

Pharyngometry Studies (updated 03/10/10)

A. Related to Measurement of Airway

1). *Effect of Mouthpiece, Nose Clips, and Head Position on Airway Area Measured by Acoustic Reflections--*
Journal of Applied Physiology, 1987

Authors: I. Rubinstein, P.A. McClean, R. Boucher, N. Zamel, J.J. Fredberg, and V. Hoffstein

Conclusion: “Acoustic reflection technique is so far the only relatively simple, noninvasive, reproducible, and inexpensive technique that permits the measurements of upper airway anatomy under dynamic conditions.”

2). *Comparison of Glottic Areas Measured by Acoustic Reflections vs. Computerized Tomography*
Journal of Applied Physiology, 1998

Authors: A. D. D’Urzo, I. Rubinstein, V. G. Lawson, K. P. Vassal, A. S. Rebuck, A. S Slutsky, and V. Hoffstein

Conclusion: “The acoustic reflection method is essentially a physiological tool, dedicated to performing only a single measurement, namely that of airway area. The major advantage of the acoustic reflections technique is its low cost, speed and simplicity of measurements, and lack of radiation hazards to the patient. In summary, despite the many assumptions inherent in the method of area inference from pulse-response measurements, rapid, noninvasive, accurate and reproducible determinations of glottic cross-sectional area may be obtained. Our results indicate that the acoustic reflection technique may be used reliably for in vivo clinical and physiological studies concerned with the glottis.

3). *Tracheal Stenosis Measured by the Acoustic Reflection Technique*
American Review of Respiratory Disease, 1984

Authors: V. Hoffstein and N. Zamel

Conclusion: “...we have shown that the acoustic technique is capable of identifying and quantitating tracheal stenosis prior to the development of characteristic abnormalities in the flow-volume curve.”

4). *In vivo Estimation of Tracheal Distensibility and Hysteresis in Normal Adults*
Journal of Applied Physiology, 1987

Authors: V. Hoffstein, R. G. Castile, C. R. O'Donnell, G. M. Glass, D. J. Strieder, M. E. B. Wohl, and J. J. Fredberg

Conclusion: "...Thus the acoustic reflection technique would appear to be a useful new noninvasive tool for investigating in vivo changes in central airway structure and function."

5). *Measurement of Upper Airway Movement by Acoustic Reflection*
Annals of Biomedical Engineering, 1995

Authors: Y. Zhou and J. A. Daubenspeck

Conclusion: "...the acoustic reflection method implemented properly is an effective tool in the study of upper airway movement as we have shown in our experimental results. The pattern of laryngeal movement estimated by acoustic reflection is very similar to that measured by laryngoscope. However, the acoustic reflection approach has an extremely important noninvasive advantage: since no anesthesia is required, airway measurements more closely reflect the subject's natural, unaltered responses."

6). *Airway Dimensions in the Human Determined by Non-invasive Acoustic Imaging*
Study Draft to Bruno Louis at INSERM U.292, 1997

Authors: B. Louis, P. Drinker, G. M. Glass, D. Isabey and J. J. Fredberg

Conclusion: "The acoustic reflection method is a powerful tool to study the physiopathological properties of the upper airways. It permits, at the bedside and in the clinical situation, an accurate non-invasive and reproducible measurement of the upper airway area. The short duration of the measurement (@ 5ms), in comparison with the breathing period, also allows the estimation of dynamic properties as well as the static properties of airway in physiological conditions. Such a tool should be useful to a better understanding of the structure and function of the upper airway in health as well as in disease. The method is robust and easy to use. Using the acoustic reflection method as a routine in intensive care units can be now envisaged."

7). *The Acoustic Reflection Technique for Non-invasive Assessment of Upper Airway Area*

European Respiratory Journal, 1991

Authors: V. Hoffstein, J. J. Fredberg

Conclusion: “It is clear from the already accumulated evidence that the acoustic technique may become a valuable tool for studying the clinical and physiological properties of the upper airway. So far this technique is the only one which allows non-invasive, accurate, reproducible and inexpensive measurements of the upper airway area. This technique is suitable not only for the measurements of static properties, but by virtue of its ability to measure airway areas...it is capable of providing the dynamic characteristics of the upper airway. This technique can be employed in adults as well as children, and requires minimum patient co-operation.”

“It is clear that having a tool for a non-invasive direct look into the airway will ultimately prove to be beneficial in extending our understanding of the structure and function of the upper airway in health and disease.”

8). *Assessing Orthotic Normalization of Pharyngeal Dynamics*

Journal of Craniomandibular Practice, 2004

Author: J. S. Viviano, B.Sc., D.D.S.

Conclusion: “Both non-invasive and accurate, acoustic reflectometry (AR) provides an objective measurement of the oral cavity and pharyngeal airway caudal to the velopharynx down to the glottis. Other advantages include ease of use and repeatability, inexpensive to perform, and high patient acceptance.”

“Although video endoscopy, CT, and MRI have all been used to assess the effect of mandibular advancement on the airway, the low cost, ease of use and repeatability, and high patient acceptance of AR make it an ideal imaging modality for the purpose. The ability to take measurements in three dimensions and at 0.2 sec intervals allows the *real time* assessment of both structural and functional dynamics and facilitates evaluation of an orthotic’s ability to normalize the airway dynamics of a pathological airway.”

9). *Effect of Position and Lung Volume on Upper Airway Geometry*
Journal of Applied Physiology, 1987

Authors: J. M. Fouke and K. P. Strohl

Conclusion: “The occurrence of upper airway obstruction during sleep and with anesthesia suggests the possibility that upper airway size might be compromised by the gravitational effects of the supine position. We used an acoustic reflection technique to image airway geometry and made 180 estimates of effective cross-sectional area as a function of distance along the airway in 10 healthy volunteers while they were supine and also while they were seated upright. We calculated z-scores along the airway and found that pharyngeal cross-sectional area was smaller in the supine than in the upright position in 9 of the 10 subjects.”

“We conclude that pharyngeal cross-sectional area decreases as a result of a change from the upright to the supine position and that the mechanism of this change is independent of the change in functional residual capacity.”

10). *Reproducibility and Accuracy of Airway Area by Acoustic Reflection*
Journal of Applied Physiology, 1984

Authors: L. J. Brooks, R. G. Casitle, G. M. Glass, N. T. Griscom, M. E. B. Wohl, and J. J. Fredberg

Conclusion: “We conclude that the measurement of Airway Area by Acoustic Reflection yields accurate and highly reproducible results that may be clinically useful for the noninvasive detection of changes in central airway geometry related to disease, bronchospasm, and airway growth.”

