27 May 2010

Nicola Miller

Relationships between vocal structures, the airway and craniocervical posture investigated using magnetic resonance imaging

Dr Nicola Miller

MBChB, MRCP, AFOM
PhD Student (Radiology)
Telephone +44 (0) 1224 559718
Fax + 44 (0) 1224 559718
e-mail n.a.miller@abdn.ac.uk
Address
Aberdeen Biomedical Imaging Centre
Lilian Sutton Building
Foresterhill
Aberdeen
AB25 2ZD

Dr Jennifer S. Gregory

PhD, BSc
Research Fellow
Telephone +44 (0) 1224 553555
Fax +44 (0) 1224 559533
e-mail j.gregory@abdn.ac.uk
Address
Bone and Musculoskeletal Programme
Institute of Medical Sciences

Foresterhill
Aberdeen
AB25 2ZD

Dr Scott I. K. Semple

PhD, SRCS
Research Fellow
Telephone +44 (0) 131 242 7757
e-mail scott.semple@ed.ac.uk
Address
Clinical Research Imaging Centre
Queen’s Medical Research Institute
47 Little France Crescent

Edinburgh
EH16 4TJ

Professor Richard M. Aspden

BA (Hons), PhD, DSc, FIPEM
Professor in Orthopaedic Science
Telephone +44 (0) 1224 552767
Fax +44 (0) 1224 559533
e-mail r.aspden.ac.uk
Address
Bone and Musculoskeletal Programme
Institute of Medical Sciences
Foresterhill
Aberdeen
AB25 2ZD

Professor Peter J. Stollery

BMus (Hons), MA, PGCE, PhD
Professor in Composition and Electroacoustic Music
Telephone +44 (0) 1224 274601
Fax +44 (0) 1224 274900
e-mail p.stollery@abdn.ac.uk
Address
Room 011
School of Education
University of Aberdeen
MacRobert Building
King's College
Aberdeen
AB24 5UA

Professor Fiona J. Gilbert

MBChB, DMRD, FRCR, FRCP (Glasg), FRCP(Ed)
Roland Sutton Chair of Radiology, Head of Imaging
Telephone +44 (0) 1224 559253
Fax +44 (0) 1224 559718
e-mail f.j.gilbert@abdn.ac.uk
Address
Aberdeen Biomedical Imaging Centre
Lilian Sutton Building
Foresterhill
Aberdeen
AB25 2ZD

Abstract

Objectives

Traditional voice research focuses upon the vocal tract, articulators and larynx. By ignoring their direct/indirect attachments (skull, cervical spine, sternum) important information may be missed. We aim to investigate vocal structures within this wider context and assess the validity of this approach for subsequent voice production studies.

Methods

Using a cross-sectional study design we obtained mid-sagittal MR images from ten healthy adults (5 males, 5 females) while at rest and breathing quietly. With reference points based upon cephalometry, 17 craniocervical, craniocaudal and antero-posterior variables were chosen to describe craniofacial morphology, craniocervical posture and airway dimensions. Relationships between variables were sought using Pearson's correlation coefficient.

Results

We found widespread correlations relating vocal structures to the craniofacial skeleton and cervical spine ($r > 0.6$). Increasing airway size (hyocervical distance) was associated with greater distances from the cranial base of the hyoid, larynx, epiglottis tip and uvula tip, and of C3 from the menton. A wider velopharyngeal opening was associated with a shorter and higher soft palate, and a greater craniocervical angle (evt/nsl) was associated with a wider laryngeal tube opening, narrower airway at the uvula tip and shorter distances of the hyoid and uvula tip from the cranial base.

Conclusion

Finding widespread correlations relating vocal structures to the craniofacial skeleton and cervical spine confirms the potential of this approach to uncover functional activity during voice production and demonstrates the importance of considering vocal structures and the airway within this wider context if important information is not to be missed.

Keywords

MRI-Cephalometry-Vocal Tract-Speech-Posture-

Introduction

Speech is a complex behaviour requiring rapid, precise and timely coordination of numerous components within the vocal system (1). The largely hidden nature of this system has challenged progress towards understanding its underlying mechanisms (2). Such an understanding is important since this could lead to improved vocal performance in health and more effective interventions and therapies in disease. The introduction of magnetic resonance imaging (MRI) in 1987as a safe and useful tool in speech research meant that for the first time we could see the soft tissue outline of the entire vocal tract (glottis to lips) in three dimensions (3). Since then, advances in technology and reductions in image acquisition time have secured MRI's position as a leading method in voice research.

Traditionally, voice research using MRI has focused upon the vocal tract, its appendages such as the piriform fossae, the articulators, particularly the lips, jaws, tongue and soft palate, and the voice source, the larynx (4,5). However, this focus tends to ignore the fact that all these structures have direct and/or indirect structural and functional links to the craniofacial skeleton, scapula, cervical spine and sternum. It follows that adjustments to these structural and functional relationships can lead to quantitative changes in variables describing vocal structures and airway dimensions. Alterations of head posture, for example, are strongly correlated with changes of airway dimensions (6-12). We reasoned that considering vocal structures within the context of their wider relationships could lead to a better understanding of the coordinated adjustments that underpin activity within the vocal system.

