.* (1994) reported preliminary results using a device to generate 250 - 500g of continuous magnetic force and found some evidence of dental and skeletal expansion in six patients

1.2.2 Summary

The technique of maxillary expansion has a long history. A number of appliance designs have been proposed however there are common features that apply to the design of appliances that appear to be more successful in the technique of RME. These are:

1. Rigidity

   This is considered a vital property of a successful RME appliance (Haas, 1965; Timms, 1974). A rigid appliance will transmit the forces generated by an expansion screw efficiently on to the maxillae and limit the degree of tipping of the skeletal components. A rigid appliance is also considered vital during retention to allow residual forces to dissipate and limit relapse (Zimring and Isaacson, 1965).

2. Occlusal and palatal coverage:

   Timms (1974) believes that as many teeth as possible should be included in the appliance for successful seperation of the suture. He advocates a cast cap splint design which limits the degree of buccal tipping and removes occlusal interference during expansion. Alpern and Yurosko (1987) proposed a rapid palatal expansion appliance with bite planes for use in adults. Hass (1961) endorsed the use of palatal coverage in appliance design to ensure that the forces generated were transmitted directly onto the maxillae to aid seperation. He also believed that as a result of direct pressure on to the palatal vault remodelling of the bone in this area took place (Haas, 1980).

3. Expansion screw design:

   Expansion screws come in a variety of sizes and design, the most common are Hyrax, Glenross VI or Leone 620 which have been calculated to give between 11 and 18 mm of expansion. Other screw designs have been tried including a springloaded screw or Mini-Expander (see above).

4. Comfort:

   Biederman and Hyrax appliances and the bonded expander do not advocate palatal coverage and are connected only to the maxillary teeth. These appliances do not have the disadvantages of palatal inflamation and difficulty in maintaining oral hygiene that can be associated with other designs.

1.3 ANATOMY AND PHYSIOLOGY OF THE FACIAL SKELETON AND NASAL CAVITY

The sources for the description of the anatomical relations of the facial skeleton and nasal cavity which follow are; Johnson and Moore (1985); Cunningham's Manual of Practical Anatomy, Volume 3 (1978) and Gray's Anatomy (1958).

1.3.1 Facial Skeleton

Upper facial skeleton is comprised of the upper jaw (maxillae) and the bony framework around the nasal and orbital cavities. The facial bones are derived from the dermal shield and palate of primitive vertebrae and ossify in membrane, with the exception of the ethmoid bone and inferior conchae, which ossify in the cartilage of the nasal capsule. The joints between the dermal bones are fibrous.

1.3.1.1 Maxillae

The upper jaw is made up of a left and right maxilla each comprising of a body and four processes (Figure 1). The body is roughly pyramidal and its interior is hollow containing the maxillary paranasal air sinus. The relations of the maxillae are as follows; superiorly the maxilla forms part of the floor of the nose while medially it contributes to the lateral wall of the nasal cavity (see below). The maxilla contributes laterally to the zygoma and infratemporal fossa and anteriorly it forms the infra-orbital area of the middle third and contributes to the anterior nasal aperture and anterior nasal spine. Inferiorly it forms the anterior three-quarters of the bony hard palate and posteriorly forms the anterior wall of the pterygo-maxillary fissure.

The four processes are: the frontal process which projects upwards to articulate with the frontal bone and contributes to the medial wall of the orbit, lateral wall of nose and bridge of nose, the zygomatic process which projects laterally from the body to articulate with the zygomatic process on the squamous part of the temporal bone and forms the anterior part of the zygomatic arch, the alveolar process which projects downwards along the length of the maxilla and contains the sockets or alveoli for the roots of the upper teeth, to end posteriorly at the maxillary tuberosity and the palatine process which projects medially to articulate with its partner from the opposite side at the median palatine suture. These two processes form the anterior three-quarters of the bony palate.

Figure 1 Frontal View of Human Skull

1.3.1.2 Palatine bone

The horizontal plate of the palatine bone articulates with its partner from the opposite side to produce the posterior one-quarter of the bony palate. Anteriorly they articulate with the maxillae and posteriorly with the lateral pterygoid plates at the pyramidal process of the palatine bones. They both contribute to the posterior nasal spine (PNS) which is a median bony projection from the hard palate.

1.3.1.3 Pterygoid plates

The medial and lateral pterygoid plates are fused anteriorly from the pterygoid process of the sphenoid and diverge posteriorly to enclose the pterygoid fossa. A small projection, called the hamulus, projects down from the medial pterygoid plate and is palpable in the mouth. The pterygoid process of the sphenoid articulates with the perpendicular plate of the palatine bone anteriorly.

1.3.1.4 Sutures

The maxilla and facial bones comprising the middle third of face articulate with each other at intermaxillary sutures. The left and right maxillae, together with the left and right horizontal process of the palatine bones, articulate in the midline at the median palatine suture. The articulation of the palatine bones with the maxillae occur at the transverse palatine suture (Figure 2).

Figure 2 Palatal View of Maxillae

1.3.1.5 Development of median palatine suture

By using material from cadavers Melsen (1975) reported the development of the median palatine suture from birth to early adulthood. In transverse section the shape of the suture formed by the articulation of the palatine process of the maxilla and the vomer was found to change with time. In infancy the suture was found to be broad and Y-shaped with the vomerine bone lodged in a furrow between the maxillae. In juveniles the suture was larger and more sinuous so that by adolescence the course of the suture was very tortuous with the palatine processes of the maxillae interdigitated. Persson and Thilander (1977) also examined material from cadavers to investigate the time and rate of ossification of the suture. These workers were looking for signs of synostosis of the median palatine and transverse palatine sutures of 24 patients aged between 15 and 35 years. They found great variations with respect to commencement and advance of closure of the median palatine suture. In this study the earliest closure was reported in a 15 year old female, and the oldest unossified suture occurred in a 27 year old female. However they reported that marked degree of closure was not usually found until the third decade of life. These workers agreed with Davida (1926) that ossification of the suture appears to start in the posterior aspect first and proceed forwards (Persson and Thilander, 1977). They were also in agreement with Isaacson *et al.* (1964) and Wertz (1970) that most of the resistance to RME was due to circum-maxillary structures.

1.3.2 Nasal Cavity

The nasal cavity is described as an irregularly shaped cavity between the bony palate and floor of the anterior cranial fossa. Superiorly it is situated between the orbits and inferiorly the lateral boundaries are formed principally by the maxillae. It is divided into right and left halves by the nasal septum which is formed by a contribution of cartilage anteriorly and bone from the perpendicular plate of ethmoid superiorly and the vomer posteriorly. The roof of the nasal cavity is formed by the nasal bones, cribriform plate of ethmoid and body of sphenoid. The floor of the nasal cavity is composed of the palatine process of the maxillae anteriorly and the horizontal plate of the palatine bones posteriorly. The lateral wall of the nasal cavity is irregular. Generally the maxilla forms the anterior and inferior parts, the palatine bone the posterior part and the ethmoidal labyrinth the superior aspect of the lateral wall. The nasal and lacrimal bones provide a small contribution to the anterosuperior part of the lateral wall.

1.3.2.1 Conchae

The inferior concha projects into the nasal cavity and is articulated with the maxilla and palatine bone appearing like a scroll-like plate of bone. The superior and middle nasal conchae project from the median plate of the ethmoidal labyrinth into the nasal cavity. These conchae incompletely divide the nasal cavity into three passages or meatus. The superior meatus is between the superior and middle conchae, the middle meatus is between the middle and inferior conchae and the inferior meatus between the inferior conchae and the palate. There are a number of structures that open into the lateral wall of the nose: sphenoidal air sinus into the spheno-ethmoidal recess, posterior ethmoidal air cells into the superior meatus, frontomaxillary anterior middle ethmoidal air cells into the middle meatus, nasolacrimal canal into the inferior meatus.

1.3.2.2 Soft tissues

The nasal cavity extends from the external nostrils to the posterior nasal apertures which open into the nasopharynx. The nasal vestibule is the area just inside the external nostrils and is lined with keratinised squamous epithelium. The remainder of the nasal cavity is lined by either olfactory or respiratory mucous membrane. Olfactory mucous membrane covers the roof and the superior aspect of the septum and lateral walls of the nasal cavity down to the superior conchae. This is a specialised mucous membrane which includes thick olfactory epithelium for the olfactory sense. Respiratory mucous membrane covers the remainder of the nasal mucosa and may be described as pseudostratified columnar ciliated epithelium with goblet cells. There are numerous serous and mucous glands associated with epithelium together with extensive areas of vascular cavernous tissue. This vascular tissue is particularly developed over the conchae and is thought to be important in warming inspired air and may be involved in host defence (see below).

1.3.2.3 Normal airflow and nasal physiology

Both the nasal and oral cavities can serve as pathways for respiratory air. Nasal breathing is physiologically normal and the mouth is usually closed during inspiration and expiration (Warren, 1979). Airflow within the nasal cavity is believed to pass through the superior and middle meati at rest, with the inferior meatus only utilised during forced respiration (Wertz, 1968).

Nasal breathing allows the inhaled air to be warmed and humidified, while filtering particulate matter. In addition, nasal breathing is thought to influence the physiology of the lower airway and lungs (Koufman, 1990). The vascular tissue of the turbinates warms and humidifies the inhaled air while the mucociliary transport mechanism entraps airbourne contaminants such as bacteria, viruses and other particulate matter, and carries them posteriorly. Here they are either swallowed or encounter the aggregations of lymphoid tissue on the posterior nasopharyngeal wall, or adenoids, and elicit an immune response.

The turbinates take part in a spontaneous congestion-decongestion reflex called the nasal cycle. This consists of periodic congestion of the nasal venous sinusoids on one side of the nasal cavity with decongestion and shrinkage of these structures on the contralateral side. The cycle continues by reversing this pattern time and again over a period of several hours (Hasegawa and Kern, 1977, 1978). It has been recently appreciated that the nasal cycle may provide a pump mechanism for the generation of plasma exudate which plays an important role in respiratory defence (Eccles, 1996).

The oral cavity may be used in the short term as the primary route for respiratory air if demand for oxygen increases beyond a threshold limit, for example during muscular effort. Alternatively the oral cavity can become established as the predominant route due to habit or nasal obstruction (see below). It is important to note that there exists a spectrum of methods of respiration from nasal, predominantly nasal, mixed, predominantly mixed to oral (Warren *et al.*, 1990). Furthermore, the predominant mode of respiration will probably change with time in some individuals.

1.3.2.4 Causes of nasal obstruction

Koufman (1990) classifies the causes of nasal obstruction as mucosal abnormalities, anatomical or structural abnormalities and lesions. The mucosal abnormalities include; URTI, allergic rhinitis, rhinitis medicamentosa and granulomatous disease. Anatomical and structural abnormalities include; nasal septal deviation, congenital or traumatic nasal deformity, choanal atresia and foreign body. The third group includes benign conditions such as allergic polyps, adenoidal hypertrophy, antral-choanal polyp and juvenile nasopharyngeal angiofibroma. Malignant lesions that can be responsible for nasal obstruction include rhabdomyosarcoma, squamous cell carcinoma, lymphoepithelioma and lymphoma.

Lateral and PA cephalometric radiographs will often reveal some of these conditions and it is imperative to examine routine films for signs of pathology. Linder-Aronson and coworkers (1970, 1974, 1979), and Schulhof (1978) have demonstrated the use of lateral cephalometric radiographs to diagnose adenoidal enlargement and blockage of the posterior nasopharyx. However these workers recommended that before a diagnosis of nasal obstruction is made a clinical examination of the nasal cavity should also be undertaken.

1.3.2.5. Nasal obstruction and general health

Although the effects of chronic nasal obstruction on general health have been appreciated for many years it is only relatively recently that the potential consequences of chronic obstruction have been fully realised (Bluestone, 1979; Sofer *et al.*, 1988). As outlined above it may be appreciated that the obstruction may be intermittent or persistent and the degree to which the individual is affected will depend on the severity and the number of episodes of obstruction. A considerable list of effects and possible sequellae due to nasal obstruction has been compiled. Nasal obstruction may be associated with three serious complications which affect the cardiorespiratory tract (Bluestone, 1979). These are:

1. hypersomnolent obstructive sleep apnoea
2. alveolar hypoventilation
3. cor pulmonare

The pathophysiology of cor pulmonare due to upper airway obstruction has been outlined by Bluestone (1979) and Sofer *et al.* (1988). Obstruction of the nasopharynx due to adenoids or oropharynx due to tonsils leads to increased upper airway resistance and decreased ventilatory capacity and alveolar hypoventilation. This can result in pulmonary vasoconstriction in a patient with susceptible pulmonary vasculature and lead to pulmonary hypertension. Right-sided heart decompensation follows with pulmonary oedema and congestive heart failure (Figure 3). Furthermore, Koskenvuo *et al.* (1985) have demonstrated that hypersomnolent obstructive sleep apneoa can be associated with risk of hypertension and ischemic heart disease.

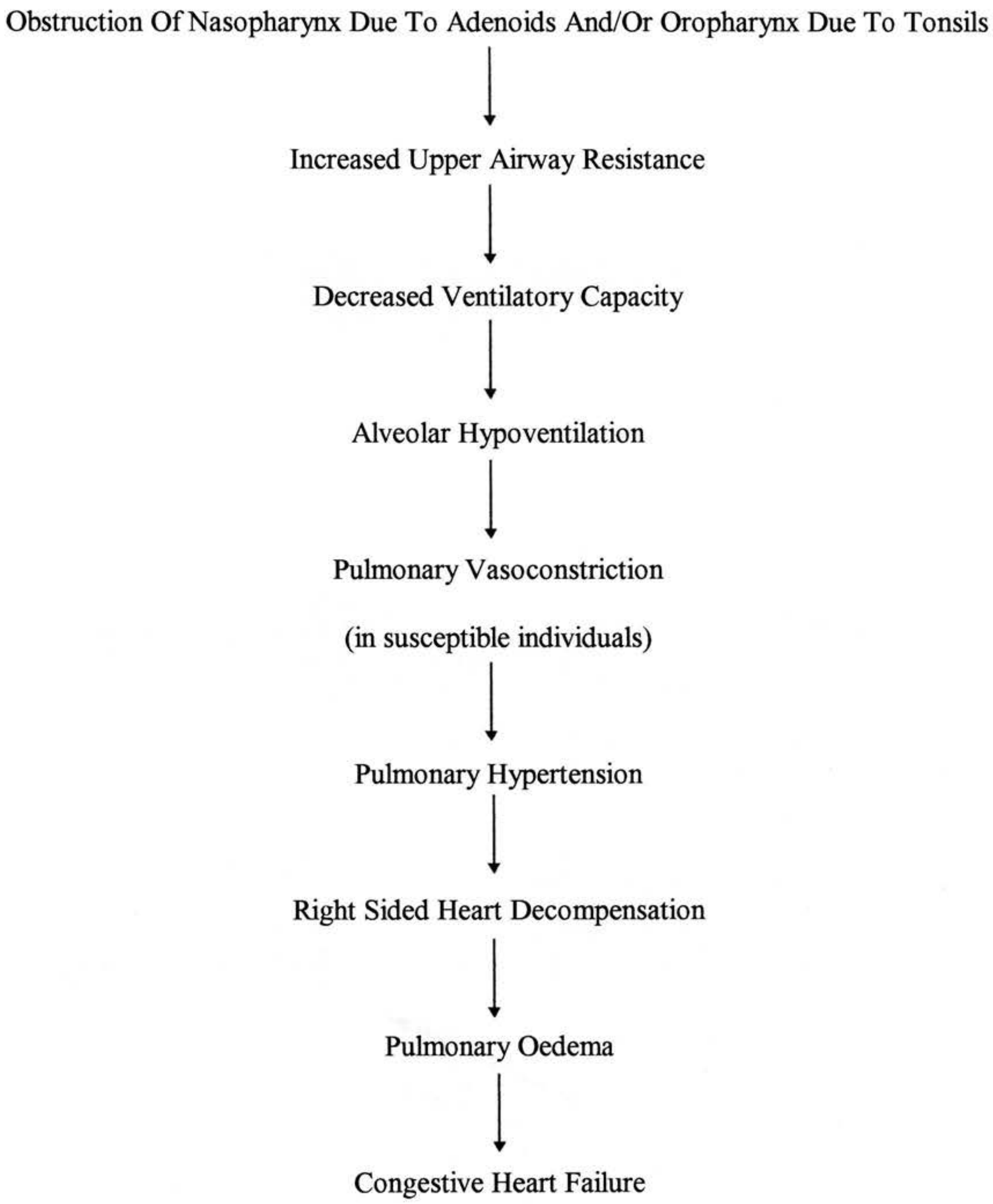


Figure 3 Nasal Obstruction and Cor Pulmonale

(after Bluestone, 1979)

However obstruction can be associated with other less severe complications or sequelae including poor pulmonary ventilation, abnormal speech, effects on cranial and dentofacial development, decreased or absent olfaction, poor general growth and development, nasal and paranasal sinus disease and middle ear disease. In addition it is believed that as a result of these factors the child may suffer from impaired cognition, language development, performance at school and psycho-social development (Bluestone, 1979). Furthermore upper airway obstruction has been recently linked with some episodes of nocturnal enuresis (Timms, 1990).

1.3.2.6 Nasal obstruction and dentofacial development

It has been appreciated for some time that nasal obstruction can be associated with a particular facial type (Bennett, 1914c). The term adenoidal facies has been used since before the turn of the century to describe the typical morphological features of a patient with chronic nasal obstruction normally attributed to enlarged adenoids (Figure 5). Classical features of adenoidal facies or long face syndrome include increased lower anterior face height, retrognathic mandible, flaccid and short upper lip, flaccid peri-oral musculature and a dull appearance due to a constant open mouth posture (Hartgervink and Vig, 1987). Intra-orally the dental features associated are proclined maxillary incisors with high V-shaped palate associated with a narrow maxillary dental arch. Several workers have suggest a strong link between nasal obstruction and dentofacial or craniofacial form (Linder-Aronson, 1970, 1974; Woodside and Linder-Aronson, 1979; Solow and Greve, 1979). In a series of papers Linder-Aronson (1970, 1974, 1975) provided some evidence for a link between dentofacial morphology and nasal respiratory obstruction due to adenoids. In 1970 he established that the presence of adenoids and mouth breathing were associated with a narrow upper arch with a tendency to crossbite, retroclined upper and lower incisors and a small sagital depth of the nasopharynx. He later demonstrated small but significant changes in all these variables towards normal values following adenoidectomy (Linder-Aronson, 1974). He proposed that these changes were due largely to a raised tongue position caused by the transition from mouth to nasal respiration. Harvold *et al.* (1973) provided further evidence of a link between mode of respiration and dentofacial form when they were able to demonstrate the development of an anterior open bite in monkeys by artificially closing off the nasal airway. Schulhof (1978) reported a case of a patient who developed a complete open bite five years after surgery to repair a submucous cleft palate. Unfortunately the surgery resulted in complete closure of the nasal airway rendering the patient an obligate mouth breather. This in turn lead to the development of a complete anterior open bite between the ages of twelve and seventeen.

Solow and Talgren (1976) suggested that in addition to altered tongue position a change in head posture may also be involved. Indeed Solow and Kreiborg (1977) proposed a hypothesis of soft tissue stretching to lead to cranio-cervical angulation and cranio-facial morphology. This involved a chain of events linking craniocervical angulation and craniofacial morphology (Figure 4). Each stage can be a point of entry triggering the cycle. Briefly, obstruction of the airway can result in altered posture via neuromuscular feedback in an attempt to improve respiratory efficiency. This may result in soft tissue stretching which produces differential forces on the skeleton and morphological changes resulting in "adenoidal facies". These changes may in turn serve to reinforce the airway obstruction.

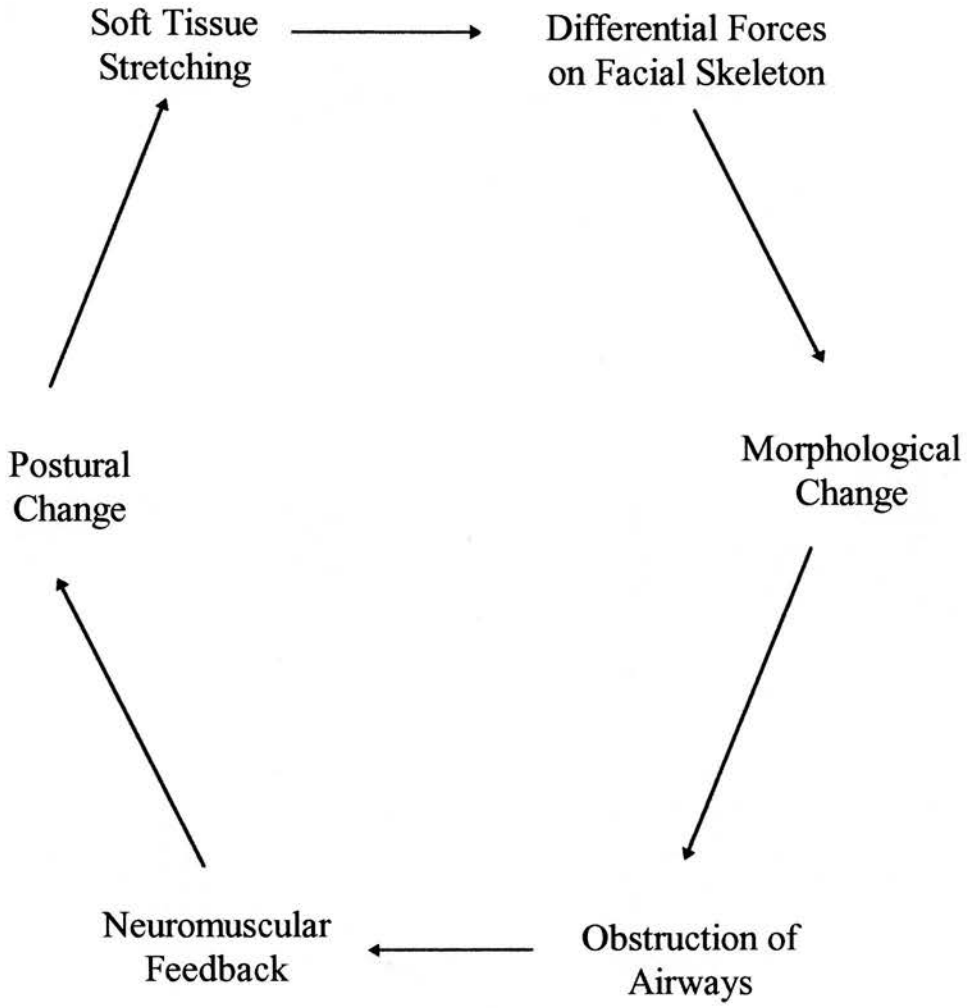


Figure 4 Craniocervical Angulation and Craniofacial Morphology

(Solow and Kreiborg, 1977)

This hypothesis was tested in a group of 24 children exhibiting obstruction of the nasopharyngeal airway due to enlarged adenoids. These children were examined before and after adenoidectomy and a reduction in the craniocervical angulation was found in children who had a reduction in nasal respiratory resistance (Solow and Greve, 1979). These authors concluded that the soft tissue stretching hypothesis had provided an explanation for the changes in craniofacial morphology seen after adenoidal nasal obstruction had been removed.

However the association between nasal obstruction and craniofacial form is not fully understood. Linder-Aronson (1970) found that only 26% of patients with adenoidal obstruction exhibited typical adenoidal facies. Indeed some workers do not believe that dentofacial growth can be influenced by respiratory mode (Vig *et al.*, 1981; Warren *et al.*, 1984). For example, Turvey *et al.* (1984) found that the majority of long-faced individuals have normal nasal resistance measurements and Hinton and Warren (1985) reported that abnormal airway pressures could not be blamed for morphological changes as they do not occur in nasally impaired individuals.

Warren *et al.* (1988) pointed out that some of this controversy may in fact originate from the definition of a mouth breather. These workers maintain that an open mouth posture does not always indicate a mouth breather and that patients who do breathe through their mouth will also breathe through their nose to some extent. Indeed, Linder Aronson (1979) notes that pure mouth breathers are in fact very rare and restricted to cases of bilateral choanal atresia or alanasi insufficiency.

In conclusion although chronic nasal obstruction itself may be a contributary cause of dentofacial features found in adenoidal facies it is unlikely to be the principal aetiological factor (Turner *et al.*, 1997). It is believed that the soft tissue features that can accompany nasal obstruction are more directly involved and can influence dentofacial morphology (Hinton and Warren, 1985). The intra-oral effects of chronic nasal obstruction have been attributed largely to the resting position of the tongue and mandible in these patients. An open mouth posture results in a lowering of the rest position of the tongue. This results in a high narrow V-shaped maxillary dental arch due to the unopposed pressure of the cheeks on the alveolar process which in turn leads to the development of a posterior crossbite.

Prevention

Rubin (1979) feels that the connection between nasal obstruction and abnormal facial and dental development is so strong that it is the Orthodontist's responsibility to prevent facial deformity by recognising the causes of nasal obstruction early in life so that the appropriate interceptive treatment may be initiated. He advocates the involvement of the Orthodontist throughout the growth and development of the child from neonate to adulthood and provides advice on the intervention of the development of allergic rhinitis, vasomotor rhinitis and septal deviation.

1.4 EFFECTS OF RME

The effects of RME on skeletal and dental tissues have been studied extensively by means of animal studies and clinical research (Haas, 1961, 1965, 1970; Wertz, 1968, 1970, 1977; Timms, 1980; Linder-Aronson and Lindgren, 1979; Adkins *et al.*, 1990; da Silva *et al.*, 1991, 1995). In comparison, there has been relatively little research into the specific effects of RME on the nasal cavity and soft tissues. These factors will now be discussed separately.

1.4.1 Skeletal and Dental Effects

1.4.1.1 General comments

The effects of RME in increasing the transverse dimensions of the upper arch have been attributed to separate orthopaedic and orthodontic effects (da Silva *et al.*, 1991). The separation of the maxillae by splitting the median palatine suture constitute the orthopaedic effect, whereas the lateral movement of the posterior teeth and alveolar process are reported as the orthodontic effects. However this may be an oversimplification. Bishara and Staley (1987) described the effects of RME on the maxillary complex in a review paper. After cementation of the RME appliance high forces are required to overcome skeletal resistance and split the median palatine suture (Isaacson *et al.*, 1964; Zimring and Isaacson, 1965; da Silva *et al.*, 1991). Haas (1961) recommended an appliance with an acrylic base plate to contact the palate and alveolus to ensure that the high forces generated were distributed not only on the teeth but on the alveolar processes themselves to aid separation of the suture. In the first few days of activation, the RME would be expected to result in compression of the periodontal ligament of the posterior teeth included in the device (Bishara and Staley, 1987). This in turn would cause bending of the alveolar bone and tipping of these anchor teeth. Continued force would cause the suture to gradually open and the maxillae to move away from each other. Haas, (1961) demonstrated both alveolar bending and lateral tipping of the anchor teeth in an animal study using pigs. Furthermore the bending of the alveolus resulted in a lowering of the palatal vault in this group of animals. Ladner and Muhl (1995) supported this series of events and stated that the transverse changes across the upper arch were the result of three factors;

1. separation of the median palatine suture allowing the maxillae to separate
2. tipping of the two maxillae and alveolar processes
3. tipping and bodily movement of posterior teeth within the alveolus and alveolar bone

These workers concluded that the final expansion observed clinically would be composed of a contribution of all three factors and that the expansion due to splitting and separation of the median palatine suture may be a small component of the overall expansion observed. This is in agreement with earlier work by Haas (1961). As the posterior teeth may be expected to be carried laterally by the separate maxillae as they tip, the separate orthodontic effects produced by the RME may be difficult to dissociate from the orthopaedic movement of the maxillae.

It has been previously observed that responses to RME can vary. Krebs (1964) attributed the individual variation in the extent of expansion seen in a group of patients with a bilateral crossbite to the relative contribution of the dental and skeletal factors together with the individual malocclusion. He also believed that some of the variation was due to the individual performance of the parent in activating the RME appliance.