11). *Airway Area by Acoustic Reflection: The Two-Microphone Method*
Journal of Biomechanical Engineering, 1993

Authors: B. Louis, G. Glass, B. Kresen, J. Fredberg

Conclusion: “In summary, the principal findings of this report are as follows. 1) Areas inferred using the two-microphone method compared favorably with the standard single microphone approach and with water displacement methods. 2) We established a correction procedure that secured both stability of the algorithm and accuracy of the area inferences. 3) We achieved accurate measurements with a wave tube with transducers separated by as little as 3 cm.”

“This new technique demonstrates two main advantages. First, it does not require a prior calibration. This allows both easier use and fewer experimental artifacts. Second, it permits a miniaturization of the experimental wave tube. A smaller apparatus might find a wider range of diagnostic utility.”

12). *Pulmonary Airway Area by the Two-microphone Acoustic Reflection Method*
Journal of Applied Physiology, 1994

Authors: B. Louis, G. M. Glass, and J. J. Fredberg

Conclusion: “In summary, we have shown that the two-microphone method permits accurate measurement of human pulmonary airway area of breathing subjects. We established a high-pass filter signal-processing method that lessened artifacts associated with nonrigidity. This is important because it permits considerable simplification of the apparatus and the measurement procedures.”

13). *Acoustic Reflectometry for Airway Measurement. Principles, Limitations and Previous Work*
Clinical Physics and Physiological Measurement, 1991

Authors: I. Marshall, M. Rogers, and G. Drummond

Conclusion: “Acoustic pulse reflectometry is a relatively recent technique which allows the non-invasive measurement of human airways. The technique consists of guiding an acoustic impulse through the subject’s mouth and into the airway. Suitable analysis of the resulting reflection (the ‘echo’) allows a reconstruction of the area-distance function. The non-invasive nature of the technique offers significant advantages over the established methods of x-ray cephalometry and CT scanning, and makes it very attractive for the investigation of ENT problems and sleep apnea, and in the anaesthetic management of patients.”

14). *Objective evaluation of velopharyngeal function by acoustic reflection measurements*
Mund Kiefer GesichtsChirurgie, 1998

Authors: M. Kunkel, U. Wahlmann, W. Wagner

Introduction: “Today, acoustic rhinometry can be viewed as an accepted diagnostic tool, frequently used in the planning and follow-up of functional nasal surgery, as well as in the quantitative evaluation of allergic mucosal reactions.

“Even for further peripheral airways, Jackson et al. reported that, although the acoustically determined cross-sectional area does not describe the exact metric anatomic size, changes in the anatomic cross-sectional area can be accurately recorded by acoustic measurements.

“...acoustic reflection techniques can be expected to measure *changes* of the epipharyngeal volume.

“A non-invasive acoustic assessment technique would be desirable for the objective evaluation of velar movement, especially in the rehabilitation of cleft-palate patients.”

Discussion: “Conventional investigation techniques for the evaluation of velopharyngeal function are based on subjective interpretation of hypernasality or direct visualization of velar movement by means of nasoendoscopy or videofluoroscopy. These methods provide an accurate assessment of the actual state of muscular function but are not suitable for repeated evaluation due to radiation exposure and apparatus or personal requirements, respectively.

“Repeated longitudinal investigations require objective assessment techniques that are non-invasive, easy to perform and not inconvenient to the patient. As acoustic reflection measurements generally fulfill these criteria, we tried to apply this technique for the of velopharyngeal function.

“Our actual measurements of cleft-palate patients and non-cleft controls demonstrate that acoustic pharyngometry is capable of discriminating velar mobility in these subjects.

“When comparing the pattern of movement of the groups, acoustic pharyngometry identifies different types of restriction in cleft-palate patients with and without a pharyngeal flap.

“When comparing the preoperative to postoperative recordings of mobility after velopharyngoplasty, acoustic pharyngometry even appears helpful in measuring the effect of therapeutic intervention on velopharyngeal function.

“As acoustic reflection measurements are non-invasive and are easily performed without any discomfort to the patient, repeated evaluation may offer the possibility of direct feedback during logopaedic training”.

15). *Objective, Noninvasive Evaluation of Velopharyngeal Function in Cleft and Noncleft patients*

Cleft Palate-Craniofacial journal, January 1998

Authors: M. Kunkel, U. Wahlmann, W. Wagner

Conclusion: “Cleft palate and control patients showed overlapping ranges of velopharyngeal mobility, indicating that muscle function cannot be classified as normal or pathologic by a single acoustic measurement. An objective method of assessing velopharyngeal mobility may, however, provide a diagnostic tool for monitoring therapeutic progress or stagnation of logopedic therapy. As acoustic reflection measurements are noninvasive and can easily be performed without any discomfort to the patient, repeated evaluation offers the possibility of direct feedback in logopedic training. Beyond logopaedic therapy of cleft palate patients, this technique may prove helpful in monitoring rehabilitation after cerebral apoplexy and other neurological deficits.”

16). *Oropharyngeal Dimensions in Adults: Effect of Ethnicity, Gender, and Sleep Apnea*
Journal of Clinical Sleep Medicine, 2005

Authors: K. Monahan, H. L. Kirchner, S. Redline

Conclusion: “We concluded that (1) acoustic pharyngometry identifies differences in upper airway characteristics based on gender, ethnicity, and SDB status and (2) novel parameters can assist in quantifying these pharyngeal phenotypes. The novel parameters can potentially facilitate quantitative, as an adjunct to qualitative, comparison of acoustic waveforms. Such analysis may be useful in further establishing risk for SDB, in the assessment of candidacy for various modalities of treatment, for more robust phenotypic analysis in genetic epidemiological studies, and to gauge the response to treatment. Furthermore, although our data provide additional evidence that reduction in airway caliber plays a role in SDB, the relatively small pharyngeal dimensions in women and African Americans without SDB suggest that factors in addition to those that influence directly pharyngeal CSA modify the predilection to SDB differentially across population subgroups”

17). *Alterations in upper airway cross-sectional area in response to lower body positive pressure in healthy subjects*

Thorax, 2007

Authors: S. Shiota, C. M. Ryan, K.L. Chiu, P. Ruttanaumpawan, J. Haight, M. Arzt, J. S. Floras, C. Chan and T. D. Bradley

Conclusion: "In healthy subject, displacement of fluid from the legs by LBPP causes distension of the neck and narrowing of the UA lumen. Fluid displacement from the lower to the upper body while recumbent may contribute to pharyngeal narrowing [measured by acoustic pharyngometry] and obstruction to airflow in patients with OSA. This may have particular pathological significance in oedematous states such as heart and renal failure.