Established protocols are not yet available for these measurements in MRI (8,13,14). However, the dimensions of the upper airway (glottis to nasopharynx) and factors contributing to these are also of interest in orthodontics (15), maxillofacial surgery (11) and obstructive sleep apnoea (OSA) research (8). In these disciplines, lateral cephalometry, traditionally using x-ray radiography, is an established method whereby soft tissue dimensions can be related to bony landmarks (16). Accordingly, the variables of interest extend beyond the vocal tract and articulators to other regions within the head and neck. Cephalometry is quicker and cheaper than MRI but lacks its superior soft tissue definition. Additionally, ethical considerations limit its usefulness in research, particularly where matched controls or repeated scans are needed (17). Recently, MRI's potential in fields traditionally dominated by cephalometry has been recognised resulting in calls to validate and standardize MRI protocols (13,14,18).

This cross-sectional study is part of a larger MRI investigation of voice production where our aim is to relate changes in vocal structures to their wider links within the head and neck. The aims of this pilot study, where subjects are at rest during image acquisition, are twofold: to measure craniocervical, angular, craniocaudal and antero-posterior dimensions based on reference points drawn from cephalometry; and to assess the potential of this approach to uncover functional changes during subsequent experiments investigating voice production.

Methods

Recruitment

Twelve healthy volunteers were recruited to the study. All but one (who had a tonsillectomy and adenoidectomy as a child) had no history of speech or hearing pathology. Exclusion criteria included a history of claustrophobia, an inability to maintain a closed mouth position within the 20 seconds time frame necessary for image acquisition during this and subsequent parts of the study, and the presence of contraindications to MRI such as pacemakers and metallic orthodontic appliances. Approval from Grampian Research Ethics Committee (now North of Scotland Research Ethics Service) was obtained and all subjects gave written informed consent.

Procedure

Volunteers were required to adopt a relaxed posture in the MRI scanner and were instructed to look straight ahead while holding the lips and teeth together, and to rest the tongue dorsum comfortably against the hard palate. Individuals were imaged in a supine position with the head placed in a Sense-Neurovascular array-16 element coil. Deformable foam wedges were used to make the subject comfortable and to restrain the head position. Ear plugs and headphones helped attenuate the scanner noise and allowed two-way communication. Para-sagittal images were obtained using a 3.0 T Achieva MR system (Philips, Best, Holland) using a turbo spin echo pulse sequence with the following parameters: field of view (FOV) 340 x 340 mm; a 768 by 768 matrix; repetition time 4106 ms; echo time 100 ms; 6 slices 4.0 mm thick with a gap of 1.0 mm centred on the sagittal plane. The number of slices was dictated by the need to optimize image resolution within the time constraint of a single breath-hold thus allowing for comparisons with subsequent vocal production studies. The FOV extended from just above the pituitary gland to the sternal notch, taking in the width of the whole head and neck. Having adopted the above posture, each individual was scanned over 20 seconds while breathing quietly. The MRI slice closest to the mid-sagittal plane was chosen for analysis (identified by the presence of the pituitary fossa, the tip of the odontoid process, the outline of the trachea and spinal cord, and the spinal processes).

Image analysis

Images were converted from DICOM to Bitmap format using ImageJ. Since the aim of subsequent experiments is to investigate the nature of adjustments that occur during voice production, the choice of variables was dictated by the need to capture adjustments secondary to any changes in craniocervical posture, angular, craniocaudal or antero-posterior dimensions. Software tools, developed by the University of Manchester, UK (19) were used manually to mark reference points as shown in Figure 1 and described in Table 1. From these points, a programme was written to automatically measure the 17 variables listed in Table 2 and illustrated in Figure 1. Small case letters are used to identify landmarks used in MRI to distinguish them from those used in cephalometry, since they may not be directly comparable.

Statistical analysis

Statistical analysis was performed using Sigmastat (v11, Systat Software, Inc.). Descriptive statistics were obtained and expressed as mean (standard deviation) and relationships between variables were sought using Pearson's correlation coefficient. Student's t-test was used to detect possible significant differences between the means of variables describing hyoid position in males and females. For all tests, a P value of 0.05 or less was taken to indicate statistical significance.

Results

Ten out of twelve subjects met the inclusion criteria for the study. One subject was unable to adopt the necessary tongue position with the tongue dorsum resting against the hard palate. Another adopted a hyper-extended neck position and was unable to take part in subsequent experiments where subjects were required to produce voice comfortably and without undue strain. We obtained a full data set for the remaining ten subjects (5 males, 5 females; age range 20-47 with a median of 25 years). Table 3 contains the descriptive statistics for the study population (mean, standard deviation and range). All linear measurements are in millimetres.

We observed widespread correlations between the craniocervical, craniocaudal and anteroposterior variables relating the larynx, hyoid, epiglottis, soft palate and airway to the cranial base, craniofacial skeleton and cervical spine (Table 4). To assist in their visual representation, uncorrelated variables are omitted from the matrix and the remainder arranged, as far as possible, to demonstrate relationships between them. Two distinct patterns of correlations can be seen: two overlapping groups of correlations ($r \geq 0.71$) and correlations associated with individual variables; those singled out for further discussion are highlighted using bold font and alternate shades of grey.