1.4.1.2 Effects on the median palatine suture

A number of studies have examined the histological events that occur following separation of the median palatine suture due to rapid maxillary expansion (Cleall *et al.*, 1965; Murray and Cleall, 1971). These workers demonstrated rapid cellular events at the suture leading to formation of new bone in the created space. Ten Cate *et al.* (1977) attempted to explain the cellular occuring during sutural expansion in an animal study using an electon microscope. They observed that sutural expansion involves injury followed by a proliferative repair phenomenon. In other tissues this would in turn be followed by the formation of scar tissue but due to the ability of sutural fibroblasts to remodel, regeneration of the suture results. They believe that an intact periosteum surrounding the median palatine suture during expansion is important in this ability to regenerate. Other studies have confirmed that fibroblasts and osteoblasts play an important role in the processes occuring at the suture during expansion. Ekström *et al.* (1977) found that the mineral content within the suture rose rapidly during the first month after expansion. This was associated with a sharp decrease in mineral content of the bone immediately beside the suture, which eventually returned to normal after three months.

Recent animal studies have found a number of factors which can influence bone formation in an expanded suture. Sawada and Shimizu (1996) produced evidence that increased levels of TGF-β_1 is present in osteoblasts and fibroblasts in the median palatine suture 24 hours after the start of expansion in rats. Futhermore these workers were able to demonstrate that when exogenous TGF-β_1 was injected into the site during early expansion, bone formation in the suture was markedly stimulated in a dose-dependant manner. In a similar study, Saito and Shimizu (1997) found that low power laser irradiation resulted in a small but significant acceleration in bone regeneration in expanded sutures of rats. Chang *et al.* (1997) suggest that exogenous endothelial cell growth factor could be used to enhance angiogenesis and result in increased osteogenic capability. They believe that mechanical seperation of the suture results in angiogenesis and an osteogenic response from quiescent preosteoblasts in the suture margins. This response is enhanced by the migration of activated pericytes from the post capillary venules which differentiate into osteoblasts and join the osteoprogenitor cell population.

1.4.1.3 Circum-maxillary sutures

Starnbach *et al.* (1966) demonstrated that during the early phases of RME the frontonasal, zygomatico-temporal and zygomatico-maxillary sutures all showed signs of increased cellular activity. The frontonasal suture in particular was affected. These changes were seen to return to normal in the weeks after active expansion was stopped.

1.4.1.4 Effects on skeletal and dental structures - Frontal View

1.4.1.4.1 Skeletal changes

Haas (1961) reported that due to the articulation of the maxillae with the other facial bones the shape of the void created by separation was pyramidal. This was supported by findings by other workers (Wertz, 1970; da Silva *et al.*, 1995). It was proposed that the base of this pyramid is at the occlusal level in frontal view with the apex located somewhere in the nasal cavity (Haas, 1961). Krebs (1964) reported results from 23 patients aged between 8 - 19 years with bilateral crossbite treated with RME using metallic implants to study the changes in width at different zones in the maxillary complex. He commented that the maxillae separate in a slightly rotating movement and that the effect of the expansion diminishes in a cranial direction. In a small animal study, Starnbach *et al.* (1966) found evidence that the maxillae rotated laterally and estimated the fulcrum for rotation to be near the frontonasal area. In a large clinical study of 60 cases, Wertz (1970) found that once separated the maxillary halves rotated outwards with the fulcrum of the rotation estimated to be near the frontonasal suture.

Effects of RME have also been demonstrated in young patients in the deciduous or mixed dentition. da Silva *et al.* (1995) reported similar results for 32 cases aged between 5 - 11 years and found a triangular opening in the frontal plane. Indeed these authors quantified the amount of opening at the level of the maxillary base and nasal cavity compared to the amount of expansion at the alveolar level. If alveolar expansion is expressed as 100%, then the maxillary basal expansion was found to be 56% on average, compared to 43% of this expansion at the level of the nasal cavity.

1.4.1.4.2 Dental changes

Maxillary incisors

The most impressive clinical effect of RME is the creation or widening of a midline diastema as sutural separation occurs. This has been reported by many workers as a consistent finding and indeed was reported as early as 1860 by Angell in the first recorded case of RME. Using PA radiographs Haas (1961) detected four stages to the process of formation of the diastema and its subsequent closure 4 - 6 months later. He proposed that initially the central incisors are carried laterally by the separating maxillae. When active expansion was complete the crowns were observed to converge and finally the roots began to move medially and assume their original inclinations. He postulated that the convergence of the crowns, then roots, to return the incisors to their formal positions was due to transeptal fibres. Wertz (1970) quantified the average size of the diastema created in his group of patients as 4 mm (range 0.5 - 7.0 mm). He stated that the created diastema was always found to have closed by appliance removal following the retention phase. Wertz agreed that transeptal fibres probably played a role in closing the diastema but that a change in tension of the circumoral musculature due to RME also had an effect. This change in muscular tension was proposed to occur due to the widening of the maxillary complex as a result of treatment and lead to an increase in pressure of the soft tissues on the upper incisors.

Maxillary posterior teeth

As stated earlier, the expansion across maxillary posterior teeth could be the result of two components (da Silva *et al.*, 1991). The orthopaedic effect of RME is found in the separation, rotation and tipping of the two maxillae while the orthodontic effect is found in the movement of the alveolus and associated teeth. As a result of the heavy forces used, the teeth are thought to cause compression of the periodontal ligament, alveolar bending in addition to bodily movement and tipping. The net effect of all these components is the observed expansion. In a recent comparative study of expansion produced by RME and a quad-helix, Ludner and Muhl (1995), attempted to separate these components and quantify the contribution of buccal tipping of molar teeth to the observed expansion. They concluded that buccal tipping was not a major factor in the expansion produced by RME.

Mandibular arch

In a small study of the effects of RME in pigs, Haas (1961) indicated that expansion of the mandibular dentition occurred as an indirect result of maxillary expansion. Results from the ten selected cases that Haas reported in 1961 indicate that mandibular intermolar width increased in all ten patients (range 0.5 - 2.0 mm). Four of these cases also showed an increase in mandibular intercanine width of between 0.5 - 1.5 mm. The remaining five cases had no change in mandibular intercanine width while in one case this measurement decreased 0.5 mm. He proposed that the increases were due to a net change in muscle balance between the cheek and tongue musculature influencing the position of these teeth after RME. Wertz (1970), on the other hand, reported that 35 patients in his study exhibited no change in mandibular intermolar width following RME. Twelve of the remaining patients showed gains in mandibular intermolar width of between 0.5 mm and 2.0 mm with one patient having a slight decrease in this measurement. Gryson (1977) reported changes in mandibular interdental distances due to RME using a Haas-type appliance in 38 patients. The main finding was a slight increase in mandibular intermolar distance as a result of RME. However he believed that this was probably due to uprighting of these teeth as a result of occlusal forces rather than any effect due to muscle imbalance. A relatively recent study by Sandstrom *et al.* (1988) also indicated that expansion of the lower arch was observed as a result of RME. These workers reported a mean increases in mandibular intercanine and intermolar width 2 years post-treatment. The mean increase in mandibular intercanine width was found to be 1.1 mm (sd = 1.5 mm), whereas the mean increase in intermolar width was 2.8 mm (sd = 2.2 mm). In a recent study, Hesse *et al.* (1997) also found small increases in mandibular intermolar width following RME (mean 0.64 mm, sd 0.9 mm). These modest increases in mandibular interdental width with large standard deviations following RME indicate that this type of expansion is variable and not consistent.

In summary there are two theories regarding the cause of the small mandibular interdental expansion seen in some cases due to RME. Some workers believe that mandibular interdental expansion is possible due to the altered position of the buccinator and buccal musculature as the superior attachments are carried laterally due to the movement of the maxillae. This results an imbalance of the equilibrium between the forces of the soft tissues of the cheek and tongue which in turn causes the change in position of the mandibular teeth. Other workers believe that the cause in more likely to result from uprighting of the posterior mandibular teeth in response to altered occlusal forces secondary to the altered position of the maxillary posterior teeth. Indeed Haas (1980) believes that the resulting movement of the mandibular teeth is a combination of both effects.

1.4.1.5 Effects on skeletal and dental structures - Lateral View

1.4.1.5.1 Skeletal changes

Maxilla

In 1961 Haas reported that the maxilla was seen to move forwards and downwards as a result of RME as viewed on lateral cephalometric radiographs. This was subsequently confirmed by Wertz (1970) who found that the maxilla was generally displaced downwards 1 - 2 mm and forwards 1.5 mm in his group of patients. In response the mandible rotated open and an increase in mandibular plane angle was observed in all cases. These findings were apparent immediately following active expansion. At appliance removal, Wertz found that the maxilla had recovered its initial position in 50% of cases, however, 20% demonstrated continuing change. In contrast, mandibular plane angle was found to recover in almost every case (Wertz, 1970). These observations are in agreement with Haas (1961) who noted that during retention, activity seemed to be directed at re-establishing former positions and skeletal relationships.

Sarver and Johnston (1989), have produced some evidence to suggest that some of these changes may be due to appliance design rather than as a direct result of expansion. Using a bonded RME appliance in 20 patients with a thin occlusal coverage of approximately 3 mm, they reported that the downward and forward displacement of the maxilla was reduced compared to the Haas type banded appliance. This difference was attributed to appliance design and advocated as an alternative treatment in some cases. Furthermore, da Silva *et al.* (1991), noted that the forward and downward displacement of the maxilla my not be a constant feature of deciduous and mixed dentitions. In a study involving 30 patients using a Haas type appliance, anterior displacement of the maxilla was not consistently observed at the end of active expansion. These workers did find a downward displacement of the maxilla associated with a downward and backward rotation of the maxillary plane.

Mandible

Haas (1961) described changes in the mandibular position in the lateral aspect due to the altered position of the maxilla. The displacement of the maxilla was postulated to result in an opening of the bite due to a backward rotation of the mandible, resulting in an increased mandibular plane angle and occlusal plane. This would also result in a posterior movement of the pogonion and an increase in lower anterior face height. Although similar changes were observed by Wertz (1970) recovery of mandibular plane angle and mandibular position were usually noted following treatment. Sarver and Johnston (1989) noted a similar backward rotation of the mandible during treatment with bonded appliances. However as there was no downward and forward movement of the maxilla detected in this study, these workers postulated that the rotation of the mandible was due to either posterior maxillary cuspal interference due to overcorrection after expansion or as a result of remnants of bonding material on the occlusal surface of the maxillary posterior teeth.

In a lateral cephalometric study of deciduous and mixed dentition subjects by da Silva *et al.* (1991) similar effects of RME were observed. Increased facial height and mandibular rotation were usually observed. The rotation of the mandible resulted in an increased mandibular plane and posterior positioning of B-point. Longterm follow-up from this group has not yet been reported and these changes may well recover.

1.4.1.5.2 Dental changes

The position of the upper incisors have been observed to alter due to RME. Wertz (1970) reported that they moved somewhat independently of the perceived change in the maxillae. The most common observation was an uprighting of these teeth, although in some cases they were found to tip forwards or backwards. At appliance removal those incisors that had tipped forward were found to drop back and decrease their angulation relative to SN becoming more upright. Unlike incisor position changes observed from the frontal aspect, theories regarding the change in position observed due to RME are limited, but possibly the influence of the circumoral musculature could have an effect. Wertz (1970) proposed that the uprighting of the incisors are also due to the influence of the soft tissues of the lips.

1.4.1.6 Effects on skeletal and dental structures - Occlusal View

1.4.1.6.1 Skeletal changes

There are relatively few studies where changes due to RME have been quantified from the occlusal aspect. Haas (1961) reported that in an animal study early opening of the suture observed from the occlusal aspect was scissor-like in nature, the widest portion anteriorly. Continued force resulted in a parallel opening from ANS to PNS. The clinical study by Wertz (1970) disagreed and reported examination of occlusal radiographs indicated that the final shape of separation of the maxillary halves were non-parallel, the wider aspect being anteriorly at the ANS and significantly narrower at the horizontal part of the palatine bone. Timms (1980) reported a clinical study directed at measuring interhamular width during RME. This was found to increase suggesting the maxillae, palatine bones and pterygoid process of sphenoid move apart during expansion. The expansion observed at the interhamular area was a percentage of the observed expansion of the maxillary molars suggesting non-parallel opening of the suture. Several authors have used RME on dried skulls to simulate changes in vivo due to opening of the median palatine suture. Observations on these specimens would seem to indicate that due to the articulation of the maxillae posteriorly with the palatine bones and pterygoid plates of the sphenoid, and laterally with the zygomatic bones, opening in an occlusal plane is non-parallel in humans (Wertz, 1970; da Silva *et al.*, 1991).

1.4.1.6.2 Dental changes

Adkins *et al.* (1990) reported the change in arch perimeter due to RME using a Hyrax appliance in 21 patients. These workers concluded that changes in premolar width were predictive of change in arch perimeter due to RME and related to approximately 0.7 x premolar expansion achieved.

1.4.2 Effects on the Nasal Cavity

The effect of rapid maxillary expansion on the nasal cavity and improvement in nasal airway was noticed early this century (Brown, 1909). It was appreciated early in the history of RME that expansion of the maxillae could result in an increase in the width of the base of the nose and likely lead to an improvement in nasal patency and function (Dean, 1909). Haas (1961) reported that as early as 1909 Black proposed that the lowering of the palatine process of the maxillae as a result of outward tilting of the alveolar processes could result in straightening of a deviated septum and therefore improve nasal patency. The effect of RME on the nasal cavity has been reported either as a change in transverse dimension of the nasal cavity or alteration of nasal function as indicated by nasal airway resistance.

1.4.2.1 Changes in nasal cavity dimensions

1.4.2.1.1 Direct measurement

A number of papers have been published that report changes in the transverse dimension of the nasal cavity at its maximum width. Haas (1961) proposed that rapid maxillary expansion had the potential to make nasal breathing possible in habitual mouth breathers due to effects on the nasal cavity. In addition to the widening of the maximum nasal cavity width seen as a result of RME, alveolar bending due to the tilting of the maxillae as they separate, results in a lowering of the palatal vault and therefore the nasal floor. He proposed that these changes resulted in improved nasal patency and function. In the small animal study conducted by Haas these changes were observed. Also seen in these animals was noted an increase in the width of the base of the nasal septum at its articulation with the palatal crests of the maxillae (Haas, 1961). For the 10 patients selected for this study the range in internasal width increase was 2.0 - 4.5 mm. However by using superimposition of serial radiographs and tracings he seems to have suggest that the effects of RME extended superiorly along the lateral walls of the nasal cavity.

Using metallic implants in 23 patients, Krebs (1958, 1964) demonstrated that following rapid maxillary expansion the mean gain in nasal cavity width was 1.4 mm (range 0.1-2.8 mm). Furthermore that following a small reduction in width of the nasal cavity after the retention period, a new increase in width was observed up to seven years post-expansion (Krebs, 1964). Using occlusal radiographs, Thorne and Hugo (1960) reported demonstrating an average increase in maximum nasal cavity width of 1.7 mm (range 0.4 - 5.7 mm). Starnbach *et al.* (1966) noted an increase in nasal cavity width during RME in monkeys although the difference due to treatment was not quantified. Wertz (1970) suggested that because of anatomical considerations of the lateral wall of the nose the effect of RME on the nasal cavity would be limited to the anterior and inferior portion of the nasal cavity, i.e. that part mainly composed of the maxillae. He suggested that the higher and more posterior the nasal stenosis the less likely RME would produce relief.

1.4.2.1.2 Indirect measurement

Warren and coworkers (1979, 1984, 1988) have demonstrated a technique to estimate the smallest nasal cross-sectional area. The smallest cross-sectional area of a structure can be estimated if the pressure difference and volume rate of airflow through it is known. These factors are linked by the following equation:

$$A = \frac{\dot{V}}{k[2\Delta p/d]^{1/2}}$$

where, A is smallest cross-sectional area, $\dot{V}$ is flow, Δp is the pressure difference and d is the density of air.

This equation holds true for laminar flow only and the measurements are recorded with standard pressure flow measurement system (section 1.5.2). Using this approach Warren and coworkers have been able to estimate normal values for children and adults. This is estimated to increase by 0.05 cm H_2O/l/seconds per year due to growth (Warren *et al.,* 1990). Furthermore, estimations of the minimum size of cross-sectional area for the nasal cavity before impairment leads to mouth breathing. For 12 year old children the nasal impairment would be estimated to occur at nasal sizes of less than 0.33 cm^2. For adults the minimal cross-sectional area is approximately 0.4 cm^2 although this may be up to 0.5 cm^2 in some cases (Warren *et al.*, 1988). These authors also quantified the change in cross-sectional area observed in a group of 16 subjects who received RME using a banded appliance. They estimated that an average nasal cross-sectional area increased by approximately 45% after RME although the response was found to be variable. Moreover they suggest that the most beneficial effect of RME is changing the shape of the nasal cavity produced anteriorly and more specifically changing the shape of the anterior nares at the liminal valve.

1.4.2.2 Changes in nasal cavity function

There are reported to be more than 30 different ways to measure resistance within the nasal cavity and this provides some insight into the various difficulties that arise in attempting to measure nasal resistance (section 1.5.2). However only a few methods have been used to monitor changes in nasal respiration as a result of RME. Wertz (1968) attempted to quantify the effect RME would have on nasal airflow. He measured velocity of air passing through the nasal cavity using a warm wire aneometer. He found that all 13 patients in the study demonstrated an increase in average nasal air volume when measured during maximum effort. However he conceded that this method of measuring nasal function was less than ideal as it was sensitive to a degree of respiratory effort and patient anxiety. Furthermore in this small study there was no attempt to correlate degree of expansion with improvement in nasal function. Timms (1986) using a standard rhinomanometry technique advocated the use of nasal airway resistance (NAR) as a measure of the effects of RME on nasal function as it is independent of muscular effort. This is because increased flow is accompanied by deepening of the pressure difference. In a study of 26 patients NAR was measured before and after RME. He reported an average improvement of 36.2% in NAR due to RME however he noted that variations were large. He also found that these reductions did not correlate well with either transpalatal expansion or transalar expansion. He suggested that the changes in air currents and morphological changes brought about by RME to produce a reduction in the NAR were complex and highly individual. He felt that this limited the predictive capacity of expansion in producing a reduction in NAR. An interesting observation of this study was that the greatest reductions were not necessarily associated with the largest expansions but usually with a high initial NAR. This is in agreement with work by Hershey *et al.* (1976). To help explain this observation they suggested that the flow through the nasal cavity may conform to Poiseuille's law where flow is proportional to r^4 rather than Ohm's law. However no further evidence was produced in support of this theory.

Hartgervink *et al.* (1987) reported the effect of RME on nasal resistance measured in a group of 38 patients before and after treatment. They found that subjects exhibited high individual variation in nasal resistance making firm conclusions due to treatment with RME difficult. However, they did find evidence for two subgroups of patients. A high resistance group had NAR in excess of 5.5 cm/H_2O/l/s whereas the low resistance group generally had values lower than this figure. These authors also commented that patients with the highest nasal resistance values before treatment described the most significant reductions in nasal resistance due to RME. Furthermore these workers agreed with Wertz (1968, 1970) and Timms (1986) that RME would benefit most those patients with obstructions in the anterior aspect of the nasal cavity in particular the anterior nares due to a small liminal valve which is the point of greatest constriction of the anterior nares. They concluded that the effect of RME on the nasal cavity away from the liminal valve was minimal and that the effect of RME could be simulated on patients by placing dilated Tygon tubing in the anterior nares. They suggested a clinical sequence to aid the determination of the location of an obstruction in the nasal cavity contributing to an increase in NAR. First, the resting NAR should first be recorded with standard rhinomanometry. The measurement should then be repeated with Tygon tubes in the anterior nares. If the resulting measurement reduced significantly then the obstruction would most likely be present at the anterior nares. However, if there was no reduction then in addition to the Tygon tubing a nasal decongestant should be used. If this significantly reduced NAR then the obstruction could be the result of soft tissue factors in the anterior part of the nasal cavity. Finally, patients with obstructions at the posture part of the nasal cavity, i.e. adenoids, would not be expected to respond to the techniques described above and could be detected by clinical and radiological examination (Linder-Aronson, 1970, Schulhof, 1978).

1.4.3 Soft Tissues

There have been few papers devoted to the soft tissue changes that occur following RME. Timms (1986) measured interalar width change due to expansion and found that it increased marginally in most cases and proposed that this resulted in a reduction in resistance at the liminal valve. Haas (1980) reported significant changes in profile due to RME alone and in combination with protraction (section 1.5.1.9.1). These were mainly due to an increase in lower anterior face height associated with a backward rotation of the mandible. A recent study by Ngan et al. (1996b) investigated the soft tissue and profile changes following maxillary expansion and protraction and concluded that significnant improvements were evident after six months of treatment.

1.5 CLINICAL ASPECTS

1.5.1 Rapid Maxillary Expansion

RME has been advocated for use in a variety of different clinical situations, whereas some are based on research and clinical experience, others are anecdotal and as yet lack any large scientific studies to substantiate improvements as a result of expansion. In a review of the literature, Bishara and Staley (1987) produce a number of indications for RME.

1. Transverse deficiencies

   Skeletal or dental deficiency or indeed a combination of both that results in either unilateral or bilateral posterior crossbite involving several teeth (Haas, 1980).

2. Anteroposterior Discrepancy associated with; Class II Division I malocclusion with or without a posterior crossbite, Class III malocclusion, borderline Class III or pseudo-Class III if associated with maxillary constriction or posterior crossbite (Haas, 1980).

3. Cleft lip and palate with collapsed maxillae (Graber, 1975; Haas, 1980; Devenish *et al.*, 1982).

4. To gain arch length in cases with moderate maxillary crowding (Adkins *et al.*, 1990)

5. Mandibular deviation

   Bell (1982) proposed that RME would redirect the developing posterior teeth into normal occlusion. This would result in correction of asymmetry of condylar position by allowing the mandible to close more vertically therefore RME should eliminate functional shifts of the mandible and prevent TMJ dysfunction developing. Hesse *et al.* (1997) have produced some evidence to support this theory.

6. Nasal obstruction

   Several workers have advocated RME for relief of nasal obstruction (Timms, 1974; Gray, 1975; Haas, 1980). The effects of nasal obstruction and general health have been discussed above.

Other possible indications include

1. Conductive hearing loss

   Laptook (1981) reported a dramatic improvement in a patient with conductive hearing loss by treatment with RME. Ceylan *et al.* (1996) reported a statistically significant improvement in hearing in 14 subjects immediately after active expansion with RME using a Biederman appliance however these changes were shortlived in that improvement generally reversed at the end of the retention period. Nevertheless five patients experienced a stable hearing improvement as a result of RME.

2. Nocturnal enuresis

   In 1990, Timms published results from a small study of RME used in 10 patients who suffered regular episodes of nocturnal enuresis. He reported that nocturnal enuresis ceased within a few months of RME despite several cases having a long history of the condition. He advocated RME to treat upper airway obstruction as a causative factor in nocturnal enuresis (Timms, 1990).

3. Primary headache

   There are isolated reports in the literature advocating RME for primary headache (Gianni and Farronato, 1995).

The advantages of RME in these areas is as yet unproven and warrants further study.

Bishara and Staley (1987) also recommend that the following four factors be taken into account when considering expansion. Rapid maxillary expansion should be considered if the magnitude of transverse discrepancy is moderate to severe. They suggets if the intermolar or premolar width of the mandible is 4 mm greater than that in the maxilla the RME should be used. Secondly the angulation of posterior teeth should be taken into account. If maxillary molars are buccally inclined conventional methods of expansion will tend to tip them further into the buccal musculature. If mandibular molars are lingually inclined uprighting these teeth will increase the need for expansion in the upper arch. Thirdly, as the number of teeth involved in the posterior crossbite increases RME should be considered more favourably. Finally, the age of the patient is an important factor. Although midpalatal splitting can be accomplished in both adolescents and adults the rigidity of the skeletal components limit extent and stability of the expansion with advancing age. They recommend that the optimal age for expansion is between 13 to 15 years of age. Several workers have reported techniques to achieve maxillary expansion in adults which will be discussed below.

Although the technique of RME is of use in a number of clinical situations, Bishara and Staley (1987) reccommend caution in patients with; poor co-operation, single tooth crossbite, maxillary or mandibular skeletal asymmetry, or if severe anteroposterior or vertical discrepancies are present, unless RME is to be used as part of a planned orthognathic surgical approach. In addition to these factors, patients with anterior open bite, increased Frankfort mandibular plane angle and convex profile are generally poor candidates for RME.

1.5.1.1 Appliances

A brief history of RME given in section 1.2 included the development of a number of appliances, the most commonly used today are as follows. Cast cap splints as advocated by Grossman (1963) and Timms (1974). Fixed split acrylic appliance with a midline expansion screw manufactured over cast cap splints covering the posterior teeth. Some workers advocate occlusal coverage should be extended as far forward as the lateral incisors (Timms 1974). The Haas type appliance was initially proposed by Haas (1961) later modified by Wertz (1970). This appliance has bands on the upper first premolars and upper first permanent molars. This is also a fixed split acrylic appliance with a midline expansion screw. The Hyrax or hygienic appliance is essentially a Hyrax screw positioned in the midline and cemented to bands on the upper first premolars and upper first permanent molars. There is no acrylic palatal coverage. The Biederman appliance is similar to the Hyrax with a midline expansion screw, and bands on molars and sometimes the canines. This appliance has no acrylic and no palatal coverage.

1.5.1.2 Expansion

Bishara and Staley (1987) suggest a simple procedure to estimate the amount of expansion required. First measure the intermolar width of the mandibular first molars using the most gingival extent of the buccal grooves on the reference point. Then measure the intermolar width of the maxillary first molars using the mesiobuccal cusp tips as a reference. Finally subtract the mandibular measurement from the maxillary measurement. Average measurements are + 1.6 mm for males and + 1.2 mm for females. Finally, allow for overexpansion of between 2 and 4 mm beyond this required figure to compensate for some relapse.This rule of thumb using the reference points above assumes a Class I molar relationship. These will be slightly different if treating to a Class II or a Class III molar relationship. Other workers including Timms (1974), Haas (1961) and Wertz (1970) recommend expansion is complete when the lingual cusps of the upper molars are riding up the buccal cusps of the lower molars.

Haas (1980) believes that 10 mm of expansion should be regarded as the minimum required with 12 mm considered the average amount of expansion. He suggested these figures because the increments of expansion resulting from alveolar bending, periodontal membrane compression, lateral tooth displacement and tooth extrusion will be lost during the retention phase. Bishara and Staley (1987) suggest that although no data is available on what would be considered a maximum amount of expansion of the maxillary arch, an upper limit of 12 mm seems reasonable. If the required expansion is greater than this limit then consideration should be given to a combined orthodontic/surgical approach.

1.5.1.3 Activation

There are a number of activation regimes reported in the literature. Haas (1961); Wertz (1970); Hershey *et al.* (1976) and Warren (1987a) all recommend one single turn of the screw immediately after insertion and one-quarter turn twice daily thereafter. Zimring and Isaacson (1965) suggest two turns each day for the first five days followed by one turn each day for the remainder of treatment for young patients. For older patients they recommend two turns each day for the first two days and one turn for five to seven days, and then one turn every other day. Timms (1986) recommends two half turns each day for young patients and four one-quarter turns spread throughout the day for older patients. In a recent study, by da Silva *et al.* (1991) suggested a 24-hour delay followed by two half turns each day. The reason for the delay however was not given although it may be assumed that this was required to allow the band cement to set completely before beginning activation.

1.5.1.4 Forces

Forces generated during RME have been investigated by a number of workers. (Martensson, 1956; Isaacson *et al.*, 1964; Zimring and Isaacson, 1965). Isaacson and coworkers reported that the maximum load produced by a jackscrew occurs at the time of activation and begins to dissipate soon after, particularly at the onset of treatment (Isaacson *et al.*, 1964; Zimring and Isaacson, 1965). A single turn can generate between 3 and 10lbs of force, with multiple turns generating loads in excess of 20lbs. These heavy forces were considered advantageous to achieve lateral positioning of the maxillae while limiting the amount of tooth movement (Isaacson *et al.*, 1964; Bishara and Staley, 1987).