18). *Mandibular Advancement Achieved through a Stepped Mouthpiece Design Can Change the Size of the Upper Airways*

Presented at Respiratory Drug Delivery 2010, Orlando, Florida April, 2010

Authors: Kurt Nikander, Ian Petherbridge, Eugene Scargerry, Dirk Von Hollen, John Viviano, Henry Chrystyn

Summary: "Maximal lung deposition of inhaled aerosols is important in the treatment of respiratory diseases. The upper airways are known to affect the deposition of aerosol in the lungs. The design of inhalers and of inhaler mouthpieces (change in vertical diameter) has been shown to affect lung and upper airway deposition of inhaled aerosol. Acoustic pharyngometry (Eccovision; Sleep Group solutions; North Miami Beach, FL) can be used to non-invasively measure the upper airway cross-sectional area. Acoustic pharyngometry has traditionally been used to evaluate the impact of various protrusive positions of the lower jaw (in mm increments) achieved through oral appliances for patients with sleep apnea. A recently published validation study of acoustic pharyngometry suggested that seated pharyngometry measurements correlated with supine MRI measurements. We have measured through acoustic pharyngometry the impact of prototype stepped mouthpieces on the dimensions of the upper airways. The stepped mouthpiece design provided the tools for both vertical and horizontal movements (mandibular advancements) of the lower jaw.

Conclusion: "Mandibular advancements through the use of stepped mouthpieces were shown to increase the volume of the upper airways. The use of acoustic pharyngometry enabled a detailed

analysis of the changes from the oral cavity to the glottis. The incorporation of stepped mouthpieces in inhalers might increase the amount of aerosol deposited in the lungs, and warrants further research."

B. Related to Endotracheal Intubation

1). *Acoustic Method to Estimate the Longitudinal Area Profile of Endotracheal Tubes* American Journal of Respiratory Critical Care Medicine, 1994

Authors: C. Van Surell, B. Louis, F. Lofaso, L. Beydion, L. Brochard, A. Harf, J. Fredberg, and D. Isabey

Conclusion: "This study has demonstrated the feasibility of the acoustic reflection method in the intensive care unit and that the decrease in hydraulic diameter and the change in area profile are both linked to ETT obstruction by mucus deposition. However, routine monitoring and clinical management of patients appear more difficult with the hydraulic method because (1)connection to a pneumotachygraph, (2)introduction and positioning of a pressure catheter in the ETT, and (3)adjustment of the setting of the ventilator are all difficult to handle clinically. This experimental complexity renders the hydraulic method less simple to use than the acoustic reflection method. In addition, long-term monitoring might be compromised with the hydraulic method since fresh mucus may obstruct the side holes of the pressure catheter. By contrast, the acoustic reflection method provides a means for short- or long-term routine monitoring of the gradual reductions in ETT patency as well as for the determination of sites of mucus accumulation. However, it is difficult from the present results to ascertain the minimum value of ETT area acceptable in ventilated patients. Further studies are needed to determine, from the acoustic area monitoring, a reliable criterion to be used as an alarm for ETT replacement. The results obtained here suggest that this new method provides a means for reducing the risk of unnecessary extubation and associated morbidity, as well as an aid to estimate the increase in the work of breathing caused by ETT obstruction.

2). *Acoustic Reflectometry and Endotracheal Intubation* Anesthesia and Analgesia, 1996

Authors: D. M. Eckmann, PhD, JD, R. Glassenberg, MD, N. Gavriely, DSc, MD

Conclusion: “As an adjunct to physical examination, acoustic reflection measurements may provide a simple method to identify difficult-to-intubate and potential failed endotracheal intubation patients not identified by physical examination and relevant medical history alone.”

3). *Using Acoustic Reflectometry to Determine Breathing Tube Position and Patency*
Journal of Sound and Vibration, 1995

Authors: J. P. Mansfield and G. R. Wodicka

Conclusion: “The acoustical guidance system developed in this study offers the potential to become an inexpensive and reliable clinical device.”

“The Accuracy of distance estimation measured in the trachea to +/- 0.8 cm over the entire insertion range is adequate to be useful in adults as well as infants. For prospective clinical use, once the ETT tip is placed through the vocal folds, the system can confirm that the tube is in the trachea and not in the esophagus through the detection of the airway reflection and an estimated cross-sectional airway area that is greater than that of the ETT. The tube can then be advanced a desired distance past the vocal cords as guided by the system.”

“In addition, any condition that reduces lumen patency such as excessive build-up of mucous or a kinked tube will be detected by the system, at which time corrective measures can be taken.”

4). *Detection of Positional Airway Obstruction in Neonates by Acoustic Reflection*
American Journal of Respiratory and Critical Care Medicine, 2000

Authors: P. Jarreau, B. Louis, L. Desfrere, P. W. Blanchard, D. Isabey, A. Harf, and G. Moriette

Conclusion: “In conclusion, this study showed that the [Acoustic Reflection] method is an effective way to diagnose abutment of an ETT against the tracheal wall in infants. The method is easy to use and non-invasive, and usually requires less than 10 seconds of ventilator disconnection. No adverse effects of the brief disconnection were noted during the study. The [Acoustic Reflection] method therefore appears to be a good tool for detecting or confirming positional airway obstruction in neonates.”

C. Related to Obstructive Sleep Apnea

1). *Test-retest Validity of Acoustic Pharyngometry Measurements*
Otolaryngology—Head and Neck Surgery, 2004

Author: I. Kamal, MD

Conclusion: “Provided that a standard operating protocol is adopted and maintained, repeatability of acoustic reflection results can be achieved. This adds to the reliability of this technique in assessing the pharyngeal airway in snorers and patients with obstructive sleep apnea.”