Three main groups of correlations were observed; those based around the hyocervical distance (hy-c3), the velopharyngeal opening (VPO) and the craniocervical angle evt/nsl. These are shown in Figures 2. Topographical correlations (where variables share reference points or lines) were observed between variables that reflect the overall size of the craniofacial skeleton and airway, and between craniocervical angles at the uppermost part of the cervical spine. The hyocervical distance was strongly and positively correlated with the perpendicular distances from the nasion-sella line of the hyoid (hy-nsl), larynx (l-nsl), uvula tip (ut-nsl) and epiglottis tip (et-nsl) and with the width of the oropharyngeal airway at the uvula tip (pt-ppw-ut) ($r \geq 0.81$, $P < 0.01$). Weaker positive correlations were observed for the antero-posterior distance between C3 and the menton (c3-me) ($r = 0.64$, $P < 0.05$). Figure 2.1 shows that, on average, an increase in craniofacial dimensions is associated with an increase in airway size. Airway size at the epiglottis tip (pt-ppw-et) is correlated not with these variables but with c3-me ($r = 0.69$, $P < 0.05$). pt-ppw-ut and pt-ppw-et are, however, positively correlated with each other ($r = 0.76$, $P < 0.05$). The craniocervical angles opt/nsl and cvt/nsl were very highly correlated ($r = 0.96$, $P < 0.001$).

Non-topographical correlations (where variables have no common reference points or lines) and topographical correlations were observed between dimensions of the VPO and between variables associated with the craniocervical angle evt/nsl. The narrowest part of the VPO, the minimal distance separating the uvula from the posterior pharyngeal wall (u-ppw), was negatively correlated with ut-nsl ($r = -0.72$, $P < 0.05$) and the length of the soft palate (pns-ut) ($r = -0.83$, $P < 0.01$). Figure 2.2 shows that, on average, a wider VPO is associated with a higher and shorter soft palate. Conversely, a narrower VPO is associated with a lower and longer soft palate. The craniocervical angle evt/nsl, influenced by alignment of C4-C6, was correlated negatively with hy-nsl, and ut-nsl, and pt-ppw-ut, and positively with the width of the laryngeal opening (ltw) (all correlations, $r \geq 0.63$, $P < 0.05$). On average, widening of evt/nsl was associated with shorter perpendicular distances of the hyoid and soft palate tip from the cranial base, narrowing of the oropharyngeal airway at the uvula tip, and widening of the laryngeal tube opening. Conversely, a reduction of evt/nsl was associated with greater distances of the hyoid and soft palate tip from the cranial base, widening of the oropharyngeal airway at the uvula tip, and narrowing of the laryngeal tube opening (Fig. 2.3). The craniocervical angle cvt/nsl, influenced by upper cervical alignment (C2-C4), was also positively and non-topographically correlated with ltw.

We found significant differences between the mean values for hy-c3 and hy-nsl for males (39.1 (2.0) mm and 115.2 (5.9) mm respectively) and females (34.2 (3.3) mm and 97.6 (8.2) respectively), for both groups (*P* = 0.032 and 0.005 respectively) indicating that, on average, the hyoid occupied a more postero-superior position in females compared with males.

Discussion

In this study, we combined MRI's superior soft tissue definition with bony reference points drawn from cephalometry to investigate the vocal tract and related structures within the context of their direct and indirect structural attachments to the craniofacial skeleton, cervical spine and sternum. Our results demonstrate the validity of this method for quantitative analysis of vocal tract-related dimensions and demonstrate the potential of this approach to uncover functional correlations between vocal tract-related structures and airway size in subsequent studies investigating voice production.

Since cephalometry is largely carried out in erect subjects and moving from erect to supine can result in changes of dimensions (20), this study does not allow a direct comparison of all our results with equivalent cephalometric findings. However, unlike other variables, hy-c3 remains unchanged in the move from an erect to a supine posture (20) and the mean value for hy-c3 fell within the range reported for cephalometry (21-23). Additionally, our demonstration that the hyoid occupies a more postero-superior position in females compared with males is consistent with previous reports (23,24). Together, these findings support earlier assertions that cephalometric variables can be successfully adapted for use in quantitative MRI investigations of vocal structures and the airway.

The power of this approach to uncover functional correlations during subsequent studies investigating voice production is demonstrated by our discovery of a group of correlations observed in association with the lower craniocervical angle evt/nsl (Fig. 2.3). The effect of these correlated dimensions is clearly illustrated in tracings of images obtained from subjects (both females) possessing the greatest and the smallest craniocervical angle evt/nsl (Figure 3). Volunteer 5 had the greatest angle evt/nsl, and the shortest distance hy-nsl amongst all volunteers whereas volunteer 4 had the smallest angle evt/nsl and the second greatest distance hy-nsl amongst all volunteers, but the greatest distance amongst female volunteers. These findings are important since non-topographical associations, such as those observed between evt/nsl and ltw, point to the presence of underlying growth coordinating mechanisms which contribute to the development of an individual's 'intrinsic shape' and facial appearance (25). Although coordinated patterns of growth-related changes involving the upper craniocervical angles (C2-C4) have been observed previously (25), as far as we are aware, this is the first study to demonstrate similar patterns of coordinated changes in association with the lower craniocervical angle (C4-C6).

In 1941, Brodie showed that during normal growth of the craniofacial skeleton, an increase in the size of one variable is accompanied by a proportionate increase in the size of other variables (26). In this cross-sectional study of subjects who vary in size, we show that, on average, the larger the individual, the greater the dimensions relating to the bony and soft tissue structures of the head and neck and the greater the size of the airway (Fig. 2.1). However, our demonstration of correlations between the size of the VPO and the height and length of the soft palate, and between the lower craniocervical posture, craniofacial morphology and airway dimensions (Figs. 2.2 & 2.3), suggest that these growth-related changes are underpinned by widespread and coordinated patterns of development which may vary between individuals.