1.5.1.5 Relapse and retention

Skeletal and soft tissue components are thought to be the two main sources of relapse following RME. As a consequence of rigidity, skeletal components are believed to offer immediate resistance to expansion (Bishara and Staley, 1987). The anatomy of the midface is complex and the maxillae articulate with ten other bones of the facial structure and anterior and middle cranial base (section 1.3). Isaacson and coworkers maintain that these articulations offer the main resistance to rapid maxillary expansion (Isaacson *et al.*, 1964; Zimring and Isaacson, 1965). Kudlick (1973) proposed that the sphenoid was the source of most of the resistance to lateral movement of the maxillae. He maintained that the pterygoid plates of the sphenoid limited the ability of the palatine bones to separate at the median palatine suture. Although bilaterally placed they are a single structure and do not have a suture. As a consequence the pterygoid plates can only bend as a result of the expansion. Resistance to bending of the pterygoid plates is thought to increase as one approaches the cranial base (Timms, 1980). The zygomatic complex also offers some resistance to expansion (Haas, 1961) but these structures are thought to remodel and adjust to their expanded positions (Krebs, 1964).

Bishara and Staley (1987) proposed that the soft tissue of the face, i.e. the muscles of mastication, facial muscles, investing fascia and skin, while relatively elastic will be stretched as a consequence of the expansion. In a recent study Halazonetis *et al.* (1994) found buccal cheek pressures increased 0.6 gm per cm^2 for each mm of expansion. They found an average of 3 gm per cm^2 before expansion which increased to an average of 9 gm per cm^2 after expansion. These workers concluded that cheek pressures due to RME may lead to relapse even after the retention period.

It is generally recommended that a period of retention should follow once the desired expansion has been achieved (Haas, 1961; Wertz, 1970; Timms, 1980). Haas (1961) proposed that approximately three months of retention was needed to allow new bone to form in the open suture which would subsequently resist the tendency for relapse. However, Isaacson *et al.* (1964) maintained that this period of retention was necessary to reduce relapse by allowing the heavy forces generated during the RME to dissipate throughout the maxillary complex before the appliance was removed. Zimring and Isaacson (1965) demonstrated that residual loads acting upon the appliance at the end of the expansion phase of treatment were entirely dissipated within a five to seven week period. The retention period normally suggested is three months although longer periods of retention have been advised, for example Ekström *et al.* (1977) recommended between 3 and 6 months of retention following RME.

Following removal of fixed appliances on completion of orthodontic treatment, Haas (1980) and Mew (1983) recommend long term retention. Haas (1980) advises six years of fixed retention in the lower arch with four years of removable retention in the upper arch. Mew (1983) suggested retention should be between 1½ to 4 years depending on the amount of expansion achieved.

1.5.1.6 Stability

From the beginning of RME there has been a debate regarding the stability of the expansion achieved. It is generally agreed that some relapse is enevitable. Figures for the amount of residual expansion are surprisingly consistent across a number of studies.

1.5.1.6.1 Stability of dental expansion

In a large study Stockfish (1969) reviewed 150 cases between five and 15 years after RME. He found between 40 and 50% of the initial expansion of intermolar width was present five years after retention. Timms (1976) reported similar results in 26 patients five years post retention. He found 44% of the initial expansion of intermolar width present. In a study of 23 patients five years post retention Linder-Aronson and Lindgren (1979) found mean final increase in intermolar width to be 45% whereas mean final intercanine width was only 23%. In a long-term study using metallic implants, Krebs (1964) reported that after a three month retention period there was a tendency for relapse in dental arch width which continued for up to five years. However in no case was complete relapse of the dental arch observed. Haas (1980) reported good maxillary and mandibular dental arch stability following RME and suggested long term retention. In a recent study Moussa *et al.* (1995) reported on 165 cases from eight to 10 years post retention. They found using a rapid palatal expander upper intercanine and intermolar width showed good stability.

1.5.1.6.2 Stability of skeletal expansion

Krebs (1964) reported that in long-term follow up of 23 patients treated with RME the increase in maxillary base was not lost by relapse over a seven year period even when expansion was carried out in older patients. In a selection of patients up to 10 years out of retention and 16 years post treatment, Haas (1980) reported good stability of the expanded maxillary base.

However not all workers agree. In a recent study, Sarnäs *et al.* (1992) used metallic implants to investigate the longterm effects of RME on one patient. They found extensive relapse of the maxillae 10 years after expansion and questioned the rationale for treatment with RME.

1.5.1.6.3 Stability of nasal expansion

Several workers have reported relative stability of expansion in the nasal cavity produced by RME. Increase in binasal width, cross-sectional area and NAR due to RME, have all been shown to be remarkably stable. This has been demonstrated by a number of authors (Haas, 1964; Wertz, 1970; Timms, 1986; Warren *et al.*, 1987).

Indeed, Krebs reported that the width of the nasal cavity increased up to seven years post-expansion (see below).

1.5.1.7 Effect on future growth

Krebs (1964) concluded that the effect of RME on the median palatine suture was greater if expansion was carried out before or during pubertal growth. In growing patients he found that following RME the width of the maxillary base and nasal cavity increased further. Melsen (1972) reported that RME in older individuals produced numerous micro-fractures in the sutural region which resulted in bridge formation between the maxillary halves following healing. Concern was raised that these may prevent future growth of the maxilla. However, in a recent retrospective study of 30 patients Velazquez *et al.* (1996) reported the longterm effects of RME and concluded that signs of normal growth were present after expansion. It may be appear therefore that RME before or during pubertal growth does not seem to be detrimental to subsequent growth.

1.5.1.8 Effect on oral tissues

1.5.1.8.1 Root resorption

Reference to root resorption has been made above. Langford (1982) published a short report of severe root resorption affecting the buccal surfaces of maxillary posterior teeth. Hill (1987) also reported a severe case of root resorption affecting the upper first permanent molar and attributed this to movements due to RME. Odenrick *et al.* (1991) reported root resorption occurring on all maxillary premolars in two small groups of RME patients. They compared the Haas type and Hyrax appliances and found more resorption lacunae with the Hyrax group. Large scale studies are limited although a recent paper by Erverdi *et al.* (1994) reported the root resorption patterns on a total of 50 premolars from 19 patients that had RME with either Haas-type appliance or cast cap splint appliance. They found resorption and repair areas on the buccal surfaces of all premolars. They reported that repair was by cellular cementum and they did not find any significant difference in quantity or quality of external root resorption from these two groups. Vardimon *et al.* (1993) studies external root resorption (ERR) and repair in eight monkeys and suggested that fixed retention following RME aided repair. Barber and Simms (1981) reported that signs of ERR were confined only to posterior anchor teeth. A number of investigators have reported ERR on buccal surfaces of anchor teeth during RME however these areas tended to repair. In summary it would appear that buccal ERR of anchor teeth occurs in most cases with RME however these areas tended to repair.

1.5.1.8.2 Gingival tissues and periodontium

Greenbaum and Zachirsson (1982) produced one of the few large studies specifically looking at changes in periodontal condition due to RME. They compared 20 patients who had RME with 33 treated with a quadhelix appliance using 28 patients treated with Edgewise appliances as controls. Following treatment mean differences were small although individual variation was large with some of the most affected patients being found in the RME group.

1.5.1.8.3 Palatal tissues

Fixed split acrylic appliances have been noted to cause inflammation and erythema of palatal tissues. These changes are considered reversible and may be reduced by good oral hygiene measures. This is not seen as a problem using so-called hygienic appliances for example, Hyrax and Biederman appliances.

Cotton (1978) published observations of slow maxillary expansion in an animal study using monkeys. He suggested that the palatal mucoperiosteum was stretched due to expansion and that post-expansion changes in molar angulation could be due to these stretched fibres. Muguerza and Shapiro (1980) assessed the effectiveness of a palatal mucoperiostomy to reduce relapse after slow maxillary expansion. These workers concluded that this surgical procedure was not effective in reducing relapse in slow maxillary expansion produced by the Mini-expander. The influence of such a procedure after rapid maxillary expansion is not known and as yet has not been investigated.

1.5.1.9 RME and other therapies

1.5.1.9.1 Orthopaedic movements

Mobilisation of the maxillae has been appreciated as a possible starting position to apply orthopaedic forces and alter the position of the maxillae in an anteroposterior direction (Haas, 1980). Starnbach and Cleall (1964), observed increased cellular activity in frontonasal, zygomatico-maxillary and zygomatico-temporal sutures in response to palatal expansion in monkeys. Following active expansion these changes were observed to revert gradually back to normal (Starnbach *et al.*, 1966). Wertz (1970) agreed and proposed that due to RME the resulting increased blood supply and cellular events at maxillary sutures presented an excellent opportunity to further move the maxilla in an antero-posterior direction.

In a recent study, Baik (1995) compared forward and downward movements of the maxilla using protraction headgear with either rapid maxillary expansion or fixed appliances in a group of 60 Korean patients. He concluded that protraction headgear and rapid maxillary expansion together resulted in more forward movement of the maxilla. Similarly, Ngan *et al.* (1996a) reported the successful use of maxillary expansion and protraction in the treatment of 30 class III cases. He was able to demonstrate mean overjet and overbite reductions of 6.5 mm and 2.6 mm respectively.

1.5.1.9.2 Orthognathic surgery

Due to the poor and unpredictable response of RME in adults, a number of workers have advocated surgery in combination with RME. There are a variety of surgical procedures available. Lines (1975) advocated lateral corticotomies and surgically assisted opening of the median palatine suture to overcome resistence before activation of the maxillary expansion appliance. Bell and Epker (1976) proposed a variety of maxillary osteotomies to be used in conjunction with maxillary expansion to correct various maxillary deficiencies with dental crossbites in adults. Kraut (1984) advocated bilateral maxillary lateral corticotomies combined with pterygomaxillary disjunction and surgical midpalatal suture seperation to achieve successful expansion in adult patients. Recently, Mossaz *et al.* (1992) proposed that unilateral crossbites in adults could be corrected with a unilateral corticotomy and rapid maxillary expansion, using the contra-lateral non-operated side as anchorage. Alpern and Yurosko (1987) reported the use of a rapid palatal expansion bite-plane appliance in treating adults with maxillary width deficiency. They were able to treat female patients up to 18 years and males up to 21 years of age without recourse to surgery. A conservative maxillary osteotomy procedure was advocated for patients aged up to 43 years. Morselli (1997) has recently reported a minimally invasive surgical technique to help reduce trauma in surgically assisted maxillary expansion in adults.

1.5.1.9.3 Cleft lip and palate

Rapid maxillary expansion has been advocated as part of the treatment of cleft lip and palate patients (Graber, 1975; Foster and Chin, 1977; Haas, 1980). However results achieved with RME in cleft patients are generally disappointing and these patients are more commonly treated using a quadhelix to expand the segments laterally. Devenish *et al.* (1982) reported a system of differential rapid maxillary expansion for use in cleft lip and palate patients. The advantages of this system are that it enables the maxillary segments to be rotated to allow an increase in intercanine width without necessarily increasing the intermolar width.

1.5.2 Rhinomanometry

Rhinomanometry has been defined as a study of nasal airway physiology. It involves the measurement of airflow through the nasal cavity together with pressure difference across it. (Kern, 1973; Clements, 1984; Timms, 1986). Rhinomanometry has a long history and a direct method of evaluating nasal passages was proposed by Kayser as early as 1895, with over thirty methods of measurement of nasal airway resistance proposed since. Nasal airway resistance may be measured relatively easily using standard equipment readily available (Broms *et al.*, 1982; Timms, 1986). Following an international meeting on standardisation in rhinomanometry in 1983, a number of recommendations were made (Clements, 1984). Nasal airway resistance may be calculated by using the following formula:

$$\text{NAR} = \frac{\Delta p}{\dot{V}}$$

where, NAR is nasal airway resisitance, Δp is the pressure difference and $\dot{V}$ is the flow.

Clements (1984) recommended that this value of NAR should be quantified at a fixed pressure of 150 pascals. Nasal airway resistance is normally quoted in units of Pa/l/s but both Pa/cc/s x 10^3 and cm/H_2O/l/s are common. One Pa is equivalent to 0.102 cm/H_2O (Timms, 1986). The use of a decongestant during the measurement has been advocated to eliminate cyclical turbinate engorgement (Lenz *et al.*, 1985) and any nasal congestion due to infection or allergy (Henrickson and Wenzel, 1984). The use of a nasal decongestant has been advocated in studies using RME to closely reflect any skeletal changes as a direct result of expansion (Timms, 1986). The calculation of NAR using the equation given above holds true for laminar flow (k_1) only. Errors due to turbulent flow (k_2) disrupt the linear relationship. To minimize this effect recordings should be taken of tidal flows when the patient is at rest (Timms, 1986). Solow and Sandham (1991) have indicated that the turbulent component of nasal airflow increases with flow rate. In a small study of 20 dental students with no history of nasal obstruction, these workers calculated both laminar and turbulent coefficents using a modified rhinomanometer. These coeffeicents may be calculated using the Rohrer equation;

$$\Delta p \quad = \quad k_1 \dot{V} + k_2 \dot{V}^2$$

where, Δp is the pressure difference, $\dot{V}$ the flow, k_1 the laminar coefficent and k_2 the turbulent coefficient.

These authors found that the turbulent component of airflow rises dramatically on switching from bilateral to unilateral nasal breathing. They suggested that switching from turbulent to predominately laminar flow may help explain the large physiological effect sometimes seen after comparatively small dimensional changes of the nasopharyngeal airway, for example following RME. The turbulent component of nasal airflow can be expressed as a percentage for any flow rate by using the following equation.

$$T \quad = \quad \frac{k_2 \dot{V}}{k_1 \dot{V} + k_2} \quad x \quad 100$$

1.5.2.1 Normal values

Principato and Wolf (1985) looked at 498 subjects between four and 16 years of age and calculated that NAR decreased from 8.28 to 3.18 cm/H_2O/l/s with increasing age and established that NAR varied inversely with age. The mean NAR in adults is approximately 2.5 cm/H_2O/l/s however this varies from 1.0 to 3.5 cm/H_2Ol/s. McCaffrey and Kern (1979) in a sample of 1000 patients determined that breathing difficulties occurred in patients with NAR of greater than 3.0 cm/H_2O/l/s. Watson *et al.*, (1968) stated that patients noted difficulties in nasal breathing above 3.5 cm/H_2O/l/s and at 4.5 cm/H_2O/l/s a significant number were predominantly mouth breathers. Warren *et al.* (1987, 1988b) indicated that these figures corresponded to a cross-sectional nasal area of between 0.36 cm^2 and 0.4 cm^2.

1.5.3 Radiology and imaging

Transverse nasal cavity dimensions may be measured either directly or indirectly. Indirect estimation of smallest cross-sectional area of the nasal cavity by using rhinomanometry and NAR has been described above. Direct methods of measuring nasal cavity dimensions involve either plane film radiographs or CT scan.

1.5.3.1 Frontal radiographs

Frontal radiographs have been used by a number of investigators to measure binasal width or maximum width of the nasal cavity which has been noted to increase with rapid maxillary expansion (section 1.4.2.1.1).

Woodside and Linder-Aronson (1979) reported a subjective assessment of nasal cavity obstruction which could be used on PA radiographs. Three categories were described; open nasal passages, when both right and left nasal passages show moderately enlarged radioluscent areas; partial nasal obstruction, when one or both sides show small radioluscent areas and total nasal obstruction, where both sides are opaque and no radioluscent areas are observed.

Holmberg and Linder-Aronson (1979) evaluated the use of lateral and frontal cephalometric radiographs for evaluating the capacity of the nasal and nasopharyngeal airway. They reported the use of the index described above and the nasal airway index. This measurement is expressed as a percentage of the following:

$$\text{NAI (\%)} = \frac{\text{radioluscent area}}{\text{nasal cavity area}} \times 100$$

These workers found a statistically significant relationship between NAI and nasal airflow velocity in 28 children with no signs of nasal obstruction. Furthermore they concluded that a subjective visual assessment of nasal cavity function was possible using frontal radiographs alone.

1.5.3.2 CT scan

Montgomery *et al.* (1979) reported the use of computed tomography to study the nasal cavity. Using four heads from human cadavers these workers evaluated the use of CT scan to measure a cross-sectional area of a series of sections 4 mm thick from the nasal cavity. These authors suggest that CT scan could be used in a number of selected cases, for example evaluation prior to nasal surgery when reduction of the turbinates is being considered. They do not suggest however that CT scan should be used for every case of nasal airway assessment.

1.6 AIMS

RME is a technique with a long history that has gone through periods of popularity and decline. The main effects of RME are seperation of the median palatine suture, rotation and expansion of the maxillae and expansion of the maxillary dental arch. Whereas the effects of RME on skeletal and dental structures have been thoroughly investigated the effects of expansion on the nasal cavity is still largely unknown.

Holmberg and Linder Aronson (1979) proposed the use of lateral and PA cephalometric radiographs for estimation of nasal obstruction. They concluded that these radiographs could be used to assess the function of the nasal cavity. However this approach is open to criticism because of the limitations of a two-dimensional representation of a three-dimensional space (Montgomery *et al.*, 1979; Schwartz and Thrash, 1985). These authors advocate the use of CT scan or MRI to carefully map the nasal cavity in three dimensions. However, CT scan and MRI are not universally available and the expense and time required for collection and analysis of data may be an obstruction to their widespread use for this purpose.

To date there have been relatively few studies that attempt to relate nasal airway resistance and airflow to the nasal cavity as seen on a PA cephalometric radiograph. While modern imaging techniques like CT scan and MRI may be considered gold standards, investigation of any possible relationship between size of nasal cavity seen on PA cephalometric radiograph and NAR is merited. Current best practice dictates that these radiographs are taken routinely for patients complaining of persistent nasal obstruction in order to detect any associated pathology in addition to direct visual diagnosis. In the event of a relationship being established this may be used as an adjunct to diagnosis and the decision to treat nasal obstruction.

The aims of this thesis are;

1. To evaluate methods of measuring the transverse dimension and cross-sectional area of the skeletal, dental and nasal structures from PA cephalometric radiographs

2. To compare these parameters between a group of patients with a narrow maxillary arch and a group of sex and age matched controls

3. To investigate the effect of rapid maxillary expansion on skeletal, dental and nasal structures

4. To establish any relationship between nasal cavity dimensions and nasal airway resistance in the healthy control group

5. To investigate changes in nasal airway resistance after treatment with rapid maxillary expansion

CHAPTER 2

MATERIALS AND METHODS

2.1 CLINICAL SUBJECTS

2.1.1 Anomaly Group

The anomaly group used in this study were selected from a previously studied population (McDonald, 1995). These patients originated from the East of Scotland, specifically from the Edinburgh and Fife areas. They were referred to the orthodontic departments of either the Edinburgh Dental Hospital or the Victoria Hospital, Kirkcaldy by General Dental or Medical Practitioners or Hospital Specialists. The criteria for selection for the study were as follows; a full cusp transverse crossbite, no evidence of adenoidal blockage of nasopharynx, no previous tonsillar, nasal or adenoidal surgery. In addition to these basic selection criteria all patients required complete medical and dental records including good PA and lateral cephalometric radiographs with RME in situ at the end of active expansion. From a total of 72 cases reported previously, 25 were selected for the study (Figure 5). The anomaly group was composed of 20 females and five males with an average age of 13 years 4 months (range 11 years 0 months - 15 years 8 months, see Table 12, p 111).

2.1.2 Control Group

Twenty-five subjects were sex and age matched to the anomaly sample as closely as possible from the control population of the original study (McDonald, 1995). These subjects were of the same Northern European racial background and had full medical and dental records available. This group also comprised of 20 females and five males with an average age of 13 years 11 months (range 10 years 5 months - 15 years 11 months, see Table 13, p 111).

Figure 5 Patient with Nasal Obstruction Exhibiting General Features of Adenoidal Facies (i.e. open mouth posture, narrow nasal base, increased lower anterior face height)

2.2 CLINICAL PROCEDURES

All clinical treatment had been undertaken previously by McDonald (1995). Full baseline records included study models, clinical photographs, orthopantomogram, PA and lateral cephalometric radiographs and rhinomanometric measurements. The commencement of orthodontic treatment of the anomaly patients arose when the maxillary canines had erupted to allow the easy transition from RME to fixed appliances to complete treatment. The RME appliance used was a cast cap fixed split acrylic appliance with the active expansion produced by a Hyrax screw (11 mm or 18 mm). The choice of expansion screw depended on the estimated amount of expansion desired. The cast cap splint was of a silver-copper alloy with full tooth coverage from the first molar to the canines with occlusal holes to aid removal. Soldered double buccal tubes with hooks were attached to the premolar-canine area to facilitate alignment of upper anteriors after expansion and during retention (Figure 6). Minor modifications of the appliance were used depending on orthodontic classification (McDonald, 1995).

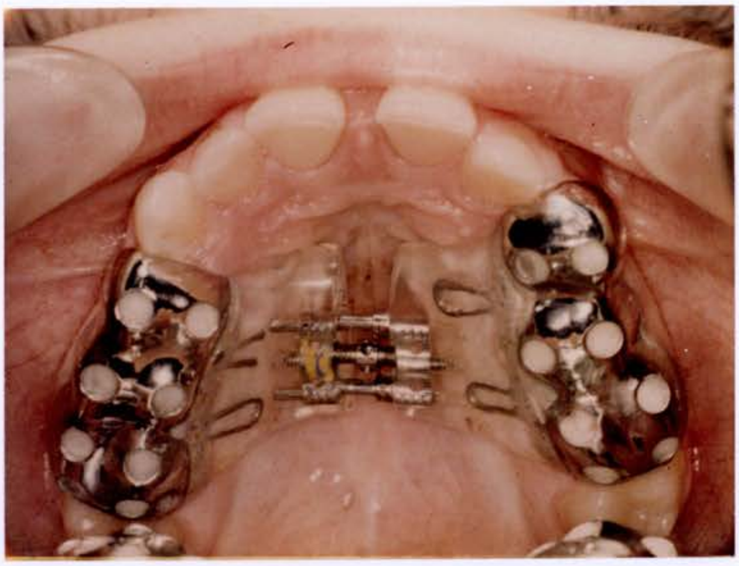


Figure 6 Intraoral View of RME Appliance Showing Successful Maxillary Expansion with Separation of the Upper Central Incisors

2.2.1 Activation Regime

The appliance was activated by the parent 24 hours following cementation and the patients were reviewed regularly during active expansion. The following regime was typical. During the first week one-quarter turn three times a day, once after breakfast, school and before bed. During the second week this was reduced to one-quarter turn twice a day, after breakfast and before bed. Finally for the third week the screw was turned one-quarter turn once a day in the mornings only. If neccessary this was continued until the crossbite had been overcorrected so that the palatal cusps of the upper molars were riding up on the buccal cusps of the lowers.

2.2.2 Retention

When the required expansion was achieved the RME appliance was removed and the teeth cleaned while the screw was locked in position with cold cure acrylic. The appliance was then recemented and used as a retainer for three months. The following records were repeated after active expansion and during the retention period, clinical photographs, orthopantomogram, PA and lateral cephalometric radiographs and rhinomanometric measurements. These records were used to analyse the skeletal, dental and nasal effects of RME in the anomaly sample.

2.2.3 Post Retention

After the period of retention was over, which was normally three months, the RME appliance was removed and the teeth were cleaned, bonded and banded. Normally a heavy utility archwire in 0.016 x 0.022 stainless steel was placed between 621/126 to retain intermolar width. Alignment of other teeth was achieved by a 0.012 Nickel Titanium archwire used as a piggyback archwire. By working up the archwires the buccal segment was aligned so that eventually a single 0.018 x 0.025 stainless steel could be inserted. Lower fixed appliance treatment was completed concurrently. Following orthodontic treatment Hawley retainers were used in both upper and lower arches. After a period of six months full-time retainer wear the lower Hawley was replaced by a lingual fixed retainer across the lower labial segment from canine to canine. The upper arch was retained by a Hawley retainer worn night only for a further six months (Figures 7 and 8).

Figure 7 Intraoral View of Patient with Posterior Bilateral and Anterior Crossbites due to Maxillary Constriction Before Treatment

Figure 8 Intraoral View of Same Patient in Figure 7 After Expansion with RME and Upper and Lower Fixed Orthodontic Appliances

2.3 RADIOGRAPHS

All radiographs for the original study were taken at the Edinburgh Dental Hospital by a single trained Radiographer. Subjects were radiographed in natural head postion as described by Solow and Talgren (1971). The selection of the anomaly sample for inclusion in this study was based largely on the quality of PA and lateral cephalometric radiographs. Both sets of radiographs before and after RME were examined closely to ensure a clear image of a wide range of skeletal, dental and nasal structures and no obvious rotations in the horizontal or vertical plane. Only those patients whose PA cephalometric radiographs included the RME appliance in situ at end of active expansion and beginning of the retention period were accepted for the study.

The original lateral cephalometric radiographs were taken with the aid of a cephalostat and a Morita Pan X E2 Orthopantomogram. Trimax 3M blue-based fast radiographic film was used in a cassette with a rare earth screen. Exposures were made at 80kvolts for 8 seconds. PA cephalometric radiographs were taken using the same equipment after the patients allowed to reposition into natural head position. The film was exposed for 1.3 seconds at 80kv (McDonald, 1995).

2.4 TRACING AND DIGITISING

In a darkened room PA cephalometric radiographs were secured to the centre of a viewing box with masking tape. A sheet of acetate tracing paper was then fixed to the radiograph with tape. The periphery of the viewing area was covered with card to mask unneccessary glare and improve landmark identification. A range of anatomical features were traced using a sharp 4H pencil. A number of skeletal, dental and nasal landmarks were identified and digitised as outlined below.

2.4.1 Digitisation and Analysis of Tracings

Two computer based systems were used in this study. The first system was used primarily to measure skeletal, dental and nasal linear measurements while the second system was used to measure the various nasal cross-sectional areas.

2.4.1.1 Digitising system 1

The following system was used to create a nasal template to aid the identification of constructed nasal landmarks (section 2.4.2.3) and to to measure skeletal, dental and nasal linear measurements. The computer hardware consisted of a 486 Compaq IBM compatible personal computer, a Numonics 2210-1212 digitising palette (Numonics, California, USA) and a Hewlett-Packard Deskjet 850c colour printer. This arrangement is demonstrated in Figure 9. The software used consisted of a commercially available cephalometric analysis program, Dentofacial Planner v7.0 (Dentofacial Software, Toronto, Canada). This program has an extensive library of PA cephalometric landmarks together with a facility to create additional operatorgenerated landmarks (see below). This system was recently calibrated by Moore (1993) by repeated measurement of a set of points and the associated method errors found to be 0.063 mm for the x-axis and 0.062 mm for the y-axis. Each tracing was secured with tape to the centre of the digitising palette to minimise errors arising from lack of linearity of the digitiser (Erikson and Solow, 1991). A short six point digitising sequence was completed first to allow the construction of a nasal template for each patient (section 2.4.2.3.1). Then a number of skeletal, dental and nasal landmarks were digitised. The definition of these landmarks is given below. From these landmarks a number of measurements were identified and analysed using a customised analysis within the Dentofacial software program.

2.4.1.2 Digitising system 2

The following system was used to measure the various nasal cross-sectional areas. The hardware for this system was a GTCO digitising palette linked to a Dell Optiplex 486 IBM compatible personal computer (Figure 10). The software used was the Cogsoft package v3.1 (COGS). This arrangement has also been calibrated recently by McDonald (1995) and the method errors associated found to be 0.08 mm for the x- axis and 0.14 mm for the y- axis. The Cogsoft package has the facility to measure the area of an irregular shape by using the cross hairs of the digitiser cursor to trace around the shape in question. Each tracing was secured as before to the centre of the digitising palette and the various nasal cross-sectional areas measured (section 2.4.3).

Figure 9 Digitising System 1

Figure 10 Digitising System 2

2.4.2 Transverse Measurements

2.4.2.1 Skeletal landmarks

A number of skeletal landmarks were chosen as candidates for investigation, the majority of these landmarks were taken from definitions by Grummonds and Kappeyne van de Coppello (1987), Athanasiou *et al.* (1992) and da Silva *et al.* (1995). A list of the skeletal landmarks and defintions are given in Tables 1 and 2. From these points a number of skeletal transverse measurements were selected and are given in Table 7 and Figure 11.