2). *Lung Volume Dependence of Pharyngeal Cross-sectional Area by Acoustic Pharyngometry*
Otolaryngology—Head and Neck Surgery, 2002

Author: I. Kamal, MD

Conclusion: “Pharyngeal cross-sectional area was measured using the acoustic technique. Men were found to have a larger cross-sectional area, and men and women were found to behave similarly in response to a change in intrapharyngeal pressure, with men showing a more significant difference in lung volume dependence, indicating the different mechanical properties of the pharynx of men. Examination of the pharyngeal compliance with acoustic pharyngometry adds to the potential of this technique as a tool for the evaluation of the pharyngeal airway in terms of area and dynamic behavior assessment. This may be of relevance in promoting the development of upper airway assessment in patients with OSA.”

3). *Acoustic Reflectometry for Airway Measurements in Man: Implementation and Validation*
Clinical Physics and Physiological Measurements, 1993

Authors: I. Marshall, N.J. Maran, S. Martin, M.A. Jan, J.E. Rimmington, J.J.K. Best, G.B. Drummond, and J.J. Douglas

Conclusion: “The real-time display of airway areas is able to show the complex interdependencies of movement of the mouth, tongue, soft palate, naso-pharynx and glottis. These aspects have not been accessible to previous researchers, who did not process data in real time. Differences in upper airway caliber between subjects are important in the pathogenesis of the sleep apnea/hypopnea syndrome (Rodenstein *et al* 1990). Our study shows that our simplified acoustic reflection technique is a valid way of assessing upper

airway caliber.”

4). *Predictive Value of Kushida Index and Acoustic Pharyngometry for the Evaluation of Upper Airway in Subjects With or Without Obstructive Sleep Apnea*
Journal of Korean Medical Science, 2004

Authors: D. G. Jung, H. Y. Cho, R. R. Grunstein, B. Yee

Conclusion: “The morphometric measurement of oral cavity and acoustic pharyngometry enables an examiner to predict the presence or absence of OSA rapidly and accurately during an initial visit. Through this study we found the sensitivity and specificity of the morphometric measurement of oral cavity to be 89% and 94%, and acoustic pharyngometry are 93% and 94%, respectively. Acoustic pharyngometry is a more accurate method for predicting the presence or absence of OSA.”

5). *Normal Standard Curve for Acoustic Pharyngometry*
Otolaryngology—Head and Neck Surgery, 2001

Author: I. Kamal, MD

Conclusion: “In patients with sleep apnea, studies involving acoustic reflection have demonstrated reductions in upper airway area compared with normal controls, yet perhaps a minimal pharyngeal cross-sectional area is rather needed as a “gold standard” to refer to in managing OSA patients. At this point, acoustic pharyngometry is meant to be a stand-alone test, its measurements for patients of OSA need to be interpreted with lateral cephalometric measurements and findings of Muller’s maneuver for better analysis and proper decision making regarding possible site(s) of airway obstruction. The technique is easy, rapid, and cost-effective and has been shown to be successfully reproducible as well as repeatable in producing normal curves.”

6). *Airway Orthotics: Normalizing the Pathological Airway*
Sleep Review—The Journal for Sleep Specialists, 2002

Author: J. S. Viviano, BSc, DDS

Conclusion: “We have discussed the concept of normalizing airway structure and function through repositioning mandibular posture with an airway orthotic (AO), and the rationale for use of acoustic reflectometry to evaluate the level of airway normalization. The

ability to isolate those individuals most likely to benefit from and AO prior to orthotic construction would reduce or potentially eliminate treatment failures for those patients prescribed this therapy. The ability to obtain immediate feedback regarding the degree of airway normalization using either a chairside fabricated bite-jig or the actual AO would provide valuable information regarding construction, titration, and maintenance parameters. Finally, acoustic evaluation of airway normalization would improve the efficiency with which airway orthotic therapy is provided, leading to meaningful savings in time and resources for both the patient and practitioner.”

7). *Dental Therapy for Obstructive Sleep Apnea*
Seminars in Respiratory and Critical Care Medicine, 2005

Author: D. R. Bailey, D.D.S.

Conclusion: “One method for determining and oral appliance’s effectiveness uses acoustic reflection imaging or pharyngometry....This technology has the ability to:

- 1). Determine the approximate site of airway collapse
- 2). Measure the volume of the airway
- 3). Determine the area of collapse, which is the area of greatest constriction in the airway, and assess it in centimeters squared
- 4). Determine the improvement in the airway volume and in the area of greatest constriction with mandibular repositioning.

Overall this can help to determine potential effectiveness and prognosis for OA therapy.

- 5). Assist in determining the potential effectiveness of vertical opening, anterior repositioning, and what combination may affect the airway optimally.

Although this technology is relatively new in its application, within dental practices that provide OA therapy there is a growing awareness of its value and application.”

8). *Utility of Noninvasive Pharyngometry in Epidemiologic Studies of childhood Sleep-disordered Breathing*
American Journal of Respiratory and Critical Care Medicine, 2002

Authors: K. J. Monahan, E. K. Larkin, C. L. Rosen, G. Graham, and S. Redline

Conclusion: “The usefulness of any diagnostic test depends on numerous factors, including its feasibility, predictive ability (regarding predicting clinical endpoints or discriminating subgroups of the population), precision (or reliability), accuracy, and cost. We have demonstrated that acoustic pharyngometry can be adapted for use in children, and trained personnel can successfully obtain highly reproducible data even in nonclinical settings (such as the home).”

“Radiographic comparisons have shown that pharyngometry allows accurate reconstructions of the geometry of other airway structures including the larynx, trachea, and nasal airways. Airway models that have been used to assess the accuracy of the technique further indicate that accuracy is greater with smaller mouth areas.”

“Longitudinal follow-up of children and young adults with simple tools such as acoustic reflectometry may shed further light on how pharyngeal dimensions change after puberty and with growth and maturation and hormonal changes.”

“...measurement of pharyngeal cross section area appears to be more strongly associated with apnea/hypopnea index levels than tonsillar size as assessed by physical exam. This result suggests that acoustic reflectometry may provide important information in the evaluation of pediatric sleep-disordered breathing not otherwise accessible via routine examination.”

9). *Upper Airway Morphology in Patients with Idiopathic Obstructive Sleep Apnea*
American Review of Respiratory Disease, 1984

Authors: J. Rivlin, V. Hoffstein, J. Kalbfleisch, W. MnNicholas, N. Zamel, and A. C. Bryan

Conclusion: “The acoustic technique is performed in the awake state and needs a minimal degree of patient cooperation. The good correlation between pharyngeal cross-sectional area and the severity of the disorder may give us a simple way to detect patients with OSA from those with other sleep-related breathing disorders.”