Knowledge and awareness of underlying patterns of head and neck development has important clinical and research implications. For example, we do not yet have a full understanding of the factors that contribute to the 'immense variability' observed between subjects in voice research (27). These are thought to be due, in part, to anatomical variations such as variations in vocal tract length (28). However, the results of this and other studies pointing to the presence of coordinated patterns of growth affecting head and neck development (29-31) suggest that improved knowledge and awareness of underlying global patterns of head and neck development might lead to a better understanding of factors contributing to normal and pathological variations of structural (and functional) relationships between bony and soft tissues. Such knowledge could lead to improved vocal performance in health, more effective interventions and therapies for those with speech difficulties, and more realistic automatic speech synthesis.

Interpretation of our results is limited by the small sample size with mixed ages, sexes and varying subject heights, all factors known to influence vocal tract dimensions. However, finding highly correlated patterns is indicative of fundamental relationships between these structures and requires further study. We suggest that the method used here offers greater potential for improved quantitative and qualitative information concerning structural (and functional) relationships between bony, airway and soft tissue variables than is possible with either MRI or cephalometry alone. Although MRI is more expensive than cephalometry, its lack of non-ionizing radiation and superior soft tissue definition offer clear advantages for research purposes, particularly where matched controls or multiple image acquisitions are required. Not all cephalometric measurements can be adapted for MRI as some bony landmarks, such as the gonion (a point at the bisection of the inferior and posterior borders of the mandible), are not present in the mid-sagittal plane. In some instances, adaptations permit the use of an equivalent landmark. For example, a carefully placed point overlying the nasion, rather than the nasion itself, allows use of a line equivalent to the nasion-sella line (NSL). More work is necessary before the reliability of this method can be established. However, previous work has shown MRI results to be highly reproducible and stable over time (13). Only one observer (NAM) annotated the images but findings of low intra-investigator variability compared with inter-investigator variability have led to the suggestion that preference should be given to such intra-investigator evaluation when comparing a series of MR images or for study purposes (13). Future studies, including the use of a positional MRI scanner, could further understanding of structural and functional relationships between bony and soft tissues in erect and supine subjects.

Conclusions

We aimed to investigate vocal structures within the context of their direct and indirect structural links to the craniofacial skeleton, cervical spine and sternum by combining MRI’s superior soft tissue definition with bony reference points used in cephalometry. Observations of widespread patterns of correlations linking craniocervical, craniocaudal and antero-posterior dimensions support earlier work pointing to the dependence of structural relationships upon underlying growth coordinating mechanisms. Our results demonstrate the potential of this approach to offer valid qualitative and quantitative information in subsequent experiments investigating voice production and, further, that important information may be missed if vocal structures are considered without taking into account their wider structural relationships within the head and neck. Recognition of and accounting for these wider associations has important clinical and research implications and could potentially lead to a better understanding of mechanisms underlying structural and functional coordinated activity within this region which, in turn, could lead to improved interventions and therapies across disciplines.

Acknowledgements

We thank the MRI radiographers for help with imaging and the volunteers for freely donating their time to this study. Any funding?

References

(1) Kent RD. The uniqueness of speech among motor systems. Clinical Linguistics & Phonetics 2004;18(6):495-505.

(2) Munhall K. Functional imaging during speech production. Acta Psychol. 2001;107(95):117.

(3) Baer T, Gore JC, Boyce S, Nye PW. Application of MRI to the analysis of speech production. Magn.Reson.Imaging 1987;5(1):1-7.

(4) Honda K, Takemoto H, Kitamura T, Fujita S, Takano S. Exploring human speech production mechanisms by MRI. IEICE Trans.Inf.Syst. 2004;87(5):1050-1058.

(5) Ventura SR. Application of MRI and biomedical engineering in speech production study. Comput.Methods Biomech.Biomed.Engin. 2009;12(6):671-681.

(6) Hellsing E. Changes in the pharyngeal airway in relation to extension of the head. Eur.J.Orthod. 1989 Nov;11(4):359-365.

(7) Pae EK, Lowe AA, Sasaki K, Price C, Tsuchiya M, Fleetham JA. A cephalometric and electromyographic study of upper airway structures in the upright and supine positions. Am.J.Orthod.Dentofacial Orthop. 1994 Jul;106(1):52-59.

(8) Solow B, Skov S, Ovesen J, Norup PW, Wildschiødtz G. Airway dimensions and head posture in obstructive sleep apnoea. The European Journal of Orthodontics 1996;18(1):571.

(9) Muto T, Takeda S, Kanazawa M, Yamazaki A, Fujiwara Y, Mizoguchi I. The effect of head posture on the pharyngeal airway space (PAS). International Journal of Oral & Maxillofacial Surgery 2002;31(6):579-583.

(10) Muto T, Yamazaki A, Takeda S, Kawakami J, Tsuji Y, Shibata T, et al. Relationship between the pharyngeal airway space and craniofacial morphology, taking into account head posture. International Journal of Oral & Maxillofacial Surgery 2006;35(2):132-136.

(11) Muto T, Yamazaki A, Takeda S. A cephalometric evaluation of the pharyngeal airway space in patients with mandibular retrognathia and prognathia, and normal subjects. International Journal of Oral & Maxillofacial Surgery 2008.