2.4.2.2 Dental landmarks

Dental landmarks were based on definitions by Athanasiou *et al.* (1992) and da Silva *et al.* (1995). and are shown in Tables 3 and 4 . The dental measurements selected for investigation are given in Table 7 and Figure 11.

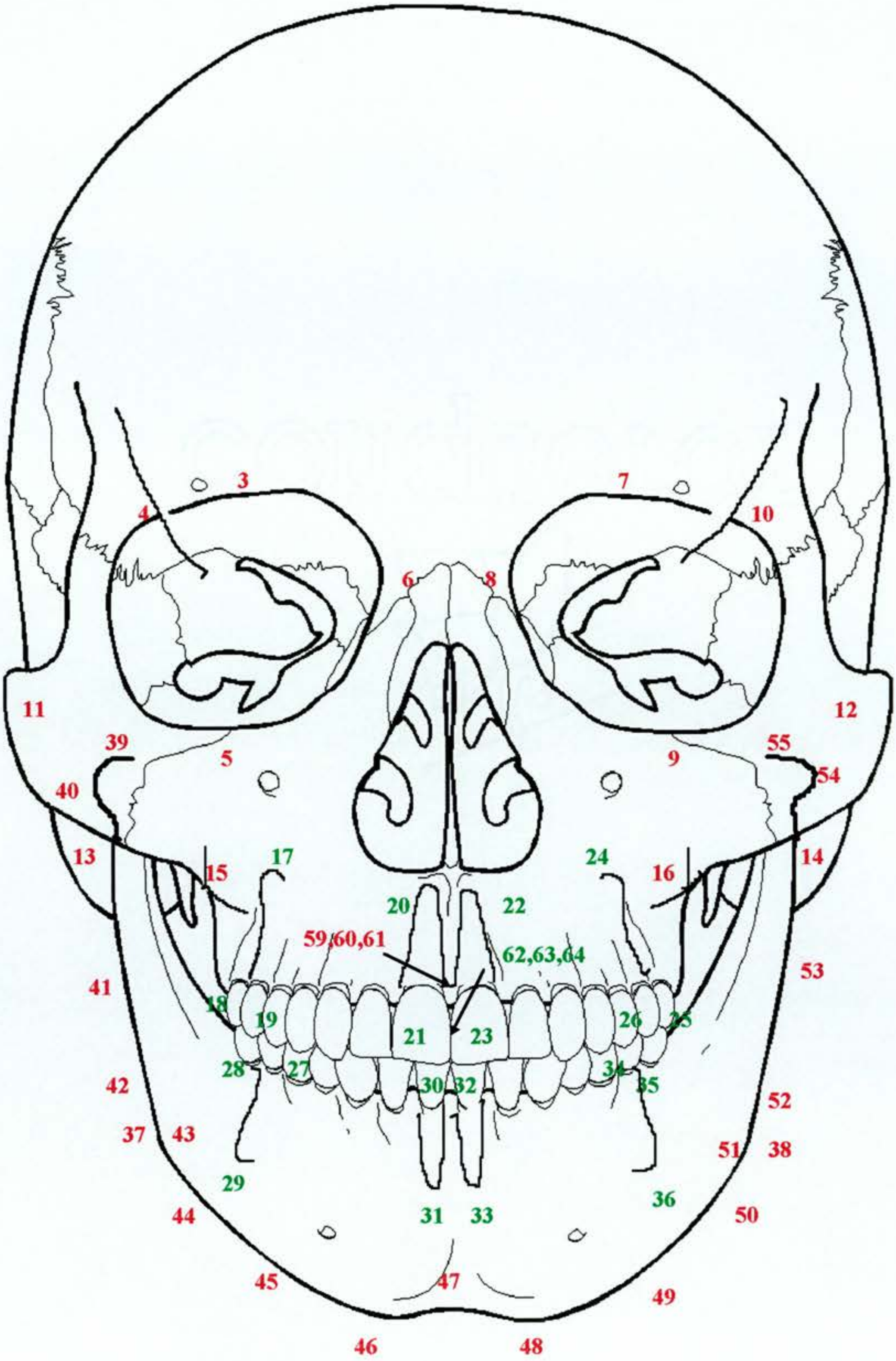


Figure 11 Skeletal and Dental Landmarks (Red are skeletal landmarks, green are dental landmarks)

No.		Point	Description
1.	Ref 1		Superior point on the vertical reference line
2.	Ref 2		Inferior point on the vertical reference line
3.	R so	R superio-orbitale	Most superior point on the outline of the right orbital margin
4.	R lo	R latero-orbitale	Intersection of the right lateral orbital contour with the innominate line
5.	R io	R inferio-orbitale	Most inferior point on the outline of the right orbital margin
6.	R mo	R medio-orbitale	Point on the right medial orbital margin that is closes to the median plane
7.	L so	L superio-orbitale	Most superior point on the outline of the left orbital margin
8.	L mo	L medio-orbitale	Point on the left medial orbital margin that is closest to the median plane
9.	L io	L inferio-orbitale	Most inferior point on the outline of the left orbital margin
10.	L lo	L latero-orbitale	Intersection of the left lateral orbital contour with the innominate line
11.	R zyg	R zygoma	Lateral aspect of the right zygomatic arch, centered vertically
12.	L zyg	L zygoma	Lateral aspect of the left zygomatic arch, centered vertically
13.	R ma	R mastoid	Lowest point of the right mastoid process
14.	L ma	L mastoid	Lowest point of the left mastoid process
15.	R mx	R maxillare	Intersection of the lateral contour of the right maxillary alveolar process and the lower contour of the right maxillozygomatic process of the maxilla
16.	L mx	L maxillare	Intersection of the lateral contour of the left maxillary alveolar process and the lower contour of the left maxillozygomatic process of the maxilla

Table 1 Definition of Skeletal Landmarks

No.		Point	Description
37.	R mn	R ectomandibulare	Most lateral point of angle of mandidle on the right
38.	L mn	L ectomandibulare	Most lateral point of angle of mandidle on the left
39.	R sc	R superior condyle	Point located on the superior surface of the head of the right condyle, centered medio-laterally
40.	R lc	R lateral condyle	Point located at the lateral pole of right condylar head
41.	R lr	R lateral ramus	Point on the lateral border of right ramus, located between the condylar head and gonial angle
42.	R sgon	R superior gonion	Point located at junction of the lateral border of right ramus and the convexity of right gonial angle
43.	R gon	R gonion	Point located at the right gonial angle of the mandible
44.	R agon	R antegonion	Point located at the right antegonial notch
45.	R mbdy	R body of mandible	Point on the inferior surface of the right body of the mandible between gonial angle and symphysis
46.	R pmen	R prementon	Point located on the inferior surface of the right body of the mandible
47.	Men	Menton	Most inferior point on the border of the mandible, at the symphysis
48.	L pmen	L prementon	Point located on the inferior surface of the left body of the mandible
49.	L mbdy	L body of mandible	Point on the inferior surface of left body of mandible, between gonial angle and symphysis
50.	L agon	L antegonion	Point located at the left antegonial notch
51.	L gon	L gonion	Point located at the left gonial angle of the mandible
52.	L sgon	L superior gonion	Point located at the junction of the lateral border of left ramus and the convexity of the left gonial angle
53.	L lr	L lateral ramus	Point on the lateral border of the left ramus, located about between condylar head and gonial angle
54.	L lc	L lateral condyle	Point located at the lateral pole of the left condylar head
55.	L sc	L superior condyle	Point located on the superior surface of the head of the left condyle, centered medio-laterally

Table 2 Definition of Skeletal Landmarks (continued)

No		Point	Description
.			
17.	R U6 apx	R upper 6 apex	Point located in the region of root apices
18.	R U6 lat	R upper 6 lateral	Most prominent lateral point on the buccal surface of the upper right first molar
19.	R U6 tip	R upper 6 tip	Buccal cusp tip of upper right first molar
20.	R U1 apx	R upper central apex	Root apex of upper right central incisor
21.	R U1 tip	R upper central tip	Central point of the incisal edge of upper right central incisor
22.	L U1 apx	L upper central apex	Root apex of the upper left central incisor
23.	L U1 tip	L upper central tip	Central point of the incisal edge of upper left central incisor
24.	L U6 apx	L upper 6 apex	Point located in the region of root apices vertically
25.	L U6 lat	L upper 6 lateral	Most prominent lateral point on the buccal surface of upper left first molar
26.	L U6 tip	L upper 6 tip	Buccal cusp tip of upper left first molar
27.	R L6 tip	R lower 6 tip	Buccal cusp tip of lower right first molar
28.	R L6 lat	R lower 6 lateral	Most prominent lateral point on the buccal surface of lower right first molar
29.	R L6 apx	R lower 6 apex	Point located in the region of root apices
30.	R L1 tip	R lower central tip	Central point of the incisal edge of lower right central incisor
31.	R L1 apx	R lower central apex	Root apex of lower right central incisor
32.	L L1 tip	L lower central tip	Central point of the incisal edge of lower left central incisor
33.	L L1 apx	L lower central apex	Root apex of lower left central incisor
34.	L L6 tip	L lower 6 tip	Buccal cusp tip of lower left first molar
35.	L L6 lat	L lower 6 lateral	Most prominent lateral point on the buccal surface of lower left first molar
36.	L L6 apx	L lower 6 apex	Point located in the region of root apices

Table 3 Definition of Dental Landmarks

No.		Point	Description
59.	R acsm	R alveolar crest suture margin	The most medial point on the right aspect of the bony margin of the maxillary suture in the region of the alveolar crest
60.	L ascm	L alveolar crest suture margin	The most medial point on the left aspect of the bony margin of the maxillary suture in the region of the alveolar crest
61.	C ascm	Central alveolar crest suture margin	Point midway between R acsm and L acsm, otherwise midway between the mesial root surfaces of the upper cenral incisors at the level of the alveolar crest
62.	R mip	R mesial incisal point	Most mesial point on the crown of the upper right central incisor
63.	L mip	L mesial incisal point	Most mesial point on the crown of the upper left central incisor
64.	C mip	Central incisal point	Contact point of upper central incisors, or the point midway between R mip and L mip at the level of closest approximation

Table 4 Definition of Dental Landmarks (continued)

2.4.2.3 Nasal landmarks

Landmarks in the nasal cavity were derived from standard measurements of nasal cavity height and width and constructed points on nasal cavity walls (Tables 5 and 6). These constructed points required the manufacture of a template for each patient.

2.4.2.3.1 Template

In order to examine the changes in transverse nasal cavity width at different heights in the nasal cavity a template was constructed for each patient. This involved digitising the nasal cavity heights and the skeletal points right and left lateral orbit. This data was used to calculate the total nasal cavity height and construct a template that would divide the nasal cavity into four equal sections by virtue of three horizontal lines at approximately one-quarter, one half and three-quarters of the nasal cavity height. These lines were constructed parallel to the intra-orbital line. This line is equivalent to the cranial reference line reported by Hicks (1978) and Mossaz *et al.* (1992). The points L lo and R lo were used to superimpose the template underneath the acetate tracing to allow identification of the constructed points on the lateral and medial nasal cavity walls (Figure 12 and Table 6).

No.		Point	Description
56.	R ans	R anterior nasal spine	The most medial point on the right aspect of the bony margin of the maxillary suture in the region of the anterior nasal spine, if distinct, otherwise the tip of the anterior nasal spine
57.	L ans	L anterior nasal spine	The most medial point on the left aspect of the bony margin of the maxillary suture in the region of the anterior nasal spine, if distinct, otherwise the tip of the anterior nasal spine
58.	C ans	Central anterior nasal spine	Point midway between R ans and L ans, otherwise the tip of the anterior nasal spine
65.	R snc	R superior nasal cavity	Most superior aspect of the right nasal cavity
66.	R inc	R inferior nasal cavity	Most inferior aspect of the right nasal cavity halfway between the lateral and medial walls
67.	L snc	L superior nasal cavity	Most superior aspect of the left nasal cavity
68.	L inc	L inferior nasal cavity	Most inferior aspect of the left nasal cavity halfway between the lateral and medial walls
69.	R lnc	R lateral nasal cavity	Most lateral point on the right nasal cavity bony margin
70.	R mnc	R mesial nasal cavity	Most mesial point on the right nasal cavity bony margin
71.	L mnc	L mesial nasal cavity	Most mesial point on the left nasal cavity bony margin
72.	L lnc	L lateral nasal cavity	Most lateral point on the left nasal cavity bony margin

Table 5 Definition of Nasal Cavity Landmarks

No.		Point	Description
73.	R 25 lnc	R lateral nasal cavity at 25 line	Point on the lateral wall of right nasal cavity where it is biscected by the 25 line
74.	R 25 mnc	R mesial nasal cavity at 25 line	Point on the medial wall of right nasal cavity where it is biscected by the 25 line
75.	L 25 mnc	L mesial nasal cavity at 25 line	Point on the medial wall of left nasal cavity where it is biscected by the 25 line
76.	L 25 lnc	L lateral nasal cavity at 25 line	Point on the lateral wall of left nasal cavity where it is biscected by the 25 line
77.	R 50 lnc	R lateral nasal cavity at 50 line	Point on the lateral wall of right nasal cavity where it is biscected by the 50 line
78.	R 50 mnc	R mesial nasal cavity at 50 line	Point on the medial wall of right nasal cavity where it is biscected by the 50 line
79.	L 50 mnc	L mesial nasal cavity at 50 line	Point on the medial wall of left nasal cavity where it is biscected by the 50 line
80.	L 50 lnc	L lateral nasal cavity at 50 line	Point on the lateral wall of left nasal cavity where it is biscected by the 50 line
81.	R 75 lnc	R lateral nasal cavity at 75 line	Point on the lateral wall of right nasal cavity where it is biscected by the 75 line
82.	R 75 mnc	R mesial nasal cavity at 75 line	Point on the medial wall of right nasal cavity where it is biscected by the 75 line
83.	L 75 mnc	L mesial nasal cavity at 75 line	Point on the medial wall of left nasal cavity where it is biscected by the 75 line
84.	L 75 lnc	L lateral nasal cavity at 75 line	Point on the lateral wall of left nasal cavity where it is biscected by the 75 line

Table 6 Definition of Nasal Cavity Landmarks (continued)

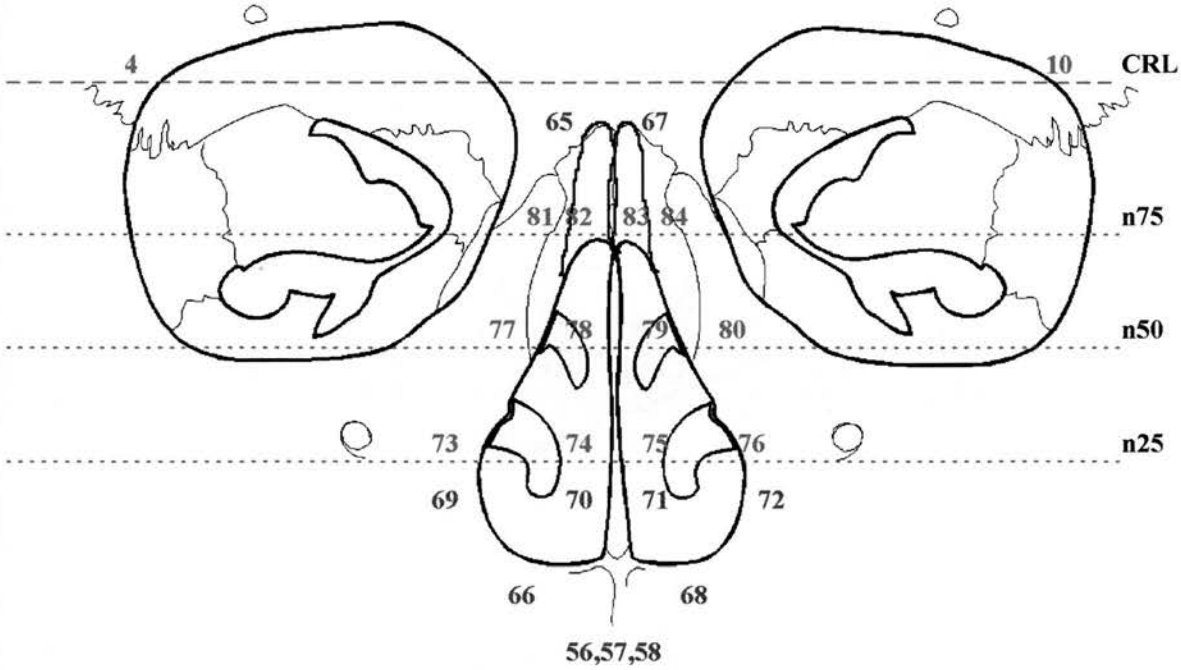


Figure 12 Nasal Cavity Landmarks (Blue are digitised landmarks, purple are constructed landmarks using the nasal template)

Description	Landmarks	Measurement
interorbital width	R lo - L lo	lo - lo
medial orbital width	R mo - L mo	mo - mo
mastoid width	R ma - L ma	ma - ma
intermaxillary width	R mx - L mx	mx - mx
mandibular width	R md - L md	md - md
antegonial width	R ag - L ag	ag - ag
upper intermolar width	R um - L um	um - um
lower intermolar width	R lm - L lm	lm - lm
upper interincisal width - apex	R U1 apx - L U 1 apx	isapx - isapx
alvoelar creastal margin width	R ascm - L acsm	isam - isam
upper interincisal width - crown	R mip - L mip	iscr - iscr
right nasal cavity height	R snc - L inc	rncht
left nasal cavity height	L snc - L inc	lncht
anterior nasal spine width	R ans - L ans	ans - ans
maximum nasal cavity width	R lnc - L lnc	nmax
maximum width of right nasal cavity	R lnc - R mnc	rnmax
maximum width of left nasal cavity	L mnc - L lnc	lnmax
width of nasal cavity at n25 line	R 25 lnc - L 25 lnc	n25
width of right nasal cavity at n25 line	R 25 lnc - R 25 mnc	r25
width of left nasal cavity at n25 line	L 25 mnc - L 25 lnc	l25
width of nasal cavity at n50 line	R 50 lnc - L 50 lnc	n50
width of right nasal cavity at n50 line	R 50 lnc - R 50 mnc	r50
width of left nasal cavity at n50 line	L 50 mnc - L 50 lnc	l50
width of nasal cavity at n75 line	R 75 lnc - L 75 lnc	n75
width of right nasal cavity at n75 line	R 75 lnc - R 75 mnc	r75
width of left nasal cavity at n75 line	L 75 mnc - L 75 lnc	l75

Table 7 Skeletal, Dental and Nasal Cavity Measurements

2.4.3 Airway Measurements

A number of different methods have been advocated to evaluate area of nasal cavity directly using PA radiographs (section1.5.3.1). In order to fully investigate any relationship between the effects of expansion and changes in nasal cavity dimensions the following measurements were selected for study (Figure 13).

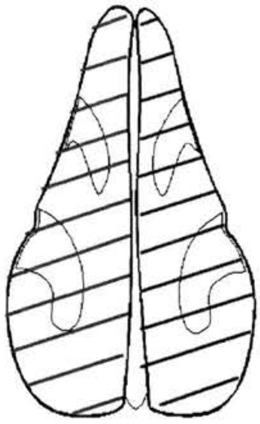
Cross-sectional area measurements

1. The area of the left and right nasal cavities seperately bounded by their lateral, medial, superior and inferior walls
2. The area of the nasal cavity trimmed at the n50 line
3. The area of the left and right nasal cavities trimmed at the n50 line

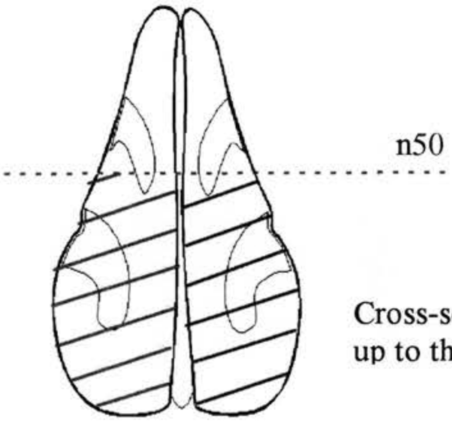
Nasal airway measurements

1. Subjective assessment as reported by Woodside and Linder-Aronson (1979)
2. Nasal Airway Index

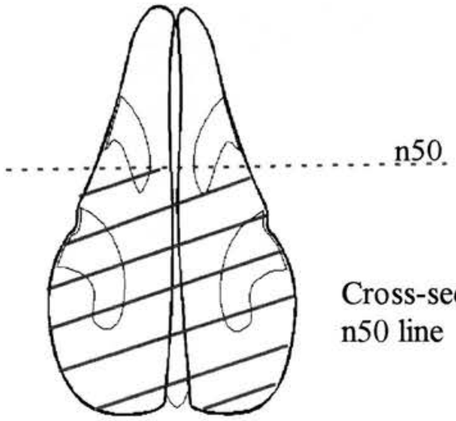
   The nasal airway index reported by Holmberg and Linder-Aronson (1979) is the total radiolucent area within the nasal cavity expressed as a percentage of the total area of the nasal cavity.



Cross-sectional area of right and left nasal cavities



Cross-sectional area of right and left nasal cavities up to the n50 line



Cross-sectional area of whole of nasal cavity up to the n50 line

Figure 13 Nasal Cavity Area Measurements

2.5 RHINOMANOMETRY

Rhinomanometric measurements were available for all patients included in this study and were taken by McDonald (1995). Recordings were obtained from controls as well as for the anomaly group both before and after expansion using a NR6 Rhinomanometer (Mercury electronics, Glasgow, UK) linked to a personal computer (BBC B Master PC, UK). As suggested by Clement (1984), the rhinomanometer was calibrated before each patient for a flow of 150cc per second peaking at 500 pascals. Nasal airway resistance was calculated at the preset pressure threshold of 150 Pa as the mean of four inspiration/expiration cycles. A nasal decongestant was administered to each patient 30 minutes before recording NAR. Xylometazoline hydrochloride spray (Otrivine, Co. UK) was used in each nostril primarily to eliminate the effect of the nasal cycle. Measurements of the nasal resistance were completed for both left and right sides of the nasal cavity by the anterior method whereas bilateral measurement of NAR was calculated by the posterior method. The NR6 Rhinomanometer was modified to allow calculation of the laminar (k1) and turbulent (k2) coefficients using the Rohrer equation (Solow and Sandham, 1991).

Anterior nasal airway resistance for left and right sides of the nose was measured by McDonald (1995) using a standard procedure (Broms, 1982; Solow and Greve, 1980). Briefly, a thin tube was fixed with tape to one nostril and connected through the visor of a scuba mask to a pneumotachograph and monitor. The resistance for each half of the nose was recorded. A total of sixteen recordings of inspiration and expiration were obtained for both left and right nostrils and mean values calculated to include turbulent and laminar coefficients. The opposite nostril was investigated in a similar manner to record a further sixteen readings. Posterior NAR was recorded by means of a large diameter polythene tube inserted into the oropharynx to record pharyngeal pressure. Sixteen recordings of inspiration and expiration were observed and again mean values calculated to turbulent and laminar coefficients.

2.6 METHOD ERROR

Method error for all linear measurements and cross-sectional area calculations were accomplished using duplicate tracings of the control sample according to Houston (1983). A period of at least four weeks elapsed between duplicate tracings and comparisons between the two sets of readings were carried out as follows. Systematic error was examined using a Student's t-test of those variables under study. Random error was examined using the modification of Dahlberg's formula suggested by Hald (1960). The results of the method error for all linear and area measurements are given in Tables 8 and 9.

2.6.1 Linear Measurements

Systematic and random error rates for the skeletal, dental and transverse nasal cavity measurements were calculated and are given in Table 8. The results indicate that no systematic differences were found for linear measurements. Method errors ranged between 0.3 mm and 0.91 mm and percentage errors varied from 1.95% to 42.52%.

2.6.2 Cross-sectional Area and Nasal Airway Index

Method error for the various direct measurements of nasal cross-sectional areas and nasal airway index were calculated in a similar way and are given in Table 9. There were no systematic differences found and percentage errors ranged from 2.36% to 88.98%.

	t1	sd	t2	diff	s(i)	s(i)%	t-test
skeletal							
lo - lo	90.9	4.9	90.91	-0.01	0.5	1.98	ns
mo - mo	24.71	2.69	24.64	0.07	0.4	5.85	ns
ma - ma	113.0	5.19	112.83	0.17	0.87	3.38	ns
mx - mx	62.75	3.08	62.71	0.04	0.38	4.01	ns
md - md	96.26	4.7	96.1	0.16	0.42	1.95	ns
ag - ag	84.67	2.4	84.83	-0.16	0.38	6.61	ns
dental							
um - um	56.4	2.89	56.5	-0.1	0.64	7.88	ns
lm - lm	55.14	2.92	55.13	0.01	0.58	7.22	ns
isapx	7.4	1.73	7.22	0.18	0.34	12.49	ns
nasal							
rncht	44.29	2.56	44.18	0.11	0.71	12.07	ns
lncht	44.68	2.35	44.52	0.16	0.59	10.77	ns
nmax	28.14	2.3	28.02	0.12	0.43	8.58	ns
rnmax	12.87	1.24	12.73	0.14	0.34	20.52	ns
lnmax	12.87	1.25	12.81	0.06	0.3	19.88	ns
n25	25.76	2.57	25.82	-0.06	0.65	10.13	ns
r25	11.42	1.84	11.41	0.01	0.61	19.42	ns
l25	11.24	1.72	11.46	-0.22	0.48	17.83	ns
n50	17.72	2.24	17.88	-0.16	0.89	16.24	ns
r50	6.62	1.66	6.7	-0.08	0.49	19.19	ns
l50	6.53	1.44	6.68	-0.15	0.77	42.52	ns
n75	7.62	2.25	7.41	0.21	0.91	16.77	ns
r75	3.09	1.32	2.94	0.15	0.56	33.37	ns
l75	2.73	1.04	2.68	0.05	0.37	37.79	ns

Table 8 Method Error for Skeletal, Dental and Nasal Linear Measurements from Duplicate Tracings of Control Group (n = 25, t_1 = time 1, t_2 = time 2, diff = t_1 - t_2)

Measurement	t1	sd	t2	diff	s(i)	s(i)%	t-test
right nasal cavity area	3.12	0.35	3.19	-0.065	0.057	47.04	ns
left nasal cavity area	3.07	0.29	3.15	-0.077	0.077	88.98	ns
right nasal cavity area A50	2.22	0.27	2.2	0.019	0.016	22.33	ns
left nasal cavity area A50	2.26	0.19	2.24	0.022	0.019	52.28	ns
total nasal cavity area A50	5.34	0.52	5.37	-0.022	0.022	8.42	ns
nasal airway index	18.44	7.45	18.32	0.12	0.012	2.36	ns

Table 9 Method Error for Nasal Area Measurements (cm^2) and Nasal Airway Index (%) from Duplicate Tracings of Control Group (n = 25, t_1 = time 1, t_2 = time 2, diff = t_1 - t_2)

2.6.3 Measurements Suitable for Further Study

The results of the method error analysis indicated there were no systematic differences found and that the majority of the measurements were associated with percentage errors of around 10% or less. However a number of measurements did have significant percentage errors and most of these measurements were excluded from further analysis. For the purposes of this study it was decided to keep the following measurements in the analysis although their associated percentage errors were larger than ideal; width between apices of upper incisors, width of nasal cavity at the n50 line and width of the nasal cavity at the n75 line. Details of the measurements selected for further study are given in Table 10.

	measurement	description
skeletal	lo - lo	interorbital width
	mo - mo	medial orbital width
	ma - ma	mastoid width
	mx - mx	intermaxillary width
	md - md	mandibular width
	ag - ag	antegonial width
dental	um - um	upper intermolar width
	lm - lm	lower intermolar width
	isapx - isapx	upper interincisal width - apex
	isam - isam	alvoelar creastal margin width
	iscr - iscr	upper interincisal width - crown
nasal	rncht	right nasal cavity height
	lncht	left nasal cavity height
	ans - ans	anterior nasal spine width
	nmax	maximum nasal cavity width
	n25	width of nasal cavity at n25 line
	n50	width of nasal cavity at n50 line
	n75	width of nasal cavity at n75 line
	A50	area of nasal cavity at A50 line
	NAI	nasal airway index

Table 10 Skeletal, Dental and Nasal Measurements Used in PA Cephalometric Analysis

2.6.4 Method Error for Rhinomanometry

Method error for the rhinomanometry measurements have been reported previously (McDonald, 1995). These were obtained by repeated measurement of fourteen subjects, eight female and six male. Measurements for right and left unilateral nasal resistance were obtained using the anterior method and total nasal resistance using the posterior method. The results for the method error analysis for rhinomanometry measurements are reproduced in Table 11. There were no systematic differences found at $p < 0.05$ level. These results compare favourably with previously published values (Sandham and Solow, 1987).