10). *Predictive Value of Pharyngometry Derived Measurements for Oral Appliance Treatment of Obstructive Sleep Apnea Syndrome*
Chest, 2000

Authors: D. I. Loube, MD, N. J. Ball, D. Phil, D. F. Schmidt, P. J. Nehring

Conclusion: “Airway volume determined by acoustic Pharyngometry may be a useful measure to predict OA treatment response and could minimize the need for post-treatment polysomnography.”

11). *Differences in Pharyngeal Properties between Snorers with Predominantly Central Sleep Apnea and Those without Sleep Apnea*
American Review of Respiratory Disease, 1987

Authors: T. D. Bradley, I. G. Brown, N. Zamel, E. A. Phillipson, and V. Hoffstein

Conclusion: “...studies to date indicate that anatomic areas of proximal structures (up to and including the carina) may be accurately measured by the acoustic technique. It is furthermore encouraging that changes in area of the distal structures, where the anatomic and acoustical equivalence may not be valid, are also resolved by this technique.”

12). *Increased Upper Airway Collapsibility in Children with Obstructive Sleep Apnea during Wakefulness*
American Journal of Respiratory and Critical care Medicine, 2004

Authors: D. Gozal and M. M. Burnside

Conclusion: “This study shows that acoustic pharyngometric measurements of the upper airway before and after topical anesthesia provide a reproducible measure of Upper Airway Collapsibility in awake children. Furthermore, a cutoff value derived from the differences in cross-section area before and after topical anesthesia predicts, with high sensitivity and specificity, the number of children who have sleep disordered breathing. Furthermore, measurements of UAC after surgical removal of tonsils and adenoids in children with SDB show normalization of upper airway dynamics in approximately two-thirds of the children, whereas in the remaining one-third increased UAC remains despite marked improvements and/or normalization of their respiratory patterns during sleep.”

13). *Evaluation of the Upper Airway in Patients with Obstructive Sleep Apnea*
Sleep, 1991

Authors: J. W. Shepard, Jr., W. B. Gelfer, C. Guilleminault, E. A. Hoffman, V. Hoffstein, D. W. Hudgel, P. M. Suratt, and D. P. White

Conclusion: “The acoustic reflection technique has...proven to be useful in studying changes in pharyngeal structure and function in response to weight loss and UPPP (uvulopalatopharyngoplasty). The acoustic reflection technique offers several advantages over other methods used to assess UA structure and function. As compared to fiber optic pharyngoscopy, the acoustic technique is less invasive and more easily quantitated. As compared to the radiographic assessment, whether by CT scans or x-ray cephalometry, the acoustic technique is inexpensive, quick, harmless and easily repeatable. One of the major advantages of the technique is its capability to provide a dynamic picture of the airway as area measurements may be carried out as rapidly as five times/sec.”

14). *Acoustic Reflection Technology for Assessing Pharyngeal Size – faster, more specific, lower cost*

American Review of Respiratory Disease, 1984

Authors: Rivlin, Hoffstein, Kalbfleisch, McNicholas, Zamel, Bryan

Conclusion: “This study demonstrates that sitting awake patients with idiopathic OSA have significantly smaller cross sectional areas of the pharynx and the glottis than do subjects without OSA. This study also demonstrates an anatomic predisposition to the development of upper airway occlusion that may not be detectable on clinical examination, but that is detectable with acoustic reflections.”

15). *Heritability of Upper Airway Dimensions Derived Using Acoustic Pharyngometry*
European Respiratory Journal, 2008

Authors: S. R. Patel, MD, J. M. Frame, E. K. Larkin, PhD, Susan Redline, MD, MPH

Conclusion: “Our results suggest that upper airway dimensions derived via acoustic pharyngometry demonstrate substantial intra-familial correlation.”

“Acoustic pharyngometry, because of its ease of use, is ideally suited for the study of the thousands of subjects required for epidemiologic studies aimed at dissecting the genetics of OSA.”

“The overall validity of pharyngometry for assessment of

pharyngeal cross sectional area is supported both by prior work showing its ability to discriminate subjects with and without OSA, as well as the high correlation we observed between minimum CSA obtained by pharyngometry with measurements obtained by MRI.”

“In summary, this work demonstrates the utility of acoustic pharyngometry in studying the genetic basis for variability in upper airway shape by demonstrating the substantial heritability of pharyngometry-derived airway measures. While clearly pharyngometry cannot provide detail on specific structures that impinge on the airway as can be obtained with MRI or other technologies, pharyngometry is relatively low-cost, minimally burdensome and non-invasive, and thus amenable to use in the large scale studies needed to discover genes for OSA-related traits.”

16). *Acoustic Pharyngometry: Clinical and Instrumental Correlations in Sleep Disorders*
Revista Brasileira de Otorrinolaringologia, 2007

Authors: M. Gelardi, A. Maselli del Giudice, F. Cariti, m. Cassano, A. Castelante Farras, J. L. Fiorella, P. Cassano

Conclusion: “In our experience, acoustic pharyngometry allowed the precise observation of oral, pharyngeal and laryngeal cross-sections in the groups we studied by defining a characteristic and easily recognized airway network geometry.”

“Pharyngometric parameters...clarified significant differences in patients with disease compared to the control group.”

“A comparison between pharyngometric parameters of the sample group and the control group allowed us to develop guidelines for using pharyngometry as a gold standard test in the management of patients with respiratory disorders. Interestingly, there is a 100% correlation between results obtained by the modified Muller’s maneuver and those obtained from pharyngometry for locating obstruction. In our view, pharyngometry provides precise discrimination and quantification of the part played by each site in the genesis of SDB.”

“Our experience shows that acoustic pharyngometry was extremely effective in defining the level of stenosis and its parameters by studying the relevant and statistically significant differences between patients with disease and the control group.”

“Most of the studies on acoustic pharyngometry focus on the diagnosis (location and identification of obstruction). We believe that this method has many other possibilities in the clinical setting, particularly in OSAS, such as monitoring medical or surgical treatments or removing upper airway obstructions.”

“Undoubtedly this method has shadow areas, the most important being the impossibility of running this test during sleep. The test is endorsed, however, by negligible biological risk, rapidity, technical ease, and reproducibility. Further studies should be done to standardize this method and to increase its use in the clinical setting.”