(12) Anegawa E, Tsuyama H, Kusukawa J. Lateral cephalometric analysis of the pharyngeal airway space affected by head posture. International Journal of Oral & Maxillofacial Surgery 2008;37(9):805-809.

(13) Stuck BA, Kopke J, Maurer JT, Verse T, Kuciak G, Duber C, et al. Evaluating the upper airway with standardized magnetic resonance imaging. Laryngoscope 2002;112(3):552-558.

(14) Stuck BA, Maurer JT. Airway evaluation in obstructive sleep apnea. Sleep Med.Rev. 2007 Nov 26.

(15) Haralabakis NB, Toutountzakis NM, Yiagtzis SC. The hyoid bone position in adult individuals with open bite and normal occlusion. The European Journal of Orthodontics 1993;15(4):265-271.

(16) Broadbent BH. A new x-ray technique and its application to orthodontia. Angle Orthod. 1931;1(2):45-66.

(17) Tangugsorn V, Skatvedt O, Krogstad O, Lyberg T. Obstructive sleep apnoea: a cephalometric study. Part I. Cervico-craniofacial skeletal morphology. Eur.J.Orthod. 1995 Feb;17(1):45-56.

(18) Leggett B, Murray M, Buzzell J, Leggitt V, Kim JS. Validation of a Non-Ionizing Radiation (MRI) Technique of Cephalometric Analysis. 2006.

(19) Available at: http://personalpages.manchester.ac.uk/staff/timothy.f.cootes/software/am_tools_doc/index.html.

(20) Sutthiprapaporn P, Tanimoto K, Ohtsuka M, Nagasaki T, Iida Y, Katsumata A. Positional changes of oropharyngeal structures due to gravity in the upright and supine positions. Dentomaxillofacial Radiology 2008;37(3):130.

(21) Muto T, Kanazawa M. Positional change of the hyoid bone at maximal mouth opening. Oral surgery, oral medicine, oral pathology 1994;77(5):451-455.

(22) Hoekema A, Hovinga B, Stegenga B, DE B. Craniofacial morphology and obstructive sleep apnoea: a cephalometric analysis. J.Oral Rehabil. 2003;30(7):690.

(23) Sahin Saglam AM, Uydas NE. Relationship between head posture and hyoid position in adult females and males. Journal of cranio-maxillo-facial surgery 2006;34(2):85-92.

(24) Marsan G. Head posture and hyoid bone position in adult Turkish Class III females and males. World J.Orthod. 2008 Winter;9(4):391-398.

(25) Solow B, Tallgren A. Head posture and craniofacial morphology. Am.J.Phys.Anthropol. 1976 May;44(3):417-435.

(26) Brodie AG. On the growth pattern of the human head. From the third month to the eighth year of life. Am.J.Anat. 1941;68(2):209-262.

(27) Moore RK. Spoken language processing: Piecing together the puzzle. Speech Commun. 2007;49(5):418-435.

(28) Fitch WT, Giedd J. Morphology and development of the human vocal tract: A study using magnetic resonance imaging. Journal of the Acoustical Society of America 1999;106(3 I):1511-1522.

(29) Houston WJB. Mandibular growth rotations-their mechanisms and importance. The European Journal of Orthodontics 1988;10(1):369-373.

(30) Solow B, Sandham A. Cranio-cervical posture: a factor in the development and function of the dentofacial structures. Eur.J.Orthod. 2002;24(5):447-456.

(31) Sonnesen L, Pedersen CE, Kjaer I. Cervical column morphology related to head posture, cranial base angle, and condylar malformation. The European Journal of Orthodontics 2007;29(4):398.

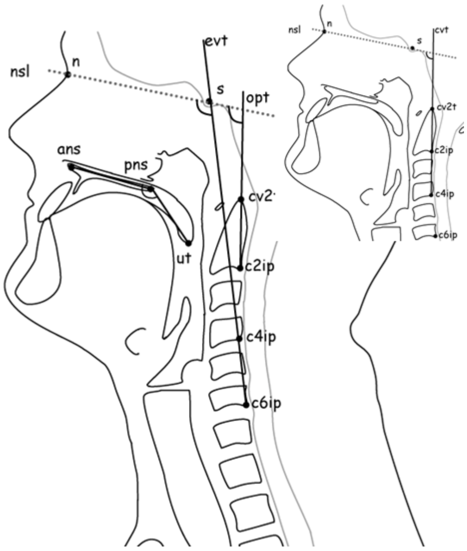
27 May 2010 Nicola Miller

Tables and Figures for Rest Paper

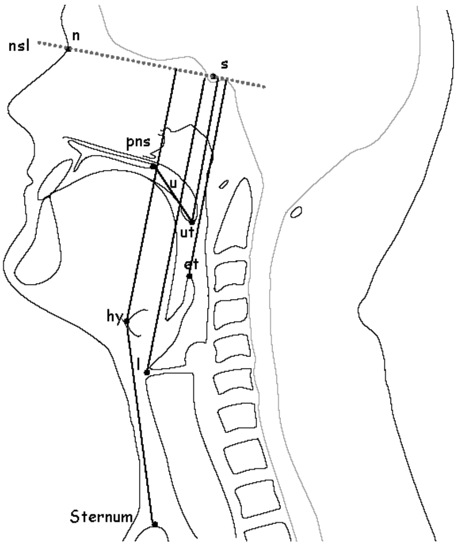
Figure 1

Bony and soft tissue landmarks chosen for craniocervical, angular and linear variables