NAR		mean diff	s(i)	S(i)%	p
Anterior Right	insp	14.1	37.91	10.13	ns
	exp	18.02	38.48	9.5	ns
Anterior Left	insp	19.8	35.9	11.76	ns
	exp	2.4	18.77	3.57	ns
Posterior	insp	16.4	27.62	9.32	ns
	exp	16.1	14.79	9.83	ns

Table 11 Method Errors for Rhinomanometric Measurements

(from McDonald, 1995, n = 14)

2.7 STATISTICAL ANALYSIS

A selection of measurements were tested for normality. As far as could be ascertained all measurements tested conformed to normal distribution and this was assumed for the remainder. Parametric statistical tests were judged to be suitable for both within group and between group comparisons. Due to the number of comparisons that would be made it was decided that the level of significance should be $p < 0.01$. All statistical tests were accomplished using an Excell spreadsheet software package (Microsoft, USA). Formulae for statistical tests are given in the Appendix.

CHAPTER 3

RESULTS

3.1 CLINICAL SUBJECTS

The age and sex distribution for the control and anomaly groups are given in Tables 12 and 13. It may be seen that each group had a total of 25 subjects and that the groups are well matched for age and sex. The anomaly group had an average age of 13 years 4 months (range 11y 0m to 15y 8m) whereas the control group had an average age of 13 years 11 months (range 10y 5m to 15y 11m). Both groups contained 20 females and five males. The mean age and range for males and females for each group are given. A Student's t-test was used to determine if the groups differed significantly with respect to age. The result proved no statistically significant difference between these groups ($p = 0.247$).

3.2 RAPID MAXILLARY EXPANSION

Active expansion using RME took an average 3.75 weeks (range 2.25 - 5.5 weeks) standard deviation 0.92. Records were repeated and the appliance used as a retainer for an average of three months. The next phase of orthodontic treatment involved fixed appliances and averaged 12 months duration.

	n	mean age	range
Male	5	13y 1m	11y 6m - 14y 8m
Female	20	13y 6m	11y 0m - 15y 8m
Total	25	13y 4m	11y 0m - 15y 8m

Table 12 Age and Sex Distribution of Anomaly Group (n = 25)

	n	mean age	range
Male	5	13y 11m	11y 6m - 14y 11m
Female	20	12y 10m	10y 5m - 15y 11m
Total	25	13y 11m	10y 5m - 15y 11m

Table 13 Age and Sex Distribution of Control Group (n = 25)

3.3 TRANSVERSE MEASUREMENTS

3.3.1 Comparison of Both Groups at Baseline

A Student's t-test was used to compare the skeletal, dental and nasal linear measurements of the anomaly and control groups at baseline. Table 14 indicates that the vast majority of those transverse measurements did not differ significantly between both groups. Upper molar transverse width (um-um) was the only transverse measurement to show a statistically significant difference between these two groups. The mean upper molar width in the anomaly group was 51.87 mm whereas the mean upper molar width of the control group was 56.4 mm. The mean difference between these groups was 4.53 mm and this difference was statistically significant

($p < 0.001$).

Several measurements did show a tendency towards statistically significance, for example maxillary skeletal width (mx-mx) in the RME group had a mean value of 59.81 mm compared to 62.57 mm. The difference between these two groups was 2.26 mm however this fell short of statistical significance ($p = 0.046$). The distance between the apices of the upper central incisors (isapx-isapx) also demonstrated a tendency for statistical significance. This measurement in the RME group was 6.34 mm compared to 7.4 mm for the control group, a difference of 1.06 mm ($p = 0.011$). Skeletal, dental and nasal linear measurements for both the anomaly and control group at baseline are given in Table 14.

		anomaly	control	difference	p
skeletal	lo-lo	90.82	90.9	0.08	ns
	mo-mo	23.58	24.71	1.13	ns
	ma-ma	111.04	113.0	1.96	ns
	mx-mx	59.81	62.57	2.26	0.046
	md-md	96.38	96.26	-0.12	ns
	ag-ag	83.92	84.73	0.81	ns
dental	um-um	51.87	56.4	4.53	< 0.001
	lm-lm	55.82	55.14	-0.68	ns
	isapx-isapx	6.34	7.4	1.06	0.011
	isam-isam	0	0	-	-
	iscr-iscr	0.51	0.66	0.15	ns
nasal	rncht	44.94	44.29	-0.65	ns
	lncht	45.26	44.68	-0.58	ns
	ans	0	0	-	-
	nmax	26.84	28.14	1.3	ns
	n25	25.36	25.76	0.4	ns
	n50	16.4	17.64	1.24	ns
	n75	6.75	7.62	0.87	ns

Table 14 Linear Measurements of Anomaly and Control Groups at Baseline (both groups n = 25, two sample t-tests)

3.3.2 Effect of RME on Anomaly Group

A paired Student's t-test was used to compare the differences in transverse width between the anomaly group before treatment and during retention phase. These results are given in Table 15. There are several transverse measurements that change significantly due to the treatment with RME in this group.

3.3.2.1 Skeletal transverse measurements

There is a small but statistically significant change in skeletal maxillary width (mx-mx). The average width before treatment was 59.81 mm compared to an average width of 60.92 mm following expansion. This represented a mean difference of 1.11 mm (sd 1.41) which was statistically significant ($p < 0.001$). Seperation of the median palatine suture was observed at the level of the anterior nasal spine with the mean width between the left and right halves of the anterior nasal spine (ans-ans) following expansion found to be 3.19 mm (range 2.1 - 4.6 mm). Further evidence of seperation of the suture was evident at the level of the alveolar process close to the upper central incisors. The width between the points isam was found to increase by a mean of 3.42 mm (range 1.6 - 5.2 mm) due to expansion.

3.3.2.2 Dental transverse measurements

Dental transverse measurements that changed by a significant amount include upper molar width (um-um), the mean width for the anomaly sample before treatment was 51.87 mm compared to a mean width of 57.37 mm after expansion. This represents a mean expansion of 5.5 mm (range 1.3 - 13.8 mm) and this difference due to treatment was statistically significant ($p < 0.001$).

A small but significant increase in lower intermolar width was found. Following treatment lower intermolar width (lm-lm) increased by 0.66 mm (sd 0.91, $p = 0.0014$). The apex of the upper central incisors were carried laterally (isapx-isapx) by a mean distance of 3.98 mm (range 0.9 - 10.5 mm) due to treatment, whereas the crowns of the central incisors (iscr-iscr) were separated by a smaller amount with a mean increase of 0.9 mm.

3.3.2.3 Nasal transverse measurements

Intranasal changes were small and generally did not reach statistical significance with the exception of maximum nasal width of the nasal cavity (nmax-nmax). This was found to increase by a mean of 1.06 mm due to rapid maxillary expansion ($p < 0.001$). The height of the left and right nasal cavity was found to increase by a mean of approximately 1 mm due to RME. These increases had a tendancy towards statistical significance (Table 15).

There were no other transverse changes in skeletal, dental or nasal measurements due to expansion that reached statistical significance. These results can be found in Table 15.

		before	after	difference	p
skeletal	lo-lo	90.82	91.14	0.32	ns
	mo-mo	23.58	24.0	0.42	ns
	ma-ma	111.04	111.74	0.7	ns
	mx-mx	59.81	60.92	1.11	< 0.001
	md-md	96.38	96.72	0.34	ns
	ag-ag	83.92	84.5	0.58	ns
dental	um-um	51.87	57.37	5.5	< 0.001
	lm-lm	55.82	56.48	0.66	0.0014
	isapx-isapx	6.34	10.32	3.98	< 0.001
	isam-isam	0	3.42	3.42	-
	iscr-iscr	0.51	1.41	0.9	< 0.001
nasal	rncht	44.94	46.06	1.11	0.02
	lncht	45.26	46.53	1.26	0.02
	ans	0	3.19	3.19	-
	nmax	26.84	27.9	1.06	< 0.001
	n25	25.36	25.52	0.16	ns
	n50	16.4	16.42	0.01	ns
	n75	6.75	7.02	0.27	ns

Table 15 Effect of RME on Linear Measurements of Anomaly Group (n = 25, paired t-tests)

3.3.3 Comparison of Both Groups After Expansion

Table 16 gives the results for the skeletal, dental and nasal transverse measurements for the anomaly group after rapid maxillary expansion and the control group for comparison. It may be seen from this table that there are no statistically significant differences between both groups in either skeletal or dental measurements. This includes those differences found before treatment between these two groups i.e. skeletal maxillary width (mx-mx) and upper molar width (um-um). There was a tendancy towards statistical significance for the increase in nasal cavity height following expansion. After treatment the anomaly patients had a mean nasal cavity height of almost 2 mm more than the control group (Table 16).

		after	control	difference	p
skeletal	lo-lo	91.14	90.9	0.24	ns
	mo-mo	24.0	24.71	-0.71	ns
	ma-ma	111.74	113.0	-1.26	ns
	mx-mx	60.92	62.57	-1.65	ns
	md-md	96.72	96.26	0.46	ns
	ag-ag	84.5	84.73	-0.23	ns
dental	um-um	57.37	56.4	0.97	ns
	lm-lm	56.48	55.14	1.34	ns
	isapx-isapx	10.32	7.4	2.94	< 0.001
	isam-isam	3.42	0	-	-
	iscr-iscr	1.41	0.66	0.75	ns
nasal	rncht	46.06	44.29	1.77	0.03
	lncht	46.53	44.68	1.85	0.03
	ans	3.19	0	-	-
	nmax	27.9	28.14	-0.24	ns
	n25	25.52	25.76	-0.24	ns
	n50	16.42	17.64	-1.22	ns
	n75	7.02	7.62	-0.6	ns

Table 16 Comparison of Linear Measurements of Anomaly Group After Expansion and Control Group (both groups n = 25, two sample t-tests)

3.3.4. Comparison with Previous Studies

3.3.4.1 Control group

In order to establish the normality of the control group they were compared to standard values and ratios published by Athanasiou *et al.* (1992). These authors recommended the use of ratios to compare between different study populations and the results of this comparison are given in Table 17. The majority of these ratios are calculated by dividing the width measurement under investigation by the lateral inter-orbital distance (lo-lo). Three ratios are produced by using other standards and these are indicated in Table 17. The ratios given as standards have been selected by data published by Athanasiou *et al.* (1992) to represent closely the age ranges encountered in this study (i.e. 10-15 years). It may be seen from Table 17 that the majority of ratios for controls in this study match very closely with those published for Northern European normals, for example, the ratio of mesio-orbital width and lateral orbital width (moR) is 0.271 for both groups. In fact all skeletal, nasal and dental transverse width ratios published by these workers for this age group match very closely to those found in the control group from the Fife and Edinburgh areas.

3.3.4.2 Anomaly group

Ratios for the anomaly sample both before and after treatment are also given in Table 17. There are a number of interesting differences between these groups, for example the intermaxillary width ratio (mxR) was 0.659 for the anomaly group before treatment. This value is much lower than that for the control group in this sample which has a ratio of 0.689 and the Northern European sample reported by

Athanasiou *et al.* (1992) of 0.686. Interestingly this ratio increased to a mean value of 0.668 following expansion which indicates improvement but not complete correction. Upper molar width ratio (umR) in the anomaly sample was lower than either the control group or published normals. For the anomaly group before treatment (RME_1) this value is 0.571 compared to 0.621 for the controls and 0.61 for the published normals. After expansion this ratio had increased to 0.629 which is greater than either of the control groups. The ratio for lower molar width (lmR) for both the control groups and published normals is 0.606. This compared to a larger ratio before treatment of 0.615 for the anomaly sample, which increased to 0.62 after expansion. Other ratios in Table 17 explore relationships between other transverse measurements, for example the relationship between skeletal base and intermolar width is shown in the ratio um/mxR whereas the control and published normal ratios are similar, 0.901 for the control sample and 0.889 for the published normals, the anomaly group before treatment had a ratio of 0.867 which increased to 0.942 following expansion. A number of other ratios are also given in Table 17.

	control	Athanasiou controls	Before RME	After RME
lo ratio				
moR	0.271	0.271	0.260	0.263
maR	1.242	1.210	1.223	1.226
mxR	0.689	0.686	0.659	0.668
mdR	1.058	-	1.061	1.061
agR	0.933	0.913	0.924	0.927
nmaxR	0.309	0.307	0.296	0.306
umR	0.621	0.610	0.571	0.629
lmR	0.606	0.606	0.615	0.620
other ratios				
um/mxR	0.901	0.889	0.867	0.942
um/lmR	1.024	1.010	0.929	1.016
mx/agR	0.739	0.754	0.713	0.721

Table 17 Comparison of Control and Anomaly Groups (before and after RME) using Ratios Calculated From Linear Measurements (Athanasiou controls from Athanasiou *et al*, 1992, all groups n = 25)

da Silva *et al* (1995) published results for changes in transverse widths following RME in a group of 50 mixed dentition patients and these results are given in Table 18. Although these are absolute values and not ratios, general trends due to treatment with RME can be seen and comparisons made between both studies. For both study populations expansion is greatest at the level of the upper molars and decreases gradually as one moves superiorly through the level of the alveolus (isam), the anterior nasal spine (ans) and the nasal cavity (nmax). Upper molar width (um-um) for the da Silva population increased by a mean of 5.468 mm and this compares well with an observed mean expansion of 5.4 mm found in this study. At the level of the alveolar process (isam) da Silva found an expansion of 4.765 mm, whereas for the patients in this study the expansion averaged 3.4 mm. Expansion at the anterior nasal spine in the da Silva group had a mean of 2.656 mm whereas in this study the expansion was 3.2 mm. Finally the increase in nasal width in the da Silva group was 2.078 mm compared with 1.1 mm in this group. These figures are given in Table 18.

Table 18 also shows the amount of expansion achieved at various levels expressed as a percentage of the total expansion observed at the alveolar level. Data for da Silva *et al.* (1995) is shown together with changes observed for all RME patients and subgroups of RME patients that responded to expansion. It may be seen from Table 17 that da Silva *et al.* found only 56% of the expansion achieved at the alveolar level was present at the level of the anterior nasal spine and only 43% present at the level of the nasal cavity. In all RME patients in this study, 94% of the expansion at alveolar level was found at the anterior nasal spine, whereas only 32% of this expansion was found at the level of the nasal cavity.

	da Silva		RME		MS_1	NS_1
	mm	%	mm	%	%	%
nmax	2.078	43	1.1	32	31	51
mx-mx	2.812	59	1.1	32	42	29
ans-ans	2.656	56	3.2	94	97	89
isam-isam	4.765	100	3.4	100	100	100
iscr-iscr	2.971	-	1.1	-	-	-
isapx-isapx	3.531	-	4.0	-	-	-
um-um	5.468	-	5.4	-	-	-

Table 18 Comparison of the Amount of Expansion Produced by RME in the Anomaly Group Expressed as Total Expansion (mm) and as a Percentage of that Recorded at the Alveolar Level. (Figures reported by Da Silva (1995) and subgroups MS_1 and NS_1 given for comparison)

3.3.5 Patients Responding to Expansion

In order to further investigate and identify groups of patients who responded to treatment with rapid maxillary expansion the anomaly group was divided into various subgroups. Two parameters were selected on the basis of clinical importance and these were skeletal maxillary width (mx-mx) and maximum nasal width (nmax-nmax). An arbitrary figure of +1 mm was used to divide the anomaly group into responders and non-responders with respect to expansion at these levels.

3.3.5.1 Maxillary subgroups

Maxillary Subgroup$_1$ (MS$_1$) consisted of those subjects whose intermaxillary distance increased by at least 1 mm. Fourteen anomaly patients fell into this category, 12 female and two male, with a mean age of 13 years 11 months (Table 19). Maxillary Subgroup$_2$ (MS$_2$) consisted of the remainder of the anomaly group of eight female patients and three male patients with a mean age of 12 years and 9 months. Transverse width changes for both subgroups are given in Tables 20 and 21. With the exception of expansion at the maxillary level there is little difference in the dental and nasal changes observed between these two groups.

Table 22 compares the amount of expansion at the level of the maxillae for both subgroups. It may be seen that the mean increase in skeletal maxillary width was 2.1 mm in the responder group (MS$_1$) compared to a mean of - 0.17 mm for the nonresponders (MS$_2$). The difference between these two groups with respect to maxillary expansion was statistically significant ($p< 0.001$). This represented the only statistically significant difference between these two groups before or after expansion.

Table 18 shows the skeletal measurements of the MS_1 patients expressed as a percentage of the increase found at the alveolar level. For this subgroup of responders 97% of the increase at alveolar level was found at the level of the anterior nasal spine with 42% of the increase at alveolar level being found at the level of the maxillae. In contrast only 31% of the expansion at the alveolar level was found intra-nasally.

	female	male	mean age	p
MS_1	12	2	13y 11m	
MS_2	8	3	12y 9m	ns
NS_1	14	1	13y 4m	
NS_2	6	4	13y 5m	ns

Table 19 Age and Sex Characteristics of Maxillary and Nasal Subgroups. (Within group comparisons using two sample t-tests)

		MS_1 before	MS_1 after	difference	p
skeletal	lo-lo	90.82	91.21	0.39	ns
	mo-mo	23.84	24.44	0.6	ns
	ma-ma	111.14	111.57	0.43	ns
	mx-mx	59.64	61.74	2.1	< 0.001
	md-md	96.85	97.27	0.42	ns
	ag-ag	83.95	84.48	0.53	ns
dental	um-um	51.44	56.86	5.42	< 0.001
	lm-lm	55.32	55.89	0.57	0.059
	isapx-isapx	6.19	10.65	4.46	< 0.001
	isam-isam	0	3.43	3.43	-
	iscr-iscr	0.24	1.52	1.28	0.0028
nasal	rncht	44.65	45.68	1.03	ns
	lncht	44.89	46.26	1.37	ns
	ans	0	3.29	3.29	-
	nmax	27.16	28.21	1.05	0.011
	n25	24.76	25.13	0.37	ns
	n50	16.16	16.68	0.52	ns
	n75	6.64	7.01	0.37	ns

Table 20 Linear Measurements of Maxillary Subgroup 1 Before and After Expansion (n = 14, paired t-tests)

		MS_2 before	MS_2 after	difference	p
skeletal	lo-lo	90.81	91.05	0.24	ns
	mo-mo	23.24	23.43	0.19	ns
	ma-ma	110.91	111.96	1.06	ns
	mx-mx	60.04	59.87	-0.17	ns
	md-md	95.77	96.01	0.24	ns
	ag-ag	83.89	84.53	0.64	ns
dental	um-um	52.41	58.01	5.6	< 0.001
	lm-lm	56.46	57.24	0.78	ns
	isapx-isapx	6.54	9.91	3.37	< 0.001
	isam-isam	0	3.41	3.41	-
	iscr-iscr	0.86	1.27	0.41	ns
nasal	rncht	45.32	46.54	1.22	ns
	lncht	45.75	46.82	1.07	ns
	ans	0	3.27	3.27	-
	nmax	26.45	27.5	1.05	0.0025
	n25	26.13	26.03	-0.1	ns
	n50	16.73	16.1	-0.63	ns
	n75	6.9	7.04	0.14	ns

Table 21 Linear Measurements of Maxillary Subgroup 2 Before and After Expansion (n = 11, paired t-tests)

	MS_1			MS_2			
	before	after	diff	before	after	diff	p
min	52.6	54.9	1.2	53.6	54.3	-2.3	
max	71.0	72.2	3.2	66.6	66.8	0.8	
mean	59.64	61.74	2.1	60.04	59.87	-0.17	< 0.001
sd	4.46	4.09	0.66	3.54	3.66	1.02	

Table 22 Comparison of Maxillary Width Change for Subgroups MS_1 (n = 14) and MS_2 (n = 11) Before and After Expansion (two sample t-test)

3.3.5.2 Nasal subgroups

Subjects were selected for Nasal Subgroup$_1$ (NS$_1$) if they demonstrated an increase in intranasal width of at least 1 mm. Fifteen patients fell into this category, 14 females and one male. Nasal Subgroup$_2$ (NS$_2$) consisted of the remaining 10 anomaly patients. The sex and age characteristics of these subgroups are given in Table 19. The skeletal, dental and nasal transverse measurements for these subgroups before and after expansion are given in Tables 23 and 24. The mean increase in intranasal width for NS$_1$ patients is 1.73 mm, which compared to 0.04 mm for NS$_2$ patients. This difference in intranasal width due to expansion between these two groups is statistically significant ($p < 0.001$, Table 25). There is a difference in nasal cavity heights between the two subgroups. For the nasal responder subgroup (NS$_1$) the mean increase in nasal cavity height is between 1.5 and 2 mm following expansion which had a tendency towards statistical significance (Table 23). In contrast the small change in nasal cavity height for the other subgroup who have limited intranasal expansion was not statistically significant (Table 24).

Table 18 shows the skeletal transverse measurements for NS$_1$ expressed as a percentage of the alveolar level increase. It may be seen that for this subgroup of responders only 51% of the expansion at the alveolar level was achieved intranasally. This contrasts with 29% at the maxillary level and 89% at the level of anterior nasal spine.

		NS_1 before	NS_1 after	difference	p
skeletal	lo-lo	90.58	91.0	0.42	ns
	mo-mo	23.39	23.82	0.43	ns
	ma-ma	110.34	111.19	0.85	ns
	mx-mx	60.41	61.32	0.91	0.0095
	md-md	96.94	97.33	0.39	ns
	ag-ag	84.55	85.16	0.61	ns
dental	um-um	51.82	57.63	5.41	< 0.001
	lm-lm	55.08	56.08	1.0	< 0.001
	isapx-isapx	6.55	11.0	4.45	< 0.001
	isam-isam	0	3.53	3.53	-
	iscr-iscr	0.57	1.46	0.89	< 0.001
nasal	rncht	44.91	46.59	1.69	0.036
	lncht	45.2	47.1	1.9	0.028
	ans	0	3.09	3.09	-
	nmax	27.05	28.78	1.73	< 0.001
	n25	24.92	25.44	0.52	ns
	n50	15.97	16.27	0.3	ns
	n75	6.59	7.18	0.59	ns

Table 23 Linear Measurements of Nasal Subgroup 1 Before and After Expansion (n = 15, paired t-tests)

		NS_2 before	NS_2 after	difference	p
skeletal	lo-lo	91.17	91.36	0.19	ns
	mo-mo	23.86	24.26	0.4	ns
	ma-ma	111.93	112.56	0.63	ns
	mx-mx	58.92	60.26	1.34	0.034
	md-md	95.53	95.8	0.27	ns
	ag-ag	82.99	83.51	0.52	ns
dental	um-um	51.94	57.57	5.63	< 0.001
	lm-lm	56.94	57.08	0.14	ns
	isapx-isapx	6.02	9.38	3.36	< 0.001
	isam-isam	0	3.26	3.26	-
	iscr-iscr	0.43	1.34	0.91	ns
nasal	rncht	45.0	45.25	0.25	ns
	lncht	45.36	45.67	0.31	ns
	ans	0	3.34	3.34	-
	nmax	26.54	26.58	0.04	ns
	n25	26.03	25.65	-0.38	ns
	n50	17.06	16.65	-0.41	ns
	n75	7.0	6.79	-0.21	ns

Table 24 Linear Measurements of Nasal Subgroup 2 Before and After Expansion (n = 10, paired t-tests)

	NS$_1$			NS$_2$			
	before	after	diff	before	after	diff	p
min	22.1	23.2	1.0	12.2	11.6	-2.1	
max	31.0	32.5	2.9	31.5	30.7	0.9	
mean	27.05	28.78	1.73	26.54	26.58	0.04	< 0.001
sd	2.61	2.93	0.61	5.4	5.68	0.96	

Table 25 Comparison of Maximum Nasal Width Change for Subgroups NS$_1$ (n = 15) and NS$_2$ (n = 10) Before and After Expansion (two sample t-test)

3.4 NASAL CROSS-SECTIONAL AREA AND AIRWAY MEASUREMENTS

3.4.1 Cross-sectional Area Measurements

The cross-sectional area reported in this section corresponds to the area of the nasal cavity trimmed superiorly at the n50 level and is designated as A50. Table 26 indicates the mean cross-sectional area for controls was 5.66 cm^2 compared to 5.43 cm^2 for the anomaly group before treatment. This difference failed to reach statistical significance. Table 26 also gives the mean cross-sectional area for the anomaly group after expansion. The mean cross-sectional area before expansion was 5.43 cm^2 and 5.74 cm^2 after expansion. The mean difference due to expansion was therefore 0.3 cm^2 which represents an increase of 5.7%. This increase in cross-sectional area due to expansion with RME was statistically significant ($p < 0.001$). Further examination of these data revealled that a subgroup of seven female patients demonstrated a mean increase of 0.7 cm^2 (sd 0.12). For this group of patients this represented an mean increase of 13.1% in cross-sectional area, whereas the remaining 18 patients had a mean increase of 0.15 cm^2 (sd 0.19) which translates into an increase of only 2.8%.

	control	anomaly	
		before	after
min	4.54	4.39	4.94
max	7.62	6.34	7.16
mean	5.66	5.43	5.74
sd	0.75	0.53	0.6

p value ns < 0.001

Table 26 Comparison of Cross-sectional Area Between Control and Anomaly Groups Before Expansion (both $n = 25$) and Between the Anomaly Group Before and After Expansion ($n = 25$, units cm^2, two sample t-tests).

3.4.2 Nasal Airway Index for Control Group

Data for the control group was used to investigate the usefulness of the subjective assessment of nasal obstruction reported by Woodside and Linder-Aronson (1979) and the nasal airway index reported by Holmberg and Linder-Aronson (1979). Figure 14 compares these two variables. Nasal airway index (NAI%) has been charted on the y-axis and three categories of nasal obstruction on the x-axis. These categories are; 1. total obstruction (to), 2. partial obstruction (po) and 3. open nasal passages (onp). It may be seen that nasal airway index correlates reasonably well with the subjective assessment.