17). *Lung volume Dependence of Pharyngeal Cross-Sectional Area in Patients with Obstructive Sleep Apnea*
American Review of Respiratory Disease, 1984

Authors: V. Hoffstein, N. Zamel, and E. A. Phillipson

Conclusion: “We examined the relationship between lung volume and pharyngeal cross-sectional area (with acoustic reflection) in 9 obese patients with obstructive sleep apnea and 10 age-matched, obese subjects without sleep apnea. The results indicate that in obese patients with obstructive sleep apnea, pharyngeal cross-sectional area is abnormally small, and varies considerably with changes in lung volume. The beneficial effects of weight reduction in such patients may relate to the coincident increase in functional residual capacity, causing an increase in upper airway size.”

18). *Is Area of the Retroglottal space Differently Affected by Posture in Apneic and Nonapneic Snorers?*
European Respiratory Journal, 1995

Authors: A. Monnier, B. Lousis, F. Lofaso, I. Gilain, C. Van Surell, D. Touchard, A. Harf, J. Fredberg and D. Isabey

Conclusion: “In conclusion, the present acoustic results do not reveal geometrical differences between apneic and nonapneic which could have been masked in previous acoustic studies. Above all, our results demonstrate again (i) the effect of body position on pharyngeal patency in snorers, and (ii) the similarity of this effect when observed in a population of snorers OSAS and non OSAS otherwise homogeneous in terms of clinical complaint and obesity. At last, although the answer to the question raised in the title of the

paper is negative, the present study confirms the advantage of non-invasive acoustic evaluations not only in terms of accuracy as already shown in the past, but also in terms of clinical and physiological compatibility when a short wave tube is used as presently done.”

19). *Acoustic Pharyngometry Patterns of Snoring and Obstructive Sleep Apnea Patients*
Otolaryngology—Head and Neck Surgery, 2004

Author: Ibrahim Kamal

Conclusion: “Because pharyngeal narrowing contributes to snoring and sleep apnea, determination of pharyngeal area may be used as a screening procedure to suggest the severity of the condition and possibly the site of obstruction. The acoustic reflection technique is reproducible, non-invasive, and free from potential side effects; the good correlation between Apnea Index and pharyngeal cross-sectional area adds to the potential of this technique. Careful study of pharyngeal cross-sectional area and curve topography may provide a good idea about the site of upper airway obstruction.”

20). *Pharyngeal Cross-Sectional Area and Pharyngeal Compliance in Normal Males and Females*
Respiration, 1998

Authors: J. Huang, H. Shen, M. Takahashi, T. Fukunaga, h. Toga, K. Takahashi, N. Ohya

Conclusion: “In conclusion, we measured pharyngeal parameters in a large number of normal subjects using the acoustic reflection technique with air breathing. The pharyngeal compliance was greater in the men than in the women, and it increased with age only in the men. The pharyngeal size in the lying positions did not change with age and was not significantly different between the genders. These data indicate that the assessment of pharyngeal compliance could contribute to the elucidation of sleep-related disorders of breathing.”

21). *Pharyngeal Size in Snorers, Nonsnorers, and Patients with Obstructive Sleep Apnea*
New England Journal of Medicine, 1986

Authors: T. D. Bradley, I. G. Brown, R. F. Grossman, N. Zamel, D. Martizez, E. A Phillipson, and V. Hoffstein

Conclusion: “In summary, our findings indicate that patients with obstructive sleep apnea and snorers without apnea have abnormalities of the anatomical and mechanical features of the pharynx that distinguish them from each other and from normal subjects who do not snore. It thus appears that anatomical abnormalities of the pharynx, coupled with abnormal pharyngeal mechanics, are important factors in the pathogenesis of both snoring and obstructive sleep apnea—two common breathing disorders of sleep.”

22). *Improvement in Upper Airway Function after Weight Loss in Patients with Obstructive Sleep Apnea*
American Review of Respiratory Disease, 1988

Authors: I. Rubinstein, N. Colapinto, L. E. Rotstein, I. G. Brown, and V. Hoffstein

Conclusion: “In summary, we have demonstrated that in overweight patients with OSA and abnormal pharyngeal mechanics, weight loss is associated with marked improvement in pharyngeal function, which may partly explain the observed improvement in sleep apnea. Furthermore, glottic abnormalities may also contribute to the pathogenesis of OSA, and weight loss may have a beneficial effect on glottic function as well.”

23). *Pharyngeal Compliance in Snoring Subjects with and without Obstructive Sleep Apnea*
American Review of Respiratory Disease, 1985

Authors: I. G. Brown, T. D. Bradley, E. A. Phillipson, N. Zamel, and V. Hoffstein

Conclusion: “Previous studies employing the acoustic reflection technique, X-ray cephalometry, fluoroscopy, and computerized tomography have shown reduced upper airway caliber in patients with OSA. Our results confirm these findings by demonstrating that patients with OSA tend to have a lower pharyngeal cross section than the nonapneic control subjects.”

24). *Acoustic Reflection: Review and Clinical Applications for sleep-Disordered Breathing*
Sleep and Breathing, 2002

Authors: J. S. Viviano, D.D.S.

Conclusion: “The potential clinical usefulness of AR in the treatment of patients with SDB involves all stages of treatment: initial screening of patients, establishing patient candidacy, evaluating nasal patency, determining mandibular posture that optimizes airway patency, determining orthotic titration settings, and verifying continued efficacy of orthotic settings at follow-up. The use of AR could facilitate front-line efforts in isolating afflicted individuals; ensure a higher level of success for surgical, positional, and airway orthotic therapies; eliminate the possibility that an undiagnosed nasal obstruction could interfere with successful treatment; establish orthotic construction parameters; and objectively verify the orthotics’ continued effectiveness. “

25). *Short- and Long-term effects of CPAP on upper airway anatomy and collapsibility in OSAH*

Sleep Breath, 2009

Authors: L. Corda, S. Redolfi, L. Taranto Montemurro, G E. La Piana, E. Bertella, C. Tantucci

Intro: “More easily and rapidly than MRI, acoustic pharyngometry can be used to assess the UA caliber and its change in OSAH patients.”