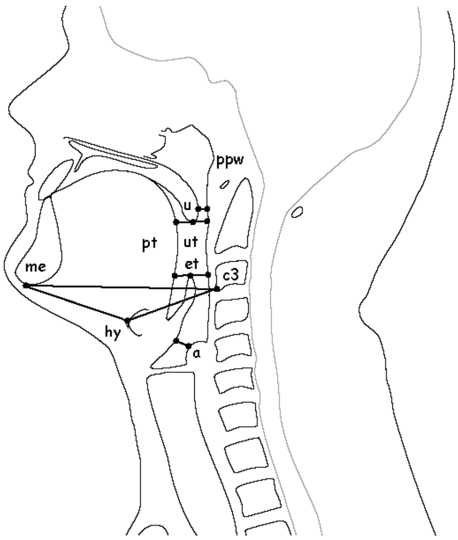
Typical MR image



Craniocervical and angular variables



Craniocaudal variables



Antero-posterior variables

Table 1

Bony and Soft Tissue Reference Points and Planes

a	Superior margin of arytenoid cartilage
ans	The most anterior point of the maxilla at level of hard palate (anterior nasal spine)
asp	Angle of soft palate
et	Epiglottis tip
cv	Cervical vertebra
cv2t	The tangent point at the superior extremity of the odontoid process of cv2
cv2ip	The most infero-posterior point on the body of cv2
cv4ip	The most infero-posterior point on the body of cv4
cv6ip	The most infero-posterior point on the body of cv6
c3	The most antero-inferior point on the body of cv3
cvt	The line through cv2t and cv4ip (cervical vertebra tangent)
evt	The line through cv4ip and cv6ip
hy	The antero-superior margin of outer cortex of hyoid bone
l	The anterior point of the vocal folds (larynx)
me	Menton-the most inferior point of bony chin
n	The point overlying the nasion (middle of naso-frontal suture)
nsl	The line joining ‘n’ and ‘s’ reflecting orientation of anterior cranial base
opt	The line through cv2t and cv2ip
pns	The most posterior point of the hard palate (posterior nasal spine)
pns-ut	Soft palate length
ppw	Posterior pharyngeal wall
pt	Posterior tongue
s	Mid-point of sella turcica
stern	The most superior point of sternum
u	Uvula
ut	Uvula tip

Table 2

Postural, Angular and Linear Variables

Variables	Measures
Craniocervical Posture	**cvt/nsl**: the angle between cvt and nsl **evt/nsl**: the angle between evt and nsl **opt/nsl**: the angle between opt and nsl
Angular	**asp**: the intersection of line joining ans and pns and pns-ut
Antero-posterior	**c3-me**: the antero-inferior point of c3 to menton **hy-c3**: the antero-superior point of hyoid body to antero-inferior point of c3 **hy-me**: the antero-superior point of hyoid body to menton **ltw**: the laryngeal tube width (measured from ‘a’ to the base of the epiglottis-line perpendicular to airway) **pt-ppw-et**: the pharyngeal airway space at level of et **pt-ppw-ut**: the pharyngeal airway space at level of ut **u-ppw**: the minimal distance between the uvula and the posterior pharyngeal wall
Cranio-caudal	**et-nsl**: the perpendicular distance of epiglottis tip from nasion-sella line **hy-nsl**: the perpendicular distance of the hyoid bone from nasion-sella line **l-nsl**: the perpendicular distance of the larynx from nasion-sella line **pns-ut**: the distance between posterior nasal spine and uvula tip **stern-hy**: the distance from sternum to antero-superior point of hyoid body **ut-nsl**: the perpendicular distance of uvula tip from nasion-sella line

Table 3

Descriptive Statistics: Mean (SD) Range

Variable	Mean (SD)	Range
opt/nsl	102.2 (7.0)	93-115.6
cvt/nsl	101.8 (7.0)	92.8-115
evt/nsl	103.3 (7.7)	90.9-118.6
asp	132.5 (5.7)	121.8-139.3
c3-me	82.8 (7.8)	75.7-94.7
ut-nsl	71.5 (8.8)	59.8-84.8
et-nsl	87.9 (9.1)	76.3-101.0
hy-nsl	106 (11)	89.7-125.1
l-nsl	129 (15)	111.2-152
pt-ppw-ut	8.6 (2.5)	5.72-17.2
u-ppw	4.2 (2.4)	0-7.0
ut-ppw	8.6 (2.5)	4.4-11.9
pt-ppw-et	13.2 (2.8)	9.7-17.2
hy-c3	36.7 (3.7)	30.6-41.2
hy-me	47.2 (6.4)	38.3-57.6
pns-ut	39.3 (5.7)	30.6-50.0
ltw	9.0 (2.6)	4.9-12.5
stern-hy	110 (15)	81.4-135.6