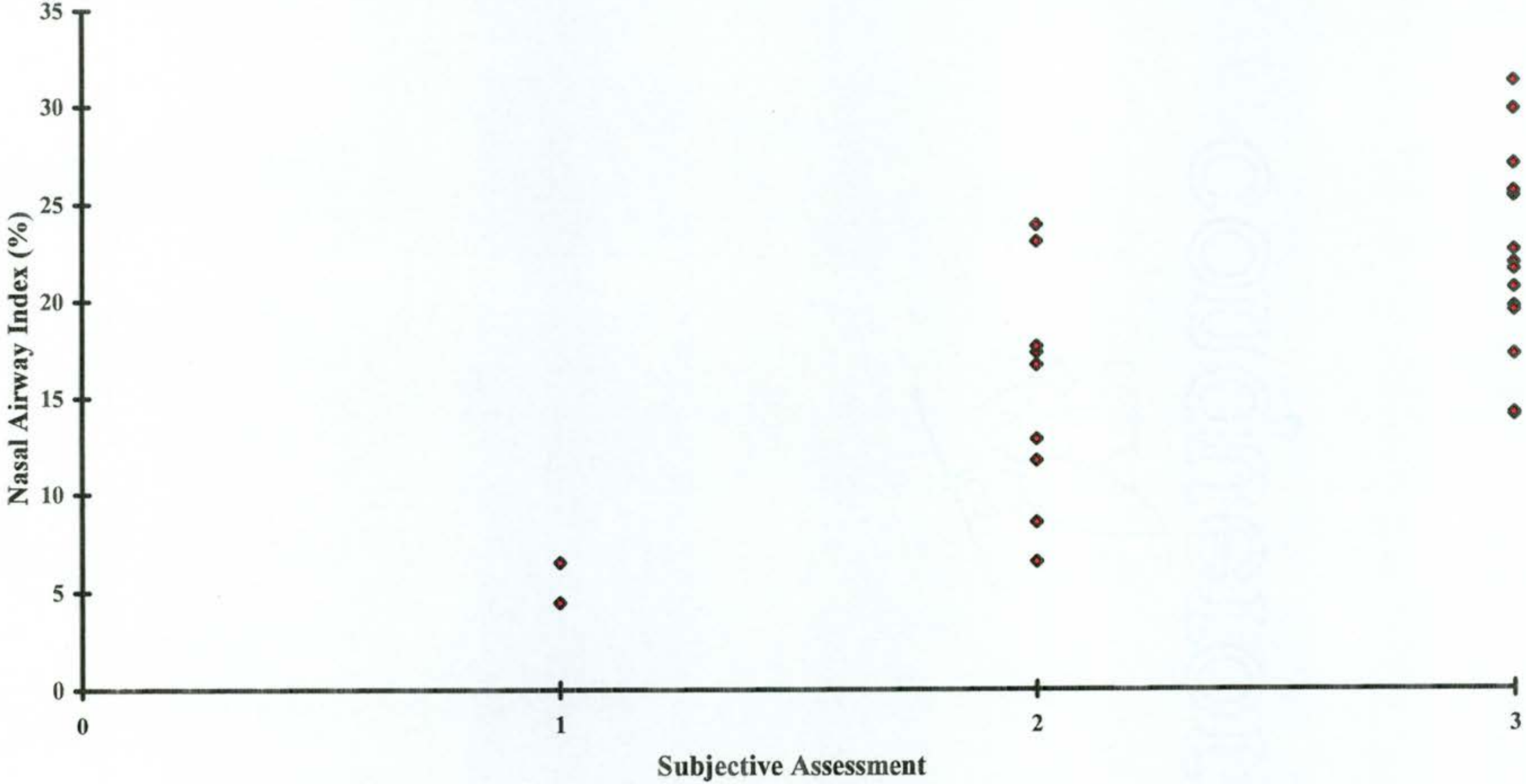


Figure 14 Nasal Airway Index (%) compared to subjective assessment of nasal patency using data collected from the control group (n = 25). Woodside and Linder-Aronson (1979) where 1 = total obstruction, 2 = partial obstruction, 3 = open nasal passages

3.4.3 Nasal Airway Index and Rapid Maxillary Expansion

For a variety of reasons it was found that nasal airway index was very difficult to measure on radiographs following rapid maxillary expansion and it was decided that this index was not suitable to compare the effects rapid maxillary expansion on the nasal cavity (section 4.5.2).

3.5. NASAL AIRWAY RESISTANCE

3.5.1 Control Group

The mean values for anterior and posterior NAR for control patients are given in Table 27. These values represent a mean of the inspiration and expiration measurements for each patient. The control group have a mean anterior NAR of 393.08 Pa/cc/s (sd 96.03) and a mean posterior NAR of 446.79 Pa/cc/s (sd 196.97). Also given in Table 27 are the mean values for the anomaly group before and after expansion.

3.5.1.1 Transverse and area measurements

A number of measurements were selected to investigate the possibility of a relationship between the dimensions of the skeletal, dental or nasal cavity in the control group and either anterior or posterior NAR. The following measurements were used; maximum nasal cavity width (nmax), width of the nasal cavity at the n25, n50 and n75 line, maxillary skeletal width (mx-mx), upper molar width (um-um), area of the nasal cavity below the n50 line (A50), and NAI. By plotting each of these variables against anterior and posterior NAR in turn a random scatter of points resulted in each case. No relationship could be established between these transverse or area measurements taken from PA cephalometric radiographs and either anterior NAR or posterior NAR.

		Anterior NAR (Pa/cc/s)			Posterior NAR (Pa/cc/s)		
		mean	sd	p	mean	sd	p
Control		393.08	96.03		446.79	196.97	
Anomaly	Before	422.17	134.1	ns	515.64	525.5	ns
	After	384.13	115.89	ns	489.32	207.98	ns

Table 27 Comparison of Anterior and Posterior NAR for Control and Anomaly Groups Before Expansion and Between the Anomaly Group Before and After Expansion (all groups n = 25, two sample t-tests)

3.5.2 Anomaly Group

The mean values for anterior and posterior NAR for the anomaly group before and after expansion are given in Table 27. The mean anterior NAR before expansion is 422.17 Pa/cc/s (sd 134.1) and the mean posterior NAR is 515.64 Pa/cc/s (sd 525.5). Although the mean values for both anterior and posterior NAR tended to be higher in the anomaly group before expansion the differences were not statistically significant from those values for the control group (Table 27). The mean values of anterior and posterior NAR after expansion are also given and although they show a tendency to reduce following expansion the differences were not statistically significant.

3.5.2.1 Effects of RME on Anterior NAR

Figure 15 charts the changes in total anterior nasal airway resistance for each patient. It may be seen that following rapid maxillary expansion, some patients have a reduction in anterior nasal airway resistance, some patients remain the same and others show an increase in total anterior nasal airway resistance.

Nominal values of plus or minus 10% change in anterior NAR were used to classify patients into three groups i.e. those who experienced an increase, a reduction or no change in anterior NAR as a result of expansion. Table 28 indicates that 11 patients demonstrated a reduction in total anterior nasal airway resistance which had a mean value of 27.5%. In 8 patients total anterior nasal airway resistance remained roughly the same with a mean change of -1%, and in 4 patients it was found that total anterior nasal airway resistance increased to a mean of + 50.6%.

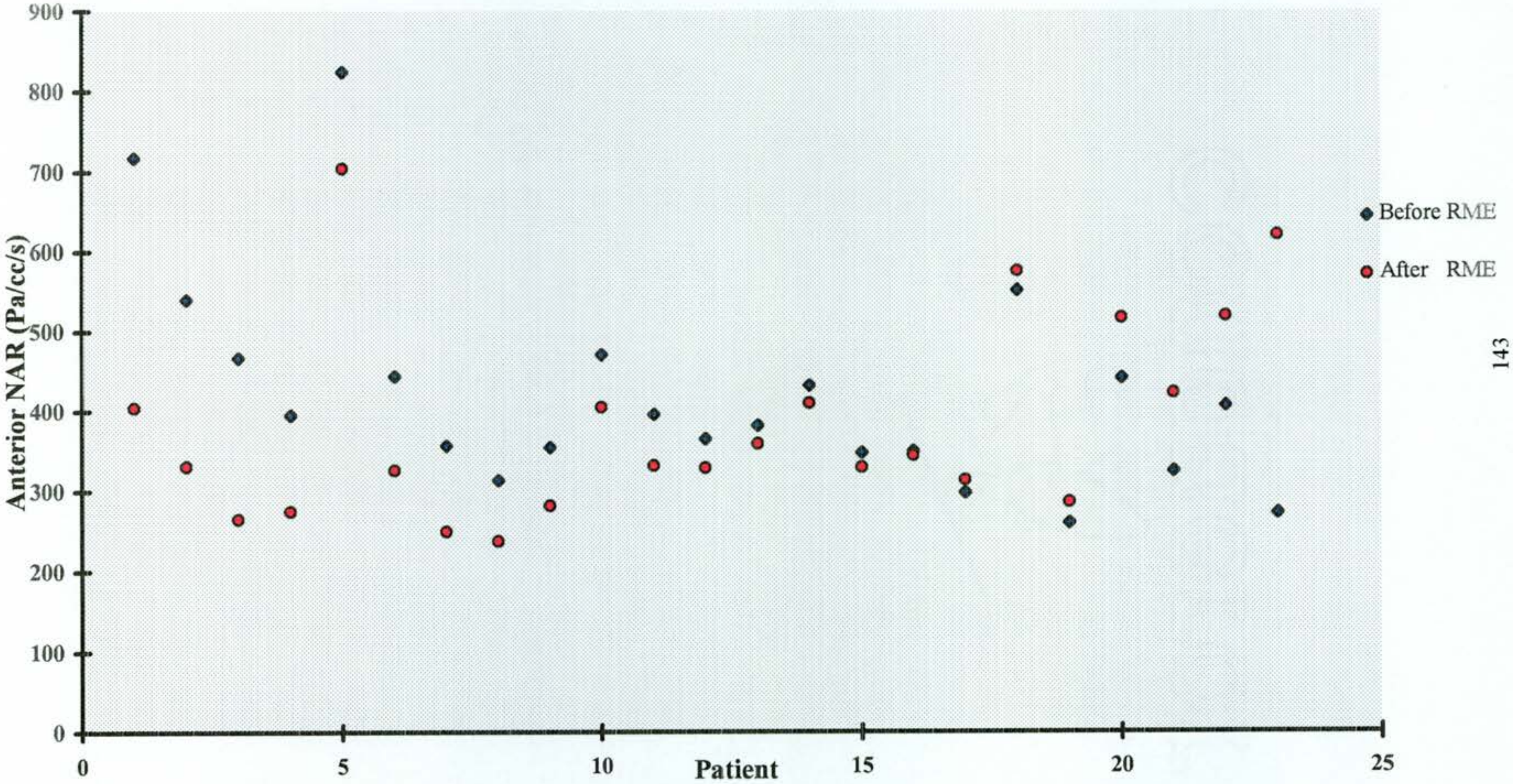


Figure 15 Change in Anterior NAR Before and After RME (n = 23, patients arranged in descending order of reduction in NAR)

anterior NAR	n	mean difference	percentage change
reduction	11	- 133.5	-27.5%
same	8	- 4.9	-1.0%
increase	4	158.0	50.6%

Table 28 Effect of RME on Anterior NAR on Anomaly Group (n = 23)

3.5.2.2 Skeletal, dental and nasal measurements affecting anterior NAR

A number of measurements were selected to investigate change in anterior NAR due to treatment. Each of these variables were plotted in turn with percentage change in anterior NAR to search for a relationship. These measurements chosen were; width of anterior nasal spine (ans-ans), maximum width of the nasal cavity (nmax), intermaxillary width (mx-mx), intermolar width (um-um) and cross-sectional area (A50).

Figure 16 plots total anterior nasal airway resistance against the increase in anterior nasal spine width and is typical of the plots for the remaining measurements. This was attempted to establish a relationship between the changes observed at the anterior part of the median palatine suture and the resistance at the anterior aspect of the nasal cavity. It may be seen from this graph that in this group of patients there was little relationship between total anterior nasal airway resistance and width of the median palatine suture at the anterior nasal spine. This was also the finding from the other plots of the remaining measurements and change in anterior nasal airway resistance due to expansion.

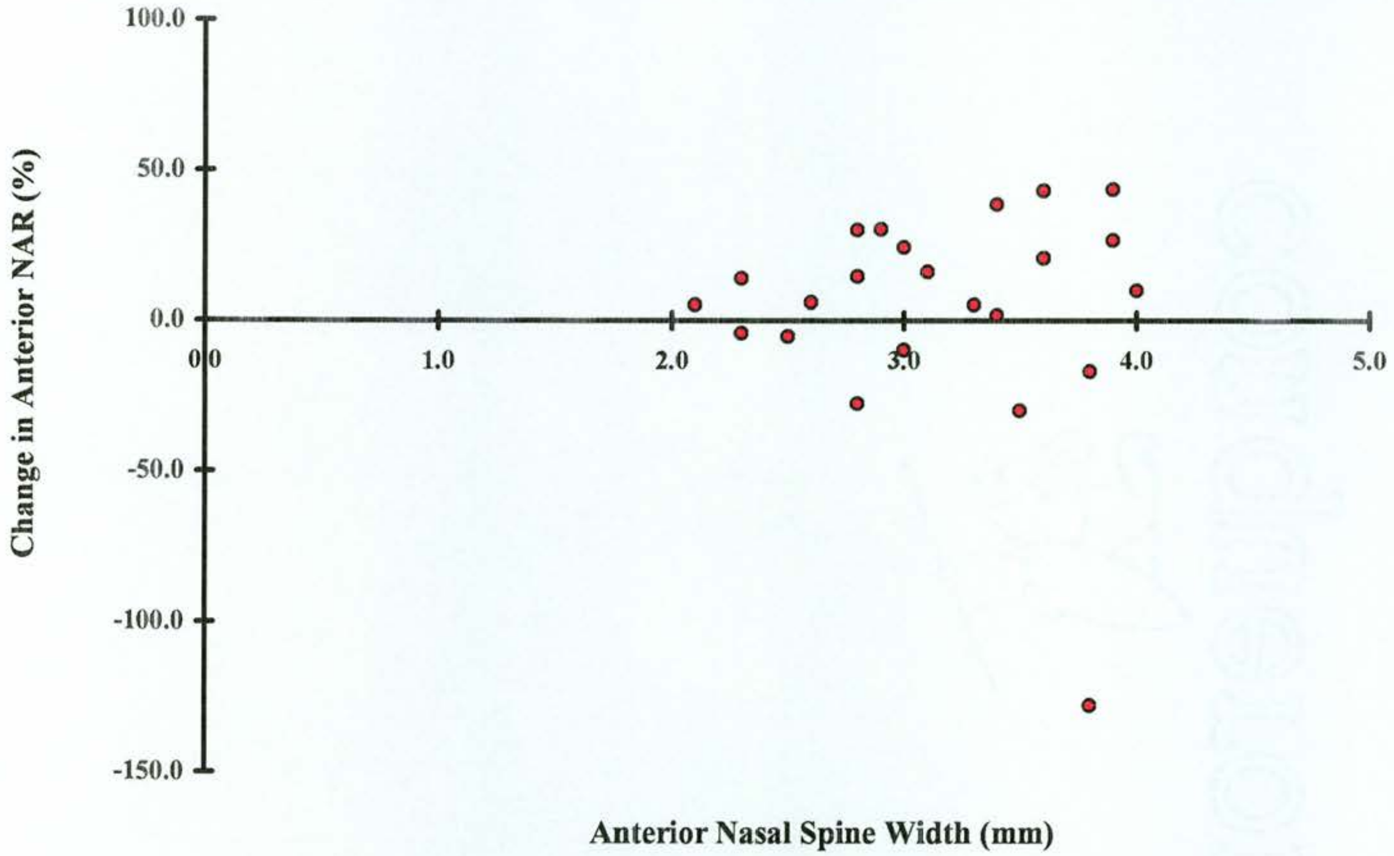


Figure 16 Change in Anterior NAR and ANS width (change in anterior NAR expressed as a percentage, n = 23)

3.5.2.3 Anterior NAR and initial linear measurements

Table 29 reports the initial skeletal, dental and nasal measurements of three groups of patients with regard to anterior nasal airway resistance. These groups are the same as described above for changes in anterior nasal airway resistance following treatment with rapid maxillary expansion. For a selection of skeletal, dental and nasal transverse widths analysis of variance was carried out to identify any statistical differences between mean values for transverse widths between groups showing changes in anterior nasal airway resistance. It may be seen from Table 29 that with regard to intra-orbital distance, group one had a mean of 89.72 mm, group two a mean of 92.42 mm and group three a mean of 89.83 mm. These differences were not statistically significant. A statistical difference was found for the mean transverse width at the maxillary level (mx-mx) with group one having a mean of 57.25 mm, group two 61.56 mm and group three 62.50 mm ($p = 0.01$). Differences were also found for the mean intermolar widths for these three groups with group one having a mean intermolar width of 50.05 mm, group two 52.42 mm and group three 55.48 mm. These differences were statistically significant ($p = 0.004$). There were no differences of statistical significance found in any of the intranasal transverse widths and this was true for maximum width of the nasal cavity and at the n25, n50 and n75 line. Details of the mean widths for these categories and their groups are given in Table 29.

Table 30 contains ratios of interorbital width with intermaxillary width and upper molar width (mxR and umR) for both control and anomaly groups. Those patients who experienced a reduction in anterior NAR had an initial mxR of 0.638 whereas those patients who experienced and increase in anterior NAR had an initial ratio of 0.696. There is a similar pattern with regard to changes in anterior NAR and initial umR ratios (Table 30). It is interesting to note that in both cases reductions in anterior NAR were observed in those patients with the lowest initial mxR and umR ratios. Furthermore those patients who did not seem to benefit from RME with respect to anterior NAR had initial ratios close to those values found in both control groups.

	change in anterior NAR			
	reduction	same	increase	p
lo-lo	89.72	92.42	89.83	ns
mx-mx	57.25	61.56	62.5	0.01
um-um	50.05	52.42	55.48	0.004
nmax	27.03	26.33	27.63	ns
n25	24.75	25.66	26.3	ns
n50	15.94	17.23	15.65	ns
n75	6.66	7.17	5.95	ns
rncht	44.8	45.12	44.98	ns
lncht	45.22	45.54	44.7	ns

Table 29 Anterior NAR and Initial Linear Measurements (n = 23) (Single factor ANOVA used to test the hypothesis that initial measurements of transverse width were related to change in anterior NAR after expansion)

			change in anterior NAR		
lo ratios	Athanasiou	controls	reduction	same	increase
mxR	0.686	0.689	0.638	0.666	0.696
umR	0.610	0.621	0.558	0.567	0.618

Table 30 Comparison with Previously Published Ratios

3.5.2.4 Effect of RME on Posterior NAR

Figure 17 charts the changes in posterior NAR due to expansion with RME for each patient. It may be seen from this graph that not all patients responded in a similar way. Table 31 subdivides these patients into three groups using the same criteria as given above; those which demonstrated a reduction in posterior nasal airway resistance, those that stayed roughly the same and those that demonstrated an increase in posterior nasal airway resistance. It may be seen that nine patients in total had a mean reduction of 32.5%, 11 patients had roughly the same nasal airway resistance and five patients showed an increase in nasal airway resistance of 86.5% following rapid maxillary expansion.

3.5.2.5 Skeletal, dental and nasal measurements affecting posterior NAR

The relationship between change in posterior NAR and selected measurements was investigated in a similar manner to that described above for anterior NAR. The selected measurements were; maximum width of the nasal cavity (nmax), intermaxillary width (mx-mx), intermolar width (um-um) and cross-sectional area (A50).

No clear relationship was established between any of these measurements and the change in posterior nasal airway resistance observed due to expansion. Figure 18 demonstrates the result of plotting posterior nasal airway resistance and percentage change in nasal cross-sectional area (A50) and is typical of the results obtained with the other measurements with a seemingly random scatter of points.

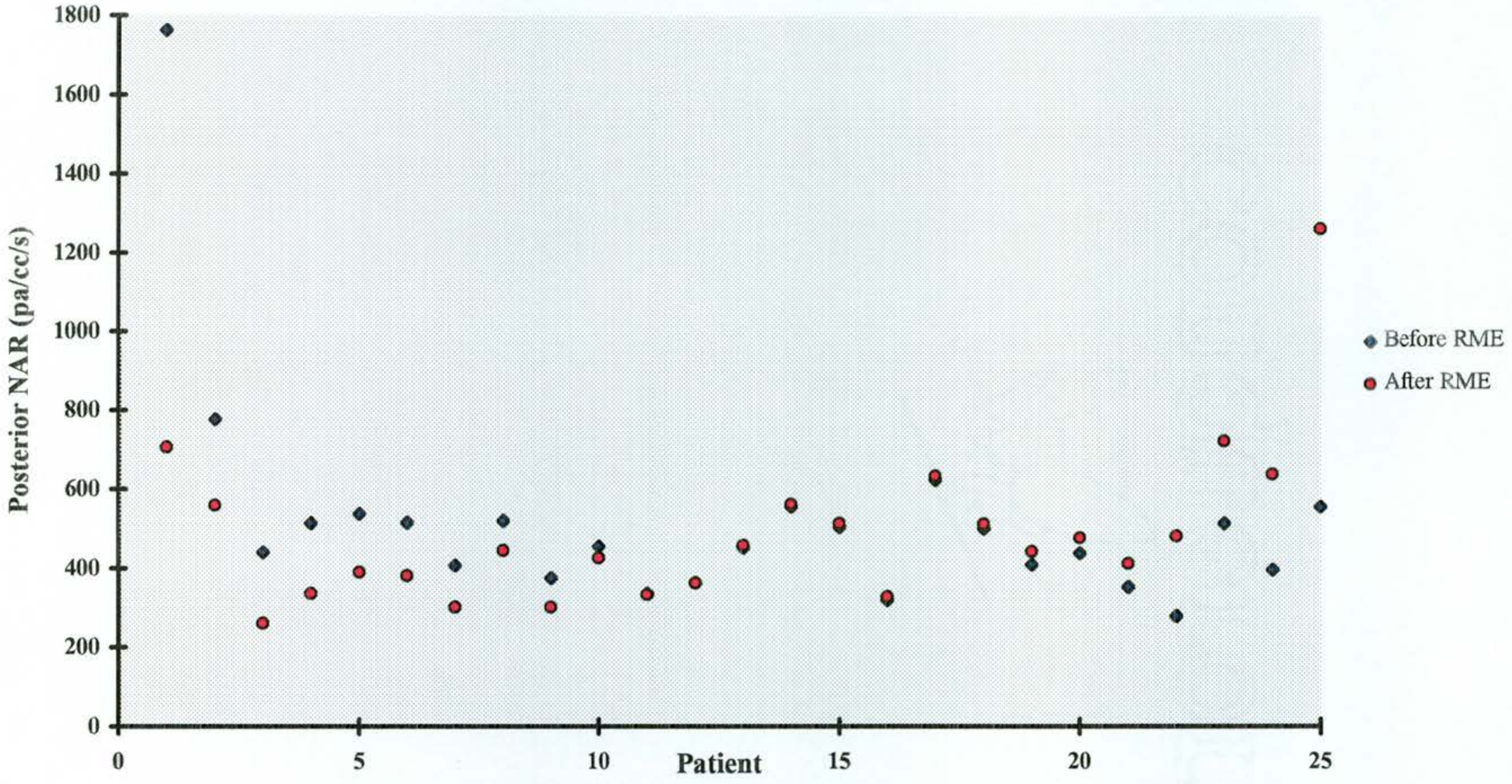


Figure 17 Comparison of Posterior NAR Before and After RME (n = 25, patients arranged in descending order of reduction in NAR)

posterior NAR	n	mean difference	percentage change
reduction	9	- 240.5	- 32.5 %
same	11	- 12.2	- 2.3 %
increase	5	282.6	86.5 %

Table 31 Effect of RME on Posterior NAR on Anomaly Group (n = 25)

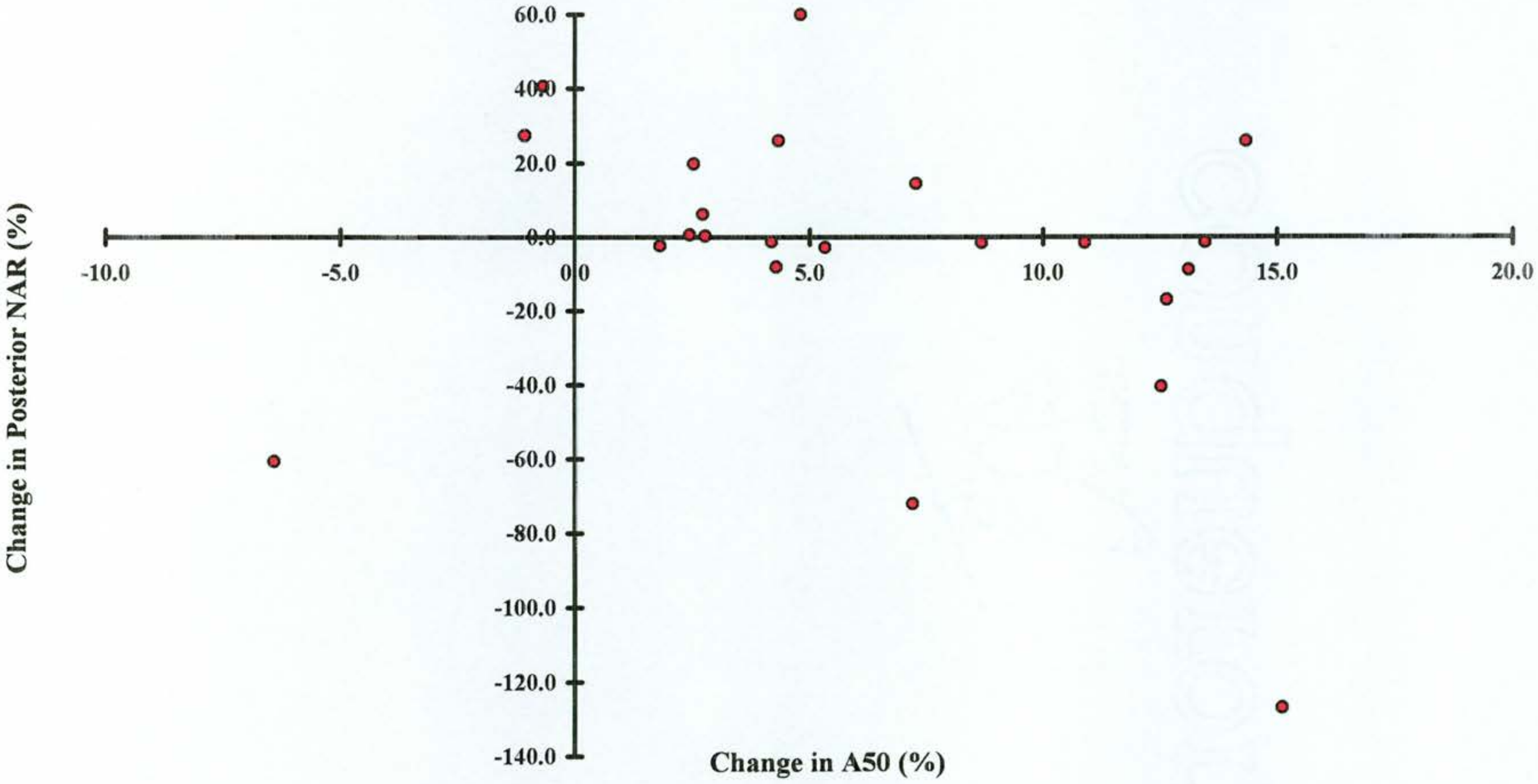


Figure 18 Change in Posterior Nasal Airway Resistance and A50 (n = 25, change in posterior NAR and cross-sectional area expressed as percentages)

3.5.2.6 Posterior NAR and initial linear measurements

To determine if change in posterior NAR was related to initial skeletal, dental or nasal measurements analysis of variance was used across the three groups of patients identified above that comprised of those who experienced a reduction in posterior nasal airway resistance, those that remained roughly the same and those that experienced an increase in posterior nasal airway resistance after rapid maxillary expansion. Results are given in Table 32 and there were no statistically significant differences found between these groups.

	change in posterior NAR			
	reduction	same	increase	p
lo-lo	91.88	90.67	89.22	ns
mx-mx	58.89	60.45	60.08	ns
um-um	51.2	51.62	53.62	ns
nmax	27.37	26.78	26.03	ns
n25	25.39	26.04	23.84	ns
n50	15.89	17.41	15.14	ns
n75	6.93	6.94	6.02	ns
rncht	46.28	43.91	44.82	ns
lncht	46.3	44.39	45.32	ns

Table 32 Posterior NAR and Initial Linear Measurements (n = 25) (Single factor ANOVA used to test the hypothesis that initial measurements of transverse width were related to change in posterior NAR after expansion)

3.5.3 Relationship Between Anterior NAR and Posterior NAR due to RME

A contingency table was used to investigate if changes in anterior nasal airway resistance were correlated with those experienced in posterior nasal airway resistance following expansion with RME (Table 33). Figure 19 charts percentage reduction in posterior nasal airway resistance on the y-axis with percentage reduction in anterior nasal airway resistance on the x-axis.