Methods: “*Acoustic pharyngometry* UA anatomy was evaluated in the supine position by means of acoustic pharyngometry (‘Eccovision’ ...). It uses acoustic reflection (AR) technology to assess cross-sectional areas from the oral cavity to hypopharynx by calculating changes in acoustic impedance that occur along these UA with variable caliber. This technique is fully described elsewhere. We obtained traces that represent UA cross-sectional area (UA-XSA) versus distance down the airway. Four technically acceptable traces (variability \leq 10%) were taken at the end of resting expiration. Three UA-XSA were read off the traces: oropharyngeal junction (OPJ) represents the area of the junction between the back of the oral cavity and the oropharynx; maximal pharyngeal area (APmax) is the maximum area in the oropharynx, generally found behind the tongue radix; mean pharyngeal area (APmean) represents the mean area from the OPJ to the glottis. OPJ and APmax, representing the narrowest and the widest sections of the pharynx respectively, can be used as indicators of UA morphology, while APmean represents a complete evaluation of pharyngeal caliber. This technique has been validated against magnetic resonance imaging for assessment of the UA-XSA.”

26). *Oral appliances for the treatment of obstructive sleep apnea*

Author: Robert L. Horchover

Discussion: “Oral devices are not for every patient. An adequate evaluation should include a full medical examination and polysomnography to document sleep apnea severity and screening for predisposing factors associated with neck and shoulder muscles, including mandibular range of motion, occlusion, dentition and the intra-oral anatomy, tongue size and architecture of the oropharyngeal junction. A device may then be selected to best meet the patient’s unique needs. Acoustic reflection pharyngometry can be a valuable tool for measuring upper airway baseline dimension and determining whether and how much mandibular repositioning will enlarge the airway. Each person seems to have an anterior/vertical position that produces his or her unique optimum airway.”

27). *Role of Extracellular Fluid Volume in Inducing or Aggravating Obstructive Sleep Apnea-Hypopnea in Patients with Resistant Hypertension*

Prosserman Centre for Health Research (Samuel Lunenfeld Research Institute), Mount Sinai Hospital, 2009

Author: Oded Friedman

Discussion: Lower Body Positive Pressure Experiment

“Upper airway cross-sectional area was determined using acoustic pharyngometry (Eccovision Acoustic pharyngometry; Sleep Group Solutions, Miami, FL) at end-expiration. Two parameters, oropharyngeal junction area and mean cross-sectional area from the velum to the glottis, were recorded via the mean of four consecutive measurements. The device was positioned in the mouth (using a modified scuba mouthpiece designed to secure the tongue in place) of subjects while they lay supine with head fixed in the neutral position by resting the head in form-shaping sand bags. The pulse emitter produced five pulses/second and two microphones detected the amplitude and temporal changes of the reflected pulse. Acoustic pharyngometry is highly reproducible and has been validated against computed tomography and magnetic resonance imaging for assessment of upper airway cross-sectional area in non-snorers and in snorers with and without OSAH in both the supine and upright positions. Given that lung volume is a determinant of upper airway cross-sectional area, changes in end-expiratory lung volume (i.e. functional residual

capacity) were assessed by respiratory inductance plethysmography calibrated against a spirometer in the DC coupled mode. BP and heart rate were monitored during LBPP application by an automated sphygmomanometer (Dinamap 1846SX NIBP; Critikon, Tampa, FL).

“Following a 30-minute stabilization period in which subjects lay supine, baseline measurements of all variables were made. Subjects were then exposed to increasing LBPP beginning at 10 mmHg and ending at 40 mmHg, at 10 mmHg increments. Each of the 4 applied pressures was maintained for 5 minutes and measurements of all variables were made at the end of the 5-minute period.

“The relationship between the reduction in mean upper airway cross-sectional area and the LBPP-induced reduction in leg fluid volume was fit best using log-transformed values of the reduction in mean upper airway cross-sectional area.

“Leg fluid volume and neck circumference prior to LBPP application were significantly greater in the RH [drug resistive hypertension] group compared to the CH [controlled hypertension] group; on the other hand, the baseline oropharyngeal junction area and mean upper airway cross-sectional area were comparable in the RH and CH groups. Compared to the CH group, the LBPP-induced reductions in oropharyngeal junction area and mean upper airway cross-sectional area were significantly greater in the RHG group. The LBPP-induced increase in neck circumference was also significantly greater in the RH group.

“Given that the effects of LBPP application on neck circumference and upper airway cross-sectional area were assessed during the wake period, the findings may not be applicable to those occurring during the sleep period. However, it would have been impractical for subjects to sleep uninterrupted while undergoing simultaneous LBPP application and acoustic pharyngometry since they would be unable to sleep or would move if they did fall asleep causing artifactual changes in the acoustic pharyngometry signal. Additionally, the literature would suggest that rostral fluid shift may have and even more pronounced effect on upper airway cross-sectional area during the sleep than wake cycle because of a withdrawal of neural input to the pharyngeal dilator muscles at sleep onset resulting in pharyngeal luminal narrowing with a corresponding increase in pharyngeal resistance and collapsibility. A limitation of acoustic pharyngometry, given that transmitted sound waves travel below the soft palate, is its inability to evaluate

the lumen size at the level of the retropalatal pharynx, the site at which the pharynx collapses in most patients with OSAH. Nonetheless, significant changes in the mean upper airway cross-sectional area and/or oropharyngeal junction have already been documented following LBPP application and diuretic therapy. Furthermore, several studies have shown consistently that the upper airway cross-sectional area from velum to glottis in the awake state is narrowed in patients with OSAH, both while upright and supine.”

D. Related to Vocal Tract

1). *Normative Standards for Vocal Tract Dimensions by Race as Measured by Acoustic Pharyngometry*

Journal of Voice, 2006

Authors: S. A. Xue and J. G. Hao

Conclusion: “Acoustic pharyngometry evaluates the geometry of the vocal tract with acoustic reflections and provides information about vocal tract cross-sectional area and volume from lip to the glottis. Variations in vocal tract diameters are needed for speech scientists to validate various acoustic models and for medical professionals since the advent of endoscopic surgical techniques. Race is known to be one of the most important factors affecting the oral and nasal structures. This study compared vocal tract dimensions of White American, African American, and Chinese male and female speakers. One hundred and twenty healthy adult subjects with equal numbers of men and women were divided among three races. Subjects were controlled for age, gender, height, and weight. Six dimensional parameters of the speakers’ vocal tract cavities were measured with acoustic reflections technology (AR). Significant gender and race main effects were found in certain vocal tract dimensions. The findings of this study now provide speech scientists, speech-language pathologists, and other health professional with a new anatomical database of vocal tract variations for adult speakers from three different races.”