Table 4

Correlation matrix for postural, craniocaudal and antero-posterior variables

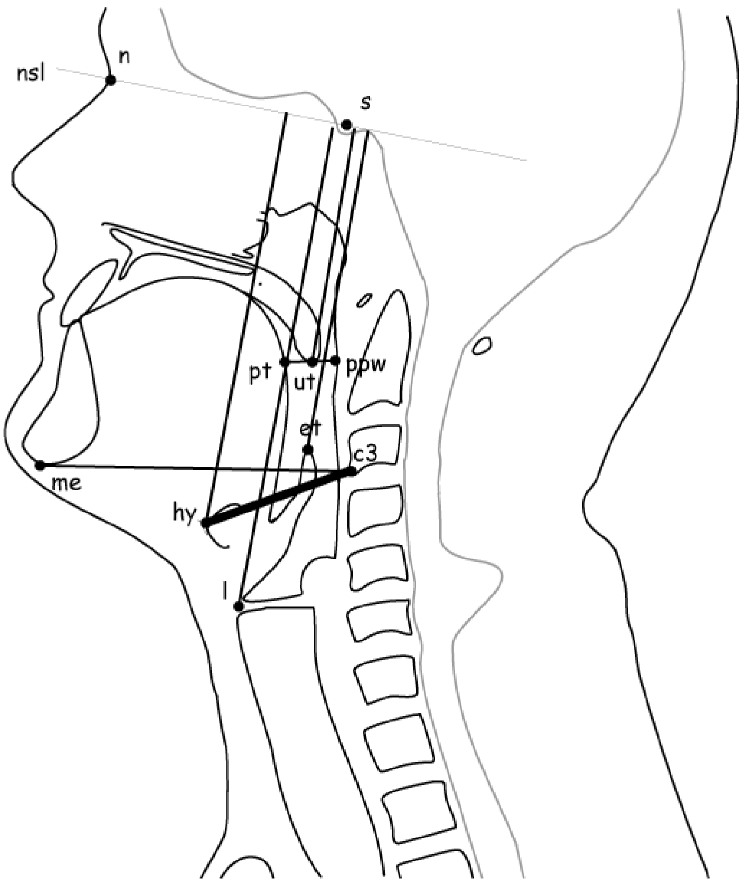
	cvt/nsl	**evt/nsl**	**hy-c3**	hy-nsl	l-nsl	et-nsl	ut-nsl	pns-ut	**u-ppw**	pt-ppw-ut	pt-ppw-et	ltw	c3-me	hy-me
opt/nsl	**0.96*** **	0.43	-0.13	-0.26	-0.27	-0.25	-0.38	-0.26	-0.01	-0.20	-0.18	0.56	0.38	0.49
cvt/nsl	1.00	0.59	-0.3	-0.43	-0.4	-0.38	-0.54	-0.30	0.04	-0.33	-0.2	**0.71***	0.3	0.48
evt/nsl	0.59	1.0	-0.51	**-0.63***	-0.46	-0.55	**-0.67***	-0.23	0.36	**-0.64***	-0.32	**0.74***	-0.05	0.1
hy-c3	-0.3	-0.51	1.00	**0.87****	**0.81****	**0.83****	**0.81****	0.6	-0.44	**0.81****	0.62	-0.47	**0.64***	0.27
hy-nsl	-0.43	**-0.63***	**0.87****	1.00	**0.95*****	**0.97*****	**0.74***	0.44	-0.34	**0.68***	0.37	-0.51	0.34	0.02
l-nsl	-0.4	-0.46	**0.81****	**0.95*****	1.00	**0.96*****	**0.71***	0.49	-0.34	0.57	0.33	-0.32	0.26	-0.07
et-nsl	-0.38	-0.55	**0.83****	**0.97*****	**0.96*****	1.00	**0.76***	0.58	-0.47	0.56	0.31	-0.38	0.26	-0.09
ut-nsl	-0.54	**-0.67***	**0.81****	**0.74***	**0.71***	**0.76***	1.00	**0.80****	**-0.72***	0.60	0.53	-0.47	0.23	-0.17
pns-ut	-0.30	-0.23	0.6	0.44	0.49	0.58	**0.80****	1.00	**-0.83****	0.2	0.44	-0.10	0.19	-0.14
u-ppw	0.04	0.36	-0.44	-0.34	-0.34	-0.47	**-0.72***	**-0.83****	1.00	-0.24	-0.49	-0.09	-0.20	0.06
pt-ppw-ut	-0.33	**-0.64***	**0.81****	**0.68***	0.57	0.56	0.60	0.2	-0.24	1.00	**0.76***	-0.48	0.6	0.35
pt-ppw-et	-0.2	-0.32	0.62	0.37	0.33	0.31	0.53	0.44	-0.49	**0.76***	1.00	-0.13	**0.69***	0.49
ltw	**0.71***	**0.74***	-0.47	-0.51	-0.32	-0.38	-0.47	-0.10	-0.09	-0.48	-0.13	1.00	-0.11	0.01
c3-me	0.3	-0.05	**0.64***	0.34	0.26	0.26	0.23	0.19	-0.20	0.6	**0.69***	-0.11	1.00	**0.89*****
hy-me	0.48	0.1	0.27	0.02	-0.07	-0.09	-0.17	-0.14	0.06	0.35	0.49	0.01	**0.89*****	1.00

Statistically significant correlations are shown in bold and level of significance indicated as follows: $P < 0.05$ *; $P < 0.01$ **; $P < 0.001$ ***.