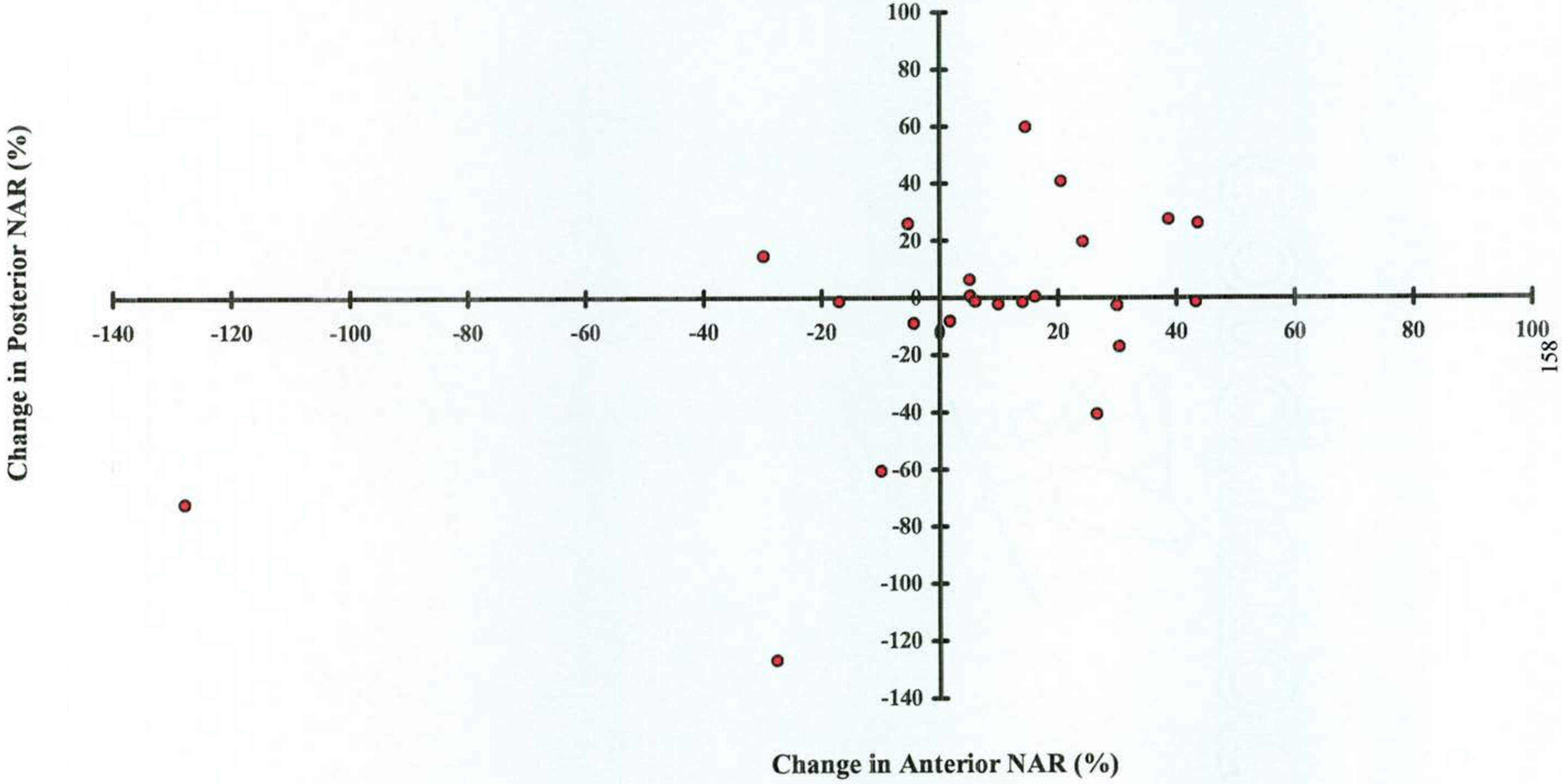


Figure 19 Changes in Anterior and Posterior Nasal Airway Resistance due to RME (n = 23, change in both anterior and posterior NAR expressed as percentages)

	posterior NAR			
	reduction	same	increase	**total**
anterior NAR				
reduction	5	4	2	11
same	1	6	0	7
increase	2	0	3	5
total	8	10	5	23

Table 33 Comparison of Change in Anterior and Posterior NAR due to Expansion Within Each Patient (n = 23)

3.5.4 Changes in Nasal Airflow due to RME

3.5.4.1 Anterior airflow

Anterior airflow was compared between the control group and anomaly groups by calculating the the turbulent component expressed as a percentage (T%) using the equation given above (section 1.5.2). Figure 20 compares the change in turbulent component of flow for unilateral breathing with increasing flow rates for the control group and anomaly groups. There is little difference in nasal airflow for unilateral breathing between these groups.

3.5.4.2 Posterior airflow

In a similar manner posterior airflow for bilateral breathing was compared. Figure 21 compares turbulent component of flow for bilateral breathing with increasing flow rates for control and anomaly groups. This comparison also indicates little difference between the groups.

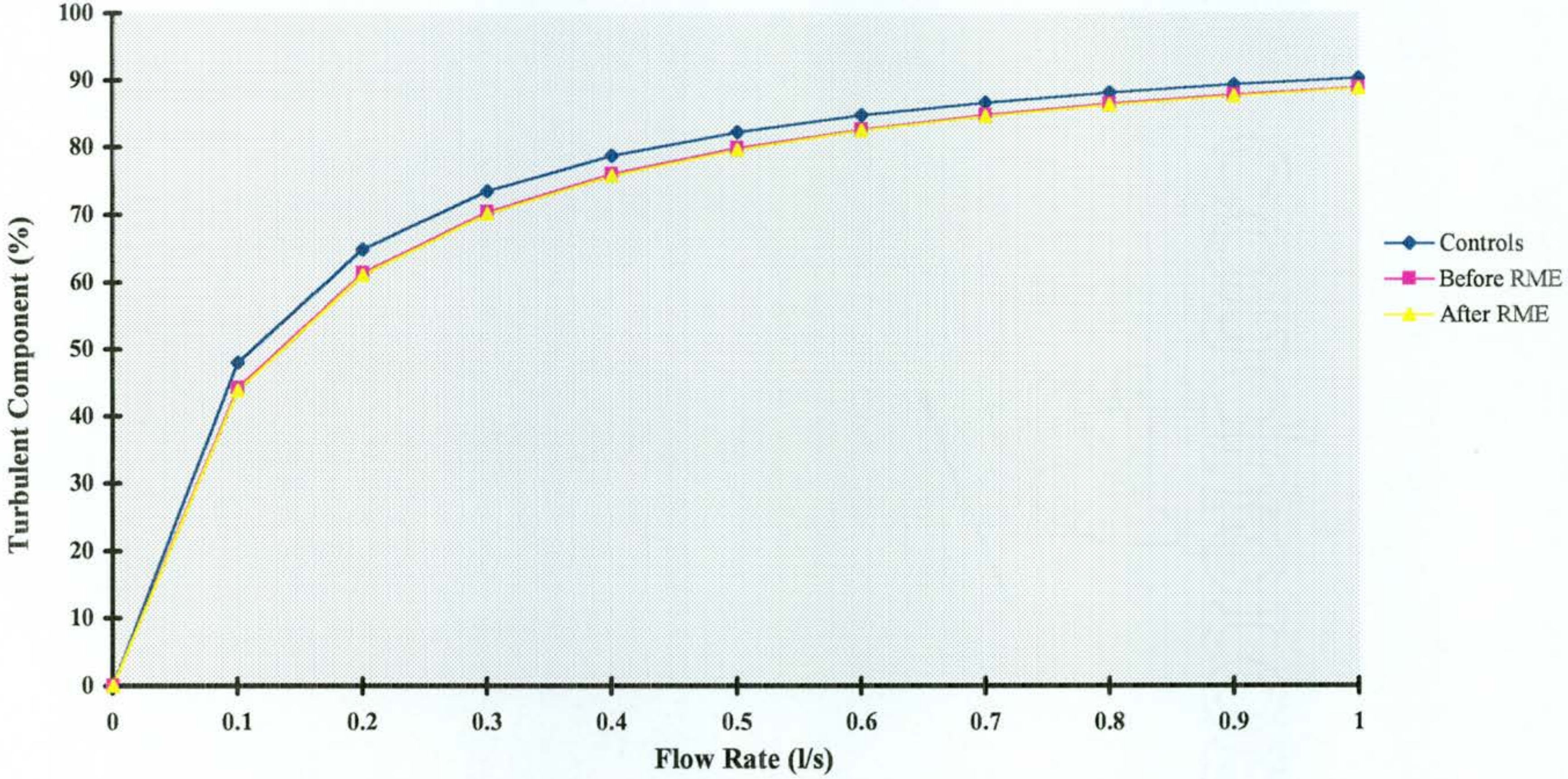


Figure 20 Turbulent Component of Flow For Unilateral Breathing (recorded at 150 Pa, n = 23)

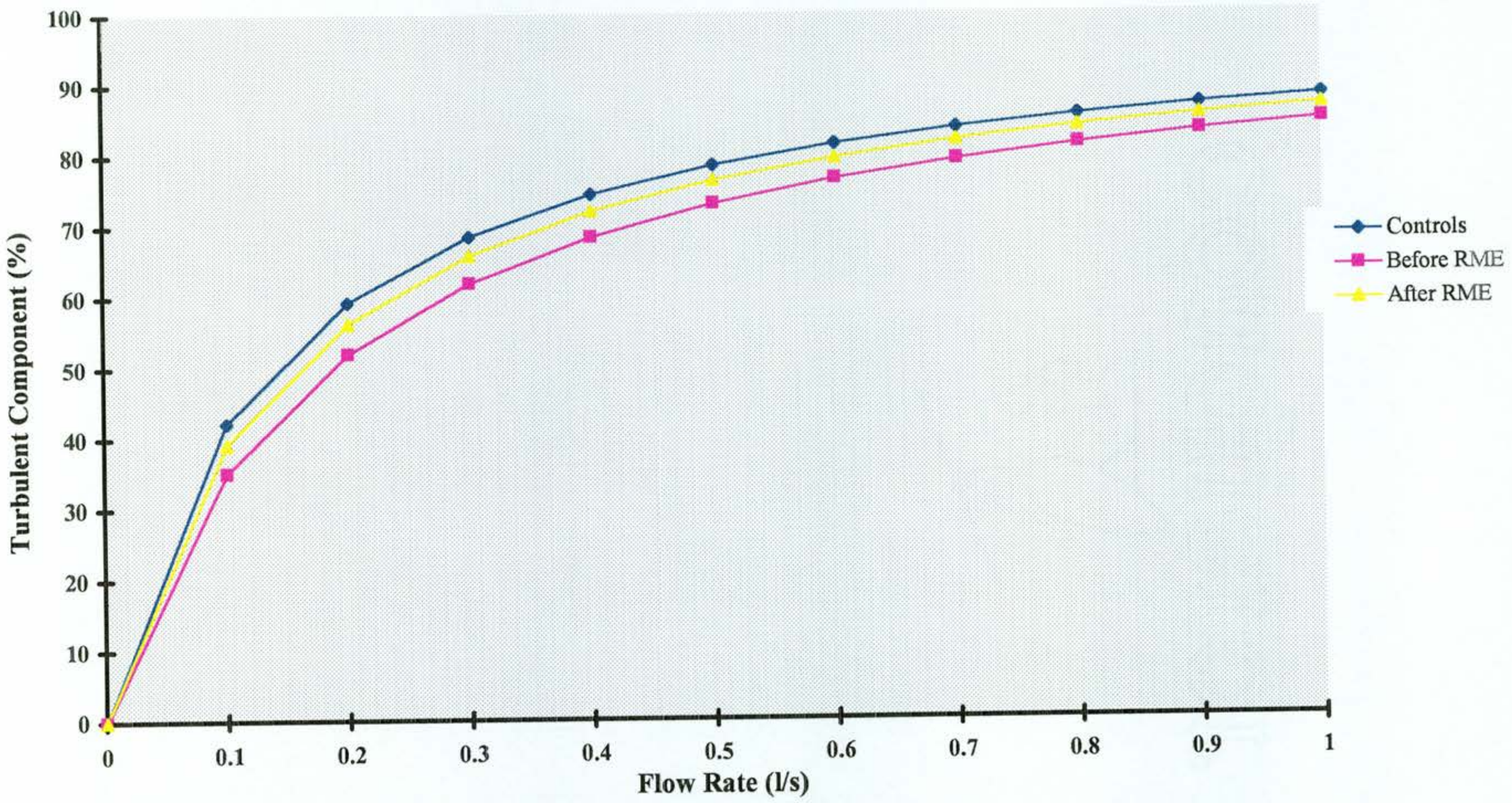


Figure 21 Turbulent Component of Flow for Bilateral Breathing (recorded at 150 Pa, n = 25)

CHAPTER 4

DISCUSSION

4.1 OBJECTIVES OF STUDY

The objectives outlined at the beginning of this thesis were:

1. To evaluate methods of measuring the transverse dimension and cross-sectional area of the skeletal, dental and nasal structures from PA cephalometric radiographs
2. To compare these parameters between a group of patients with a narrow maxillary arch and a group of sex and age matched controls
3. To investigate the effect of rapid maxillary expansion on skeletal, dental and nasal structures
4. To establish any relationship between nasal cavity dimensions and nasal airway resistance in the healthy control group
5. To investigate changes in nasal airway resistance after treatment with rapid maxillary expansion

To discuss the fulfilment of these objectives this section will begin with comments on study design and the radiological and digitising techniques used. Then follows an explanation of method error and finally a discussion of the results is undertaken.

4.2 GENERAL COMMENTS ON STUDY DESIGN

This was a retrospective study using a selection of control and anomaly patients from a previous research project based in the Edinburgh and Fife area (McDonald, 1995). The patients used in this study were selected as follows.

4.2.1 Anomaly Group

Twenty-five subjects were chosen from the anomaly sample of 72 cases that exhibited maxillary narrowness and a posterior crossbite. These subjects were selected because they fulfilled strict criteria. Full medical and dental records had to be available including good quality PA and lateral cephalometric radiographs. It was felt important that the post-expansion radiograph should include the RME appliance in situ. This was considered the only way to ensure that the changes observed were due to maxillary expansion alone and not affected by any tendency towards relapse following the removal of the appliance.

The anomaly group contained 20 females and five males which reflected to a degree the difference in sex ratio in the original sample. This difference in sex distribution could be expected to have little effect in the transverse widths and ratios as seen on the PA radiographs for either the control group or anomaly group before treatment. Previous workers have commented on the similarity in PA transverse dimensions between the sexes (Athanasiou *et al.*, 1992). However in a study of the effects of rapid maxillary expansion differences between the sexes may prove to be important as it is known that the facial skeleton increases its resistance to expansion significantly with increasing age and maturity (Zimring and Isaacson, 1965; Bell, 1982). As girls complete puberty earlier than boys this may affect resistance to the forces of expansion. The pattern of expansion produced by RME may be expected to vary according to skeletal maturity and this may be assumed to occur on a highly individual basis.

4.2.2 Control Group

Twenty-five subjects were age and sex matched to the anomaly group from the control population of the previous study by McDonald (1995). A Student's t-test (two sample) demonstrated that these two groups did not significantly differ with respect to age (Table 12 and 13).

4.3 SOURCES OF ERROR

There are three main sources of error that can arise from a cephalometric study (Athanasiou and Van der Meij, 1995). These are as follows

1. Errors arising from radiological sources and x-ray projection
2. Errors in identification of landmarks
3. Errors inherent in the measuring systems used

The following sections on radiology and digitising methods take account of these sources of error and report ways or steps taken to minimise them.

4.3.1 Radiology

All cephalometric radiographs were taken at the same centre using the same equipment by the same Radiographer. This helped reduced systematic errors arising due to differences in equipment and technique. All subjects were radiographed in natural head posture (NHP) for both lateral and PA cephalometric radiographs. Some practical problems may be encountered when using NHP for PA cephalometric registrations (Athanasiou and Van der Meij, 1995). The main problem arises because the patient's head faces the cassette film which makes it difficult for the patient to look into a mirror and reproduce NHP.

Linear and angular measurements taken from cephalometric radiographs may be affected by rotations and tilts of the head within the cephalostat. Although it would appear that cephalometric variables that describe widths on PA cephalograms are least affected by postural errors of the head (Athanasiou and Van der Meij, 1995). Indeed according to Ishiguro *et al.* (1976) changes of up to + 10° or - 10° in tilt or left and right rotations may be tollerated as the associated errors are less than the method error. As a result minor rotations and tilt of the head may be considered negligible factors in width or breadth measurements of a PA cephalogram. The use of a single trained Radiographer aware of all these problems will have helped reduce errors arising from these difficulties.

Athanasiou *et al.* (1992) has proposed the use of ratios to allow comparisons between centres or groups working with PA cephalometry. The advantage of using ratios is that it removes errors due to unknown or uncontrolled enlargements of cephalometric structures. This approach would appear to be of most benefit when studying populations or groups of patients rather than comparing individuals. A similar approach by da Silva *et al.* (1995) is to express the amount of expansion achieved at different levels of the maxilla as a percentage of that achieved at the alveolar level. This has the advantage of allowing comparisons between centres by taking into account the overall pattern of expansion rather than concentrating on the absolute increases in width expressed in mm. Both of these methods were used to help the interpretation of the results (see below).

4.3.2 Tracing and Digitising

4.3.2.1 Landmark identification

Wherever possible PA landmarks were taken from previously published work. Skeletal landmarks were taken from Grummonds and Kappeyne van de Coppello (1987), Athanasiou *et al.* (1992), Athanasiou and Van der Meij (1995) and dental landmarks from da Silva *et al.* (1995). All of these landmarks were found to be well defined and easily identified on PA radiographs.

It proved to be difficult to find any information on landmarks within the nasal cavity which may help explain why the effects of RME within the nasal cavity are poorly understood. Previous investigators have commented that expansion due to RME extends well into the nasal cavity with the fulcrum of expansion being somewhere in the region of the frontonasal suture (Haas, 1961;Wertz, 1968; da Silva *et al.*, 1995). The main basis for this assumption would appear to be based on work with dry skulls rather than being demonstrated in vivo. Timms (1974) has commented that the shape of expansion within the nasal cavity may not be strictly triangular with straight sides but may have a flat base and concave or sigmoidally shaped edges if the appliance used to achieve expansion is not rigid enough. In order to investigate the effects of RME on the nasal cavity obvious points that would define nasal cavity height, and maximum nasal cavity width were adopted as landmarks. Other points within the nasal cavity required the construction of an individual template for each patient.

4.3.2.2 Nasal Template

It was necessary to devise a method of constructing points within the nasal cavity on the lateral and medial walls to assess the degree of expansion at different levels. A horizontal reference line was chosen to lie between the lateral orbital points as these are easily identified and highly reproducible (Athanasiou *et al.*, 1992). This reference line corresponds to the Cranial Referrence Line proposed by Hicks (1978) and Mossaz *et al.* (1992). The construction of the nasal template was simple. Breifly after the maximum height of the nasal cavity was measured a template was produced for each patient with horizontal lines parallel to the lo-lo line. These divided the nasal cavity into quarters by virtue of the lines n25, n50 and n75. This template could be placed under any PA tracing for that patient and constructed points at various levels identified on the lateral and mesial walls of the nasal cavity. Changes in width of the nasal cavity due to rapid maxillary expansion could be assessed by comparing these constructed points on the PA tracing before and after treatment. It is appreciated that such a template is unlikely to result in exactly the same level being measured on both tracings if there are minor rotations especially in head tilt, however it was felt that this method would result in roughly the same level being measured. It was hoped initially to assess expansion on the left and right nasal cavities at various levels separately.

4.3.2.3 Calibration of digitising systems

Two different computer systems were used in this study to measure transverse widths and cross-sectional areas on the tracings. The first digitising system was used to measure all linear measurements and to construct a nasal template for each patient.

This system used the equipment outlined in section 2.4.1 and was recently calibrated by Moore (1993). The second digitising system was used to measure the cross-sectional areas within the nasal cavity and used the equipment outlined in section 2.4.2. This arrangement was used in the previous study and was recently calibrated by McDonald (1995).

4.4 METHOD ERROR ANALYSIS

4.4.1 Linear Measurements

The estimation of method error was undertaken as recommended by Houston (1983). The procedure involved dual tracings of the PA cephalograms for the twenty-five members of the control group. Systematic error was identified by a paired Student's t-test and random error estimated by the modified Dalberg formula (Houston, 1983). This was repeated for all skeletal, dental and nasal linear measurements together with cross-sectional area measurements of the nasal cavity. All skeletal and dental linear measurements were associated with an acceptable method error.

This was not the case for some of the nasal transverse measurements and cross-sectional area measurements. The nasal template was used to measure the nasal width at various levels within the cavity and help define one of the cross-sectional areas of the nasal cavity. Random errors in the total width of the nasal cavity at the n25, n50 and n75 levels were higher than ideal (10.13%, 16.24% and 16.77%). It may be seen that the percentage error increases the higher up the nasal cavity one goes which probably reflects the relatively smaller transverse widths observed and the overall shape of the nasal cavity (Table 8). It was decided to keep these transverse measurements and interpret any results or differences found with caution as no other system of measuring the nasal cavity at different levels is available.

Unfortunately the method error associated with measuring the expansion within the separate halves of the nasal cavity was too high to be accepted (Table 8). It is believed that this was due to two factors, firstly, the effect of the nasal septum due to its tortuous path projects a blurred image onto radiographic film making increased error in tracing and point identification and secondly the effect of the small distances being measured are below that practical using the present system.

4.4.2 Cross-sectional Area Measurements and Airway Measurements

Several area measurements were associated with random error rates considered too high to be acceptable (Table 9). The cross-sectional area of the left and right halves of the nasal cavity below the n50 line were associated with a high random error rate. This was also the case with the area of the left and right nasal cavities. This is probably due again to the difficulty in tracing the nasal septum accurately. In contrast the area of the whole of the lower half of the nasal cavity (A50) did have an acceptable error rate and so was the only cross-sectional measurement to be investigated further (Table 9). Nasal airway index as a measure of patency of the nasal cavity was considered acceptable with regard to method error (Table 9).

4.4.3 Rhinomanometry

Rhinomanometry readings for patients selected for this study were collected as part of the previous work by McDonald (1995). Method error analysis was carried out on duplicate measurements of fourteen anomaly patients and revealled no systematic differences for either anterior or posterior recording method at the $p < 0.05$ level. Error percentages ranged between 3.57% and 11.76% (Table 11).

4.5 INTERPRETATION OF RESULTS

4.5.1 Linear Measurements

4.5.1.1 Comparison of groups at baseline

A Student's t-test (two sample) was used to compare both groups with respect to transverse skeletal, dental and nasal measurements and the results may be found in Table 14. Upper molar width was the only transverse measurement to show a statistically significant difference. The mean upper molar width in the RME group was 51.87 mm compared to 56.4 mm for the control group. This in itself is not surprising in that the anomaly group was chosen because of the transverse dental deficiency. Skeletally there was a tendency towards narrowness in intermaxillary width in the RME group compared with the control group ($p = 0.046$).

Both these findings taken together suggest that the anomaly group was composed of a heterogeneous sample. Although all patients exhibited a crossbite the relative contribution of the skeletal and dental components may differ between patients. Some patients may have had a dental crossbite due to maxillary narrowness, whereas others mainly due to the inclination of the upper molars. There were no statistically significant differences found intranasally although the mean intranasal widths were generally lower for the RME group. This may also be due to the orthodontic criteria for selection of the anomaly sample.

Another measurement indicating a tendency was the distance between the apices of the upper central incisors (isapx-isapx). This distance was generally narrower in the anomaly group than the control group. This finding probably reflects a degree of anterior crowding not uncommon in patients with high narrow palatal vaults and narrow skeletal bases.

4.5.1.2 Effects of RME on Anomaly Group

A paired Student's t-test was used to compare the transverse skeletal, dental and nasal measurements before and after treatment. These results can be found in Table 15.

4.5.1.2.1 Skeletal changes

The most significant skeletal change was the increase in maxillary width by a mean of 1.11 mm. The standard deviation for this measurement was 1.41 which reflects the variation between individuals in response to RME. This variation may be due to two factors. Firstly, the point mx lies at the intersection of the lateral contour of the maxillary alveolar process and the lower contour of the maxillozygomatic process of the maxilla (Athanasiou *et al.*, 1992). This landmark lies posteriorly close to where one would expect maximum resistance to expansion. The anatomical relationships of this point are such that the horizontal part of the palatine bone and its articulation with the pterygoid plates are close by. Timms has suggested that the pterygoid plates may provide the greatest resistance to expansion and so it is not surprising that the expansion achieved at this level should be modest (Timms, 1980; 1986). Secondly, as mentioned above the median palatine suture closes or ossifies from the posterior aspect first and this may restrict the degree of expansion at this point. It was observed that some patients exhibited very little change at this level and prompted further investigation into patients who responded to expansion at this level (see below).

4.5.1.2.2 Dental changes

The most impressive changes as a result of expansion were observed in the dental transverse measurements. The upper molar width increased by a mean of 5.5 mm although in one patient an increase of 13.8 mm was recorded. As the force of expansion is applied directly to these maxillary teeth it is to be expected that the greatest increase will be found in this area. Interestingly lower molar width also increased by a mean of 0.66 mm. However the increase in lower molar width was variable with a standard deviation 0.91, but this finding would appear to support work by other authors that uprighting of lower molars can occur (Gryson, 1977; Sandstrom *et al.*, 1988). The mechanism of this uprighting would appear to be either due to altered muscle balance or occlusal forces secondary to maxillary expansion or a combination of both (Haas, 1980).

Rapid maxillary expansion is usually responsible for the creation of a diastema as upper central incisors are carried away from one another on their respective maxillae. After expansion the apices of the incisors were seperated by a mean distance of greater than 10 mm, whereas the crowns were only 1.41 mm apart following treatment. This indicates that during the retention phase the crowns drift together presumably due to the action of elastic fibres and the orofacial musculature as reported previously (Haas, 1961, 1965; Wertz, 1970). In retrospect the point iscr is not ideal in a study of the effects of expansion. The width between these points is defined as the shortest distance between the mesial surfaces of the upper central incisors (da Silva *et al.*, 1995), but due to the tilting movement of the incisors medially after expansion, these points are likely to become progressively incisal. The value of the information gained by such a width measurement is questionable. In contrast the width between the points isam also suggested by da Silva *et al.* (1995) is defined as the shortest distance at the level of the alveolar bone crest adjacent to the mesial surfaces of the roots of the upper central incisors. These points were easy to identify and this width provided some information on the amount of expansion achieved at alveolar level anteriorly. This measurement is unlikely to be affected by the tilting of the anterior incisors.

4.5.1.2.3 Nasal changes

Intranasal changes of statistical significance were restricted to maximum width of the nasal cavity (Table 15). The maximum width of the nasal cavity was found to increase by a mean distance of 1.06 mm. This is a modest increase compared to other studies (see below). Interestingly there was no difference detected in width at the other levels within the nasal cavity, ie at the levels n25, n50 and n75, for the group as a whole. The n25 line was typically above the maximum width of the nasal cavity by 3 or 4 mm, therefore it is likely that expansion achieved intranasally in this group of patients was restricted to the lower part of the nasal cavity. It would appear that expansion in vivo does not reach the nasofrontal suture as reported by others but diminishes rapidly once inside the nasal cavity. This means that the shape of the expansion seen on from a frontal aspect in this group of patients was not pyramidal as reported elsewhere (Haas, 1961; Wertz, 1970) but may have concave sides. This pattern of expansion was predicted by Timms (1974) as the likely result if a non-rigid appliance was used for expansion. However the appliance used in this study was of a cast cap splint design which was recommended by Timms (1974) because it is in fact the most rigid. An alternative explanation for this observation is that in vivo the resistance produced by the facial skeleton to expansion causes more bending of the bony elements than was previously appreciated. This finding is supported by work by da Silva *et al.* (1995) and is discussed further later.