2). *Volumetric Measurements of Vocal Tracts for Male speakers from Different Races*

Clinical Linguistics and Phonetics, 2006

Authors: S. A. Xue, G. J. Hao, and R. Mayo

Conclusion: “Research examining physiologic and acoustic characteristics of culturally diverse populations is sorely needed, but rarely reported.

The major aim of this study was to quantify vocal tract dimensional parameters (oral length, oral volume, pharyngeal length, pharyngeal volume, total vocal tract length and total vocal tract volume) of adult male speakers from three different racial populations (White American, African American, and Chinese). It also attempted to investigate if volumetric differences in the speakers' vocal tracts, like length differences, would contribute to the acoustic characteristics of these speakers from different races. The findings of this study support the hypothesis that speakers from different races may have morphological differences in their vocal tract dimensions, and these morphological differences (especially volumetric differences) could be partially responsible for the formant frequency differences in a vowel sound void of specific language/dialectal impacts. The study has provided speech scientists, speech-language pathologists, linguists and other health professionals with a new and preliminary acoustic and physiological database for adult male speakers from these three different races.”

3). *Changes in the Human Vocal Tract Due to Aging and the Acoustic Correlates of Speech Production*

Journal of Speech, Language, and Hearing Research, 2003

Authors: S. A. Xue and G. J. Hao

Conclusion: “This investigation used a derivation of acoustic reflection (AR) technology to make cross-sectional measurements of changes due to aging in the oral and pharyngeal lumina of male and female speakers. The purpose of the study was to establish preliminary normative data for such changes and to obtain acoustic measurements of changes due to aging in the formant frequencies of selected spoken vowels and their long-term average spectra (LTAS) analysis. Thirty-eight young men and women and 38 elderly men and women were involved in the study. The oral and pharyngeal lumina of the participants were measured with AR technology, and their formant frequencies were analyzed using the Kay Elemetrics Computerized Speech Lab. The findings have delineated specific and similar patterns of aging changes in human vocal tract configurations in speakers of both genders. Namely, the oral cavity length and volume of elderly speakers increased significantly compare to their young cohorts. The total vocal tract volume of elderly speakers also showed a significant increment, whereas the total vocal tract length of elderly speakers did not differ significantly from their young cohorts. Elderly speakers of both genders also showed similar patterns of acoustic changes of speech production, that is, consistent lowering of formant

frequencies (especially F1) across selected vowel productions. Although new research models are still needed to succinctly account for the speech acoustic changes of the elderly, especially for their specific patterns of human vocal tract dimensional changes, this study has innovatively applied the non-invasive and cost-effective AR technology to monitor age-related human oral and pharyngeal lumina changes that have direct consequences for speech production.”

4). *Solid Modeling of Human Vocal Tract using Magnetic Resonance Imaging and Acoustic Pharyngometer*

Proceedings of the 26th Annual International conference of the IEEE EMBS , 2004

Authors: H. Z. Tameem and B. V. Mehta

Conclusion: “The geometric information such as cross-sectional area and the volume of the vocal tract can be obtained using the [Eccovision] Acoustic Pharyngometer. The accuracy of this device is verified during this research and is found to be satisfactory. The Pharyngometer is extremely cost effective as compared to MRI for vocal tract analysis. Hence using parametric techniques to create models for other subjects will be extremely beneficial. Researchers looking to study the vocal tract dimensions during various human speech conditions can create the particular solid model by getting the cross-sectional areas through the Pharyngometer using Rapid Prototyping. Hence this method provides researchers a variety of models they can choose from.”

5). *Quantification of Vocal Tract Configuration of Older Children with Down syndrome: A Pilot Study*

International Journal of Pediatric Otorhinolaryngology

Authors: S. A. Xue, L. Kaine, M I. Ng

Abstract: AR technology has been extensively used as an objective diagnostic tool for locating structural and functional abnormalities within the oral and pharyngeal cavities, and in a variety of clinical applications, including (1) locating site and severity of vocal tract obstructions for patients with sleep apnea [45,46]; (2) establishing degree of nasal airway abnormalities [47,48]; and (3) determining optimal endotracheal tube positioning [41]; and (4) documenting changes in the vocal tract due to race and aging [33–35,49]. AR can be a valuable alternative to other objective diagnostic techniques, such as MRI, fluoroscopy, or ultrasound, for assessment of the vocal tract, as the procedure is completely non-invasive and does not expose the participants to radiation.

Comparative studies by D'Urzo et al. [50] and Marshall et al. [51] found that AR measurements could be used in lieu of MRI and CT for quantifying some aspects of vocal tract configurations

Despite the documented lumen abnormalities associated with Down syndrome, little is known about the oral and pharyngeal dimensional characteristics of these children. The objective of this study was to measure the vocal tract lumen of children with Down syndrome by using acoustic reflection (AR) technology (Eccovision Acoustic Pharyngometer; SensorMedics Corp., Yorba Linda, CA). Specifically, the purposes of this study were to (1) quantify the vocal tract configurations of children with Down syndrome; (2) compare this data against that of typically developing children to determine if significant differences are observed between these two populations; (3) locate specific structural differences along the vocal tract, thereby indicating a potential relationship to speech and/or swallowing difficulties observed in children with Down syndrome; and (4) establish preliminary data of the vocal tract configuration for this population. The study applied non-invasive and cost-effective AR technology that was quite suitable for similar studies that involved large numbers of participants, particularly older children with different types of disorder.

Pharyngometric measurements were obtained using an Eccovision Acoustic Pharyngometer™. This device consisted of two microphones and one sound generator mounted on a 30-cm-long, 1.89-cm inner diameter wave tube, and a microcomputer equipped with digital-to-analog and analog-to-digital converters for software and data processing. The use of AR technology has been demonstrated as a viable option for delineating the parameters of the human upper airway [39–44]. This procedure uses acoustic energies, which are transmitted through a tube into the airway. A fraction of the acoustic wave is reflected back at each point of discontinuity in the upper airway and is recorded by a microphone attached to the mouthpiece [43]. The other end of the transmitting tube is connected with the CPU that transforms the wave signal with algorithms into dimensional values shown on the monitor (see Fig. 1). The device underwent an automatic self-calibration as set by the manufacturer each time a participant was tested. The cross-sectional area of the vocal tract as a function of the distance from the lips to the glottis was plotted (see Fig. 2) according to the amplitude and arrival times of acoustic returns. The measured area–distance curves through mouth breathing, that correspond to major vocal tract morphological marks were selected for analysis according to the following criteria: (a) the oral pharyngeal juncture