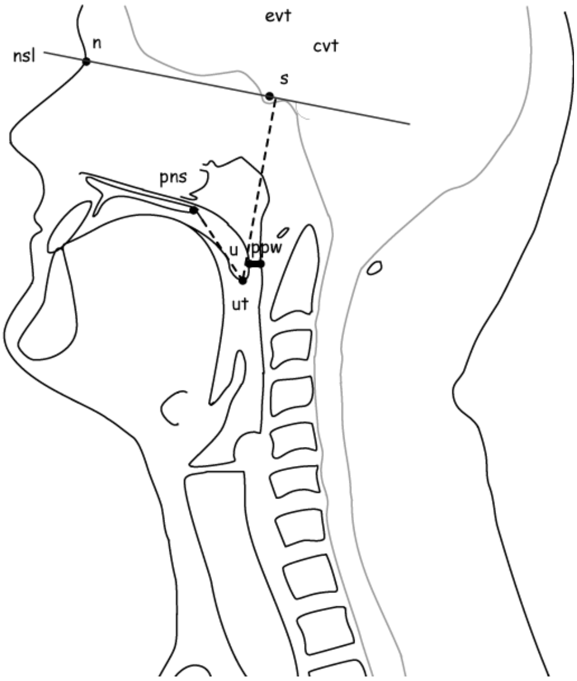
Figure 2

Significant correlations associated with (a) hy-c3, (b) u-ppw and (c) evt/nsl each shown by a thick solid line. Positive correlations are indicated by a thin solid line, negative correlations by a dashed line.

2.1 Measures correlated with hy-c3 (c3-me, hy-nsl, l-nsl, ut-nsl, et-nsl and pt-ppw-ut)



2.2 Measures correlated with u-ppw (pns-ut and ut-nsl)



2.3 Measures correlated with evt/nsl (hy-nsl, ut-nsl, pt-ppw-ut and ltw)

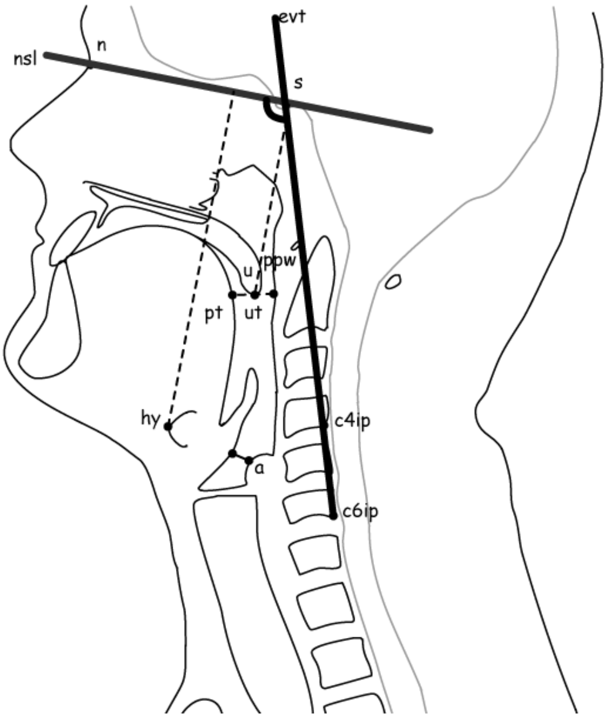
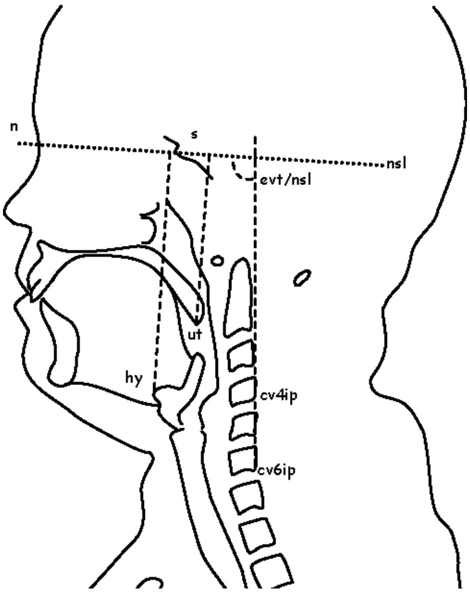
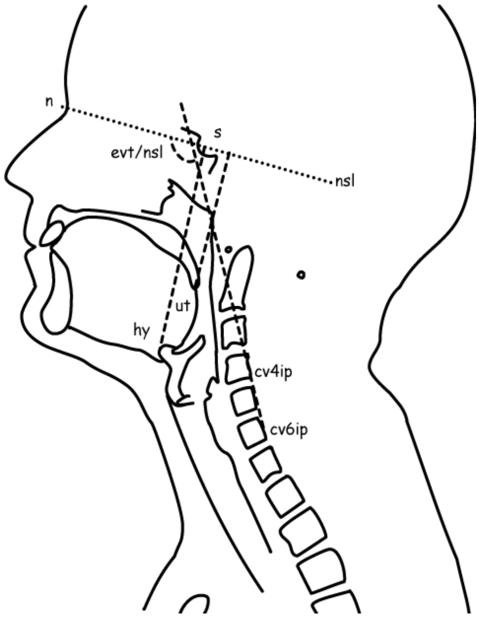


Figure 3

Comparison between volunteers with (a) the smallest and (b) the largest craniocervical angle evt/nsl





3.1 Volunteer 4 3.2 Volunteer 5

In (a) , evt/nsl is associated with kyphosis of the cervical spine, a greater hyoid-cranial base distance, widening of the oropharyngeal airway at the uvula tip, narrowing of the laryngeal tube opening and a more posterior tongue position, whereas in (b) evt/nsl is associated with extension of the head, lordosis of the cervical spine, shortening of the hyoid-cranial base distance, narrowing of the oropharyngeal airway at the uvula tip, and widening of the laryngeal tube opening.