An interesting finding in this group of patients was the increase in nasal cavity heights of approximately 1 mm following expansion which showed a tendency towards statistical significance. A possible explanation for this finding is that as the maxillae rotate outwards due to expansion, a lowering of the nasal floor results which leads to a slight increase in nasal cavity height. This phenomenon has been observed in other studies (Haas, 1961; Wertz, 1970; da Silva *et al.*, 1991, 1995; Spillane and McNamara, 1995)

Seperation of the ANS was found in every case with the distance between the respective halves of the anterior nasal spine a mean value of 3.19 mm apart after expansion. This indicates that the RME appliance in this study did achieve seperation of the median palatine suture anteriorly. However taken with the results reported above for the seperation at the maxillary level, non-parallel expansion of the suture was common in this group. Reasons for this are outlined below.

4.5.1.3 Comparison of both groups after expansion

The comparison of the control group with the anomaly group after expansion demonstrated that following treatment no significant differences in transverse measurements remained between these groups (Table 16). This could be interpreted as evidence that the rapid maxillary expansion had normalised the anomaly group. However there remain differences between these groups as indicated by the ratios given below.

Following RME nasal cavity heights for the anomaly group were slightly larger than for the control group although this finding just failed to reach statistical significance.

4.5.1.4 Comparison with other studies

The use of ratios as advocated by Athanasiou *et al.* (1992) allows comparison of measurements between centres and groups of patients. These ratios were used in Table 17 to successfully demonstrate that the control population used in this study matched closely to figures produced for Northern European normals for that age group. The ratios were also used to demonstrate differences between the anomaly group and both sets of controls. The intermaxillary width ratio (mxR) was found to be 0.659 for the anomaly group before treatment compared to 0.689 for the control group and 0.686 for the Northern European normals. This would appear to corroborate the results found above, that the anomaly group exhibited a general maxillary narrowness. Following treatment this ratio increased to 0.668 which would appear to indicate that overall this ratio improved but due to a poor maxillary width increase in some individuals this value is still lower than either of the control groups. A similar pattern was found in the upper molar ratios (umR) with an increase from 0.571 to 0.629 following treatment. The value of umR for the anomaly group after expansion is slightly higher than either of the control groups and reflects the slight overexpansion in each case. The ratio um-ux provides some information on the relationship between intermolar width and maxillary skeletal base. The figures for the control groups are 0.901 for the study and 0.889 for the published normals. A ratio of 0.867 for the anomaly group reflects that the crossbites in this group were due to a mixture of dental and skeletal elements. The increase in this ratio to a mean of 0.942 after expansion reflects the difference in expansion achieved at the dental level compared to the maxillary skeletal level.

Evidence for the lateral rotation of the maxillary halves is provided by comparison of these results with da Silva *et al.* (1995). Whereas the total amount of expansion achieved at the various levels was similar between these two study groups (Table 18), it should be remembered that the da Silva population comprised of subjects in the mixed dentition. These subjects had a mean age significantly younger than that of the anomaly group in the sample. This may explain the different pattern of expansion achieved by RME at different levels when this is expressed as a percentage achieved at the alveolar level (Table 18). The IP level in da Silva *et al.* (1995) is equivalent to the isam level in the study. These points are at the level of the alveolar crestal margin adjacent to the central incisors. For the da Silva population 56% of the expansion at this level was achieved at the ANS and 43% at the nasal cavity level. This is represents a mean increase of 2.1 mm at the level of maximum nasal cavity width. It may be appreciated that little measurable expansion may be achieved above this level in the nasal cavity. For the anomaly group in this study, 94% of the expansion at the alveolar level was achieved at the level of the ANS and only 32% intranasally. It is therefore not surprising that above this level in the nasal cavity very little expansion was measurable.

Some indication of the pattern of expansion achieved in a coronal section if a comparison between the widths isam-isam and mx-mx are studied. Interestingly in the da Silva group 59% of the expansion achieved at the more anterior point (IP) was achieved at mx points. In this anomaly group only 32% of the anterior expansion (isam) was achieved at the more posterior intermaxillary points (mx). This difference in overall shape of expansion between these two groups may reflect again the difference in age. Although the appliances used in both studies were not identical it may not be unreasonable to assume that the increased maturation of facial structures and sutures in the older patients will help resist the forces of expansion and possibly result in more bone bending. Some of this resistance may be due in part to the partial ossification of the median palatine suture beginning at its posterior aspect.

In summary the comparison of results with other studies provided some interesting findings. Firstly the control population used in the study was established as a representative group from a Northern European racial background. Secondly the pattern of expansion in both the coronal and transverse plane may differ markedly between different populations of different ages. Factors that would be expected to influence pattern of expansion will include, age and maturity of the subject, appliance design, rate of expansion and possibly degree of closure of the median palatine suture. In general it is unlikely that expansion that extends into the nasal cavity beyond the maximum width will be measureable.

4.5.1.5 Patients responding to expansion

Examination of the raw data indicated that whereas all patients experienced expansion in intermolar width and separation of the anterior nasal spine into right and left halves, some patients had little or no expansion at the maxillary base (mx-mx) or intranasally (nmax-nmax). As these are two areas that may be of specific interest to the clinician it was decided to investigate further. An arbitrary figure of 1 mm was chosen as a cutoff point to divide the anomaly group into various subgroups. The patient was classified as a maxillary responder if they exhibited 1 mm or more of expansion in maxillary width and a maxillary non-responder if less than 1 mm expansion was found. Similarly a nasal responder exhibited more than 1 mm of expansion intranasally and a non-responder less than 1 mm. These results were given in Tables 19 to 25.

The age and sex characteristics for these subgroups are given in Table 19. The maxillary subgroups (MS_1 and MS_2) comprised of roughly similar numbers of males and females in each. The mean age for the maxillary non-responders (MS_2) is lower than the responder group (MS_1), however the difference did not reach statistical significance. It is difficult to explain this apparent anomaly, but may be due to poor parent/patient co-operation when the child is at a younger age.
The skeletal, dental and nasal measurements for the maxillary subgroups are given in Tables 20 and 21. These two groups generally responded to expansion in a similar manner. The main difference between these subgroups remained maxillary width change, with the mean increase in mx-mx widths for the responder subgroup (MS_1) being 2.1 mm compared to almost no change for the non-responders (MS_2). Interestingly the degree of separation of the anterior nasal spine was similar in both groups with a width increase of 3.29 mm for maxillary responders and 3.07 mm for non-responders. This may indicate that the maxillary responders demonstrated more parallel opening of the median palatine suture compared to the non-responders. It is tempting to speculate that this situation arises because of less resistance to separation offered by the facial skeleton in the maxillary responder group. For instance, perhaps closure of the median palatine suture had not yet begun in these patients. As yet there would appear to be no way of assessing the optimal time for expansion in individual patients.

The intranasal responder subgroup (NS_1) comprised of 14 females and one male compared to six females and four males in the non-responder subgroup (NS_2). The mean ages of these subgroups are similar and are given in Table 19. The NS_1 patients exhibited a mean increase intranasally of 1.73 mm compared to 0.04 mm for the NS_2 patients. Interestingly no other intranasal width measurements were found to be significantly different between these groups which indicates that even in the subgroup of intranasal responders, expansion was restricted to the lower aspect of the nasal cavity. Those patients who belonged to the nasal responder subgroup also exhibited increases in nasal cavity heights although these differences fell short of statistical significance. It is perhaps not surprising that patients who experienced relatively large changes in nasal cavity width also have an increase in nasal cavity height due to expansion.

In summary the main reason for investigating subgroups of responders within the anomaly sample was to help predict which patients would be more likely to experience greater intranasal or skeletal expansion. Unfortunately it would appear difficult to predict who will respond skeletally or intranasally. In theory, in patients who are less skeletally mature seperation of the maxillae may be easier and result in more parallel expansion. However to date there would appear to be no way of determining this but perhaps patients should be treated younger than in the present study. As a result of studying these subgroups it is possible to say that all patients do not respond to RME in a similar manner. Furthermore, those that experience an increase in nasal cavity width will also have a small increase in nasal cavity height. Although it remains to be seen if these changes will be clinically significant.

4.5.2 Cross-sectional Area Measurements and Airway Measurements

The cross-sectional area measurements in this study proved less useful than initially hoped. The main obstacle to a more detailed analysis of nasal cross-sectional area was in part due to the tortuous path of the nasal septum. This projects a blurred image on the radiographic film which in turns leads to increased tracing errors. For this reason only the following measurements were assessed; subjective assessment, nasal airway index and cross-sectional area of the lower half of the nasal cavity (A50).

The nasal airway index and a subjective assessment of nasal obstruction have been proposed as ways of assessing nasal cavity patency from PA radiographs. It was clear from a review of the literature that the subjective assessment of nasal obstruction had not been fully evaluated. This was investigated by comparing this assessment to the NAI as reported by these workers and was shown in Figure 14. The results indicate that compared to NAI the subjective categorisation of nasal patency from a PA radiograph is an unreliable way of estimating the amount of nasal obstruction. Although it is possible to differentiate total nasal obstruction from open nasal passages, difficulty arises when determining partial nasal obstruction. It may be seen from Figure 14 that there is considerable overlap of categories 2 and 3. A possible explanation may a tendency to ignore thin areas of radioluscency which have a relatively large cross-sectional area. For this reason the subjective assessment of nasal obstruction on PA radiographs was not used.

Nasal airway index proved more reliable and was associated with an acceptable method error. However on a number of PA cephalograms after expansion the nasal cavity appeared less clearly defined than before treatment. This resulted in a smaller radioluscent area following expansion and occasionally complete obliteration of this area was observed. This may reflect the different pattern of expansion between patients due to RME and result from the superimposition of structures. If the maxillae resist separation posteriorly it may be that the anterior aspect of the lateral walls of the nasal cavity bend outward which causes the conchae also to bend. This could result in more superimposition after expansion and therefore reduce the apparent reduction in radioluscent area. On the other hand if the median palatine suture opens in a parallel fashion the conchae will be carried laterally and the radioluscent area may be observed to increase. Due to these unpredictable changes and the difficulty in measuring NAI after treatment this measurement was not used to assess increase in patency due to expansion with RME.

The cross-sectional area measurement of the lower half of the nasal cavity (A50) was the only area measurement associated with an acceptable method error. Although there was no difference in A50 between the control group and the anomaly group before treatment, expansion resulted in a mean increase in this area measurement of 0.31 cm^2 (Table 26). A subgroup of seven females were identified that demonstrated a mean increase of 0.7 cm^2 whereas the mean figure for the remaining 18 patients was only 0.15 cm^2. Unfortunately it was not possible to identify any distinguishing features of this subgroup of patients that indicated why they had experienced such an increase in the cross-sectional area.

4.5.3 Nasal Airway Resistance

4.5.3.1 Control group

The results for both anterior and posterior NAR were available for all control patients in this study. Total anterior NAR is a combined measure of resistance at the anterior nasal apertures whereas total posterior NAR is comparable to the resistance measurements reported previously (Timms, 1986).

The mean values for anterior and posterior NAR for the control group are given in Table 27. The mean value for anterior NAR was 393.08 Pa/cc/s and for posterior NAR was 446.79 Pa/cc/s. Solow and Sandham (1991) reported average values for a normal sample of 308.8 Pa/cc/s for anterior NAR and 246.4 Pa/cc/s for posterior NAR recorded at 75 Pa. The reason for the apparent increased posterior resistance in this control sample is not known although it should be remembered that in this study the recordings were taken at 150 Pa as recommended by Clement (1984).

One of the aims of the study was to investigate the relationship between nasal cavity dimensions and nasal airway resistance. A number of measurements from the control group were plotted against both anterior and posterior NAR. However no evidence of any relationship between measurements from PA cephalometric radiographs and NAR could be found. This is dissapointing although perhaps not surprising due to the complex nature of nasal airflow and the limitations of PA radiographs (Timms, 1986; Hartgervink *et al.*, 1987).

4.5.3.2 Anomaly Group

The mean values for anterior and posterior NAR for the anomaly group before and after expansion are given in Table 27. Unfortunately it was not possible to obtain values of anterior NAR for two members of the anomaly group. The mean values for anterior and posterior NAR before expansion although greater than the control group were not significantly different. An explanation for this observation may come from the fact that the anomaly group were selected for RME treatment largely on the basis of orthodontic considerations i.e. patients with a posterior crossbite. Whereas some of these patients may have had nasal obstruction and relatively high values of anterior and posterior NAR, this was not necessarily true in every case. Anomaly patients with near normal values of anterior and posterior NAR are undoutedly present in this sample.

4.5.3.2.1 The effect of RME on anterior NAR

The mean effect of RME has been attributed to changes in the anterior aspect of the nasal cavity (Wertz, 1970). In particular changes in NAR due to RME are thought to occur due to reduction in resistance at the liminal valve (Timms, 1986; Hartgervink *et al.*, 1987). Indeed Hartgervink *et al.* (1987) advocate the use of Tygon tubing in the anterior naries to simulate the effects of rapid maxillary expansion. Figure 15 indicated that not all patients had a reduction in total anterior NAR due to RME, indeed some patients experienced little change and some patients had an increase in anterior NAR (Table 28). In order to investigate this further a number of linear and area measurements were selected that would be expected to influence anterior NAR. These were increase in anterior nasal spine width, maximum nasal cavity width, intermaxillary width, intermolar width and cross-sectional area (A50). The ANS lies at the most anterior aspect of the nasal cavity it is not unreasonable to assume that large increases in anterior nasal spine width will be associated with alteration in the morphology of the soft tissues of the anterior nasal cavity and perhaps lead to reduction in anterior NAR. However when ANS width increase was plotted against anterior NAR, this was found not to be the case in this study (Figure 16). Timms (1986) found the change in trans-alar width and posterior NAR following expansion with RME only weakly correlated. The most likely explanation may be that the soft tissue changes in the region of the liminal valve do not exactly follow the underlying skeletal changes. This is a common observation in orthognathic surgery and it is likely to apply here also. Alternatively the increase in width at the anterior aspect of the maxillae due to expansion with RME may not be the main effect in causing a reduction in resistance at the liminal valve. It could be that the anteroposterior change in the maxillae that can occur due to expansion affects tissue morphology in this area significantly (Hartgervink *et al.*, 1987).

Other comparisons were made between change in anterior NAR and percentage change in nasal cavity width, intermaxillary width, intermolar width and cross-sectional area (A50). It was hoped that by expressing these changes as a percentage, a relationship could be established between reductions in anterior NAR. No such relationships were established and it would appear that reduction in anterior nasal airway resistance is not related to simple transverse and area measurements.

4.5.3.2.2 The effect of RME on posterior NAR

Previous workers have demonstrated a reduction in posterior NAR due to rapid maxillary expansion (Hershey *et al.*, 1976; Timms, 1986). In order to establish if such a relationship existed in this study population this assessment was repeated. The results indicate that for this study group RME did not result in a reduction in posterior NAR in every case (Figure 17). Whereas in 16 patients little or no change occurred, a mean reduction in posterior NAR of 32.5% in the remaining nine patients demonstrated that RME is successful in some cases (Table 31). This percentage reduction in posterior NAR is in agreement with a mean reduction of 36.2% reported by Timms (1986). It is interesting to note that Timms also reported that RME did not result in reduction of posterior NAR in every case either. To investigate reasons for this, a number of measurements were selected that would be expected to influence posterior NAR in a similar manner to that described above. There was no relationship between changes in maximum width of the nasal cavity, intermolar width, intermaxillary width or cross-sectional area (A50) and change in posterior NAR for the anomaly sample after expansion (Figure 18). In some ways it is disappointing to find no clear relationship between these factors but this serves to underline the complex nature of nasal resistence and airflow.

4.5.3.2.3 Initial Measurements and NAR - Possible predictors of NAR change due to RME

It was hoped to identify skeletal, dental or nasal variables that could help predict those patients that were likely to benefit from reduction in nasal resistance. Analysis of variance was used to test the hypothesis that initial skeletal or dental measurements could be used to predict nasal airway resistance change due to expansion. This was investigated by using analysis of variance (one factor) across the three broad groups for both anterior NAR and posterior NAR described earlier and selected measurements.

Anterior NAR

One skeletal and one dental variable were found to be related to the change in anterior NAR by analysis of variance. Table 29 indicates that patients who were narrow either dentally across the upper first molars or skeletally across the maxillary base were statistically significantly more likely to experience a reduction in anterior NAR following RME. According to Table 29 if a patient had a skeletal maxillary width of 57 mm or less they would be likely to benefit by a reduction in anterior NAR ($p = 0.01$). Similarly if they had a dental maxillary width of 50 mm or less then they were likely to experience a reduction in anterior NAR ($p = 0.004$). Interestingly there was no relationship found for initial nasal width and change in anterior NAR due to treatment. This correlates with the previous finding that initial nasal cavity width was not related to anterior NAR. Athanasiou *et al.* (1992) have commented on the usefulness of ratios in PA cephalometry and some of these were reproduced in Table 30 together with ratios for the three groups that were associated with changes in anterior NAR. It may be seen from this table that a mxR of 0.638 or less before treatment is likely to be associated with a reduction in anterior NAR after treatment. Similarly if the initial umR is 0.558 or less then the patient may be more likely to experience a reduction in anterior NAR after RME. These values may be of use in the decision to treat patients with RME, however further work will be required.

Posterior NAR

A similar analysis of variance revealed that there were no statistically significant differences between reductions in posterior NAR and any of the skeletal or dental variables shown in Table 32. This may be because the effects of RME occured mainly in the anterior region of the maxilla in this group with changes elsewhere being small.

4.5.3.2.4 Relationship between changes in anterior and posterior NAR due to treatment with RME

Table 33 and Figure 19 indicated that some patients experienced reductions in both anterior NAR and posterior NAR due to treatment, others did not benefit greatly from treatement and a few experienced increases in both measurements after expansion. Overall 10 patients experienced reductions in either posterior or anterior NAR or both and six patients had no real change in either anterior or posterior NAR. Of the remaining seven patients only three experienced an increase in both posterior and anterior NAR. The results of this study therefore indicate that in the short term RME would seem to be of benefit to approximately 40% of patients in respect to nasal airway resistance, a further 25% will have little or no change with respect to their nasal airway resistance. Of the remaining patients 13% may experience an increase in both posterior and anterior nasal airway resistance. While it is disconcerting that some patients appear to be worse off as a result of treatment with respect to NAR it is worthwhile to remember that all patients were selected primarily for orthodontic reasons and all crossbites were treated sucessfully. Furthermore this study was concerned only with the changes recorded towards the end of the retention phase and the long term effect of RME on the nasal cavity has been shown to be stable and result in continued improvement over at least a seven year period (Haas, 1980). Further study of this group several years after expansion is merited.

In summary these results indicate that reductions in anterior or posterior NAR due to RME were unpredictable in this group of patients. In general some patients will experience benefit due to rapid maxillary expansion but others will have little or no change and a minority may get worse. It may be possible to predict from either direct clinical measurement or measurements taken from study casts or PA radiographs those patients who are narrow either dentally or skeletally who will most likely experience a reduction in anterior nasal airway resistance due to treatment with RME. From these results if the patient has a maxillary skeletal width of less than 57 mm or an upper molar dental width of less than 50 mm they are most likely to benefit intranasally from rapid maxillary expansion. The ratios for upper molar width and maxillary width compared to intraorbital width that are associated with a reduction in anterior NAR are 0.558 for umR and 0.683 for mxR. These figures may help in the decision to treat a case of maxillary narrowness with rapid maxillary expansion if anterior nasal resistance is an additional feature and should be investigated further.

4.5.4 Changes in Nasal Airflow due to RME

Solow and Sandham (1991) produced normal values for turbulent component of airflow for twenty healthy subjects for both unilateral and bilateral breathing. Using the equations given it was possible to produce a graph of the turbulent component for both unilateral and bilateral breathing for both control and anomaly groups (Figures 20 and 21). These graphs indicate that both groups were broadly similar with respect to turbulent component of flow before treatment and only minor changes resulted due to RME. It should be remembered that the selection criteria for the anomaly sample were orthodontic rather than rhinometric and this may have lead to the similar appearence of these graphs.

4.6 SUMMARY

This study attempted to compare two well matched groups of patients from the East of Scotland. The anomaly sample had a dental crossbite and were treated with RME. The first aim of the study was to evaluate methods of measuring transverse width and cross-sectional areas of skeletal, dental and nasal structures from PA cephalometric radiographs. A number of transverse skeletal and dental measurements were selected from the literature, however with the exception of maximum nasal cavity widths there were no intranasal points described previously. A nasal template was developed which divided the nasal cavity into quarters and allows the identification of constructed points on the lateral and medial walls of the nasal cavity. A number of methods of assessing the cross-sectional area of the nasal cavity were proposed and evaluated. Following method error analysis the majority of the transverse measurements were associated with acceptable error rates however the individual transverse widths of the right and left nasal cavities had high error rates and were therefore discarded. The width of the whole of the nasal cavity at different levels as determined by the template had error rates higher than normally acceptable but for the purpose of this study it was decided to include them. The majority of the cross-sectional area measurements had very high percentage errors and were also discarded. Only two area measurements were investigated further and of these only the cross-sectional area of the lower half of the nasal cavity or A50 may prove to be of benefit. For the perhaps the first time normal values of nasal cavity width at various levels and cross-sectional area of the lower half of the nasal cavity were produced by analysing data from the control group. This data may be of use in further studies.

In conclusion the majority of skeletal and dental transverse measurements proved useful. However it was difficult to assess transverse dimension and cross-sectional area of the nasal cavity. This may be due to the relatively small size of the nasal cavity and the methods of measurement used. Measurements of the left and right nasal cavities separately were unsuccessful largely due to the blurred image of the nasal septum on the PA cephalometric radiograph.

The second aim of the study was to compare the control and anomaly groups using the skeletal, dental and nasal measurements validated previously. The only differences found between these two groups was the upper molar width, with a tendency for upper incisal apex width and intermaxillary width to be reduced in the anomaly group. These findings are not surprising given that the selection criteria for the anomaly group were orthodontically based, i.e. full cusp buccal crossbite. This may mean that the anomaly group was composed of a mixture of individuals with varying contributions of dental and skeletal narrowness to the aetiology of the posteior crossbite. It is interesting to note that there were no differences of statistical significance in the nasal cavity measurements between these two groups as a whole.

The third aim of the study was to investigate the effect of RME on skeletal, dental and nasal structures. The effects of RME observed were in close agreement with previously published studies. The intermaxillary width, upper molar width, lower molar width and nasal cavity width all increased. Comparison of skeletal and dental measurements following expansion with controls established that rapid maxillary expansion had normalised the anomaly group as a whole. In other words the upper molar width and intermaxillary width narrowness had been corrected due to expansion. Further evidence of this came from comparison with the ratios published by Athanasiou *et al.* (1992). The majority of these ratios were found to improve towards values obtained for the controls in this study and previously published normals. These changes in the ratios generally reflected that observed with the transverse measurements.

Comparison of the effects of RME with work by da Silva *et al.* (1995) showed general agreement however differences did exist with regard to the pattern of expansion produced. Da Silva *et al.* (1995) was able to report near parallel separation of the median palatine suture in his group of young patients. The most likely explanation for the difference between these two studies is the difference in ages of the two groups. Previous studies have shown a reduced response to RME with advancing age and this is thought to be due to increasing resistance of the facial skeleton to expansion as a result of maturation of the circum-maxillofacial structures (Zimring and Isaacson, 1965; Wertz, 1970; Melsen, 1972; Perrson, 1977). The formation of mechanical interlocking at the articulations of the maxillae and reduced cellular activity have also been suggested as possible reasons (Bell, 1982).

For the anomaly group in this study separation of the anterior nasal spine was observed in all cases. Small increases in nasal cavity height were detected which may have been due to the lateral rotation of the maxillae. There were no statistically significant differences found within the nasal cavity at levels above the maximum width. This suggests that in this study the effect of RME on the anomaly group was largely confined to the lower aspect of the nasal cavity. It was possible to detect small but statistically significant changes in the area of the lower half of the nasal cavity due to expansion with RME. Within the anomaly group a small number of patients were identified who had comparatively large changes in this area measurement however no distinguishing features of this subgroup of patients could be identified.

Further investigation of intranasal changes with respect to RME also produced evidence of a subgroup of patients who responded well to expansion. It is interesting to note that these patients not only had an increase in width but also height of the nasal cavity due to RME. Unfortunately using the present data no distinguishing feature could be found that would help identify these patients before treatment.

The nasal airway index proved disappointing; this measurement was found to be neither reliable as a means of measuring nasal patency nor worthwhile to use to observe the effects of rapid maxillary expansion.

The fourth aim of the study was to search for any relationship between nasal cavity dimensions and nasal airway resistance measurements using the control group. No relationship could be established between anterior or posterior nasal airway resistance with any of the transverse or area measurements taken from the PA cephalometric radiographs. This finding served to underline the complex nature of nasal airflow and resistance, and to an extent could have been predicted given that a PA radiograph is a two-dimensional representation of a three-dimensional structure. However it has been worthwhile to rule out the possibility of using such a simple tool in the analysis of nasal function.

The final aim of the study was to investigate changes in nasal airway resistance due to RME. Not all patients benefited with respect to anterior or posterior nasal airway resistance after expansion with RME however it is fair to say that the majority of patients did benefit. Changes in anterior nasal airway resistance with respect to changes in anterior nasal spine separation and nasal cavity width were generally unpredictable. This again is probably due to the limitations of measurements taken from a PA radiograph to describe a three-dimensional structure. Changes in posterior nasal airway resistance were again unpredictable with no relationship established.

However a possible relationship was established between some of the initial transverse measurements and improvements in anterior nasal airway resistance due to rapid maxillary expansion. It was found that patients with narrow skeletal width and upper molar width benefited most from rapid maxillary expansion and experienced a reduction in anterior nasal airway resistance. This information could be used to help predict those patients most likely to benefit from RME in these cases. No such association between the transverse measurements studied and posterior nasal airway resistance could be found.

The characteristics of nasal airflow were investigated and compared between the control and anomaly groups before expansion. Nasal airflow was found to be broadly similar between both groups however an analysis of this type may be of more benefit if carried out on individuals. This approach could be used in future studies and may indeed help explain the effects of RME on nasal airflow.

4.7 CONCLUSIONS

Rapid maxillary expansion is a relatively simple and versatile technique producing fast and effective maxillary arch expansion. Long term studies indicate that long term stability can vary, however careful attention to methodology and appliance design appear crucial to improving success rate. As a result of this study the following conclusions may be drawn.

1. Postero-anterior cephalometric radiographs are useful in the study of skeletal and dental effects of rapid maxillary expansion. However they are of little use in the assessment of nasal patency or nasal airway function. Measurements taken from postero-anterior radiographs do not correlate with either anterior or posterior nasal airway resistance.

2. A nasal template could be useful in measuring the dimensions of the nasal cavity at different levels. This would enable comparisons between various expansion techniques including those that involve a surgical approach that claim intranasal effects. The long term stability of these changes could be assessed using this technique.

3. All patients do not respond to rapid maxillary expansion in a similar way. The reasons for the differing responses probably lie in the maturity of the maxillofacial structures. Efforts should be directed at identifying the optimum

time for expansion so that treatment may be targeted at those who are most likely to benefit.

4. Rapid maxillary expansion can influence both anterior and posterior nasal airway resistance. It may be possible to predict those patients most likely to benefit from a reduction in anterior nasal airway resistance by a simple clinical or indirect measurement. Further studies will be required to investigate this possibility.

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APPENDIX

STATISTICAL FORMULAE

Arithmetical mean

$$\frac{\sum x}{n}$$

Standard deviation

$$\sqrt{\frac{\sum \left(x - \overline{x}\right)^2}{n - \mathbf{1}}}$$

Variance

$$\frac{\sum \left(x - \overline{x}\right)^2}{n - 1}$$

Method error
(Hald, 1960)

$$\mathbf{S(i)} = \sqrt{\frac{\sum \left(x_1 - x_2\right)^2}{2n}}$$

Method error percentage

$$\mathbf{S(i)\ \%} = \frac{\mathbf{S(i)}}{\mathbf{(sd)^2}}\ \mathbf{x\ 100}$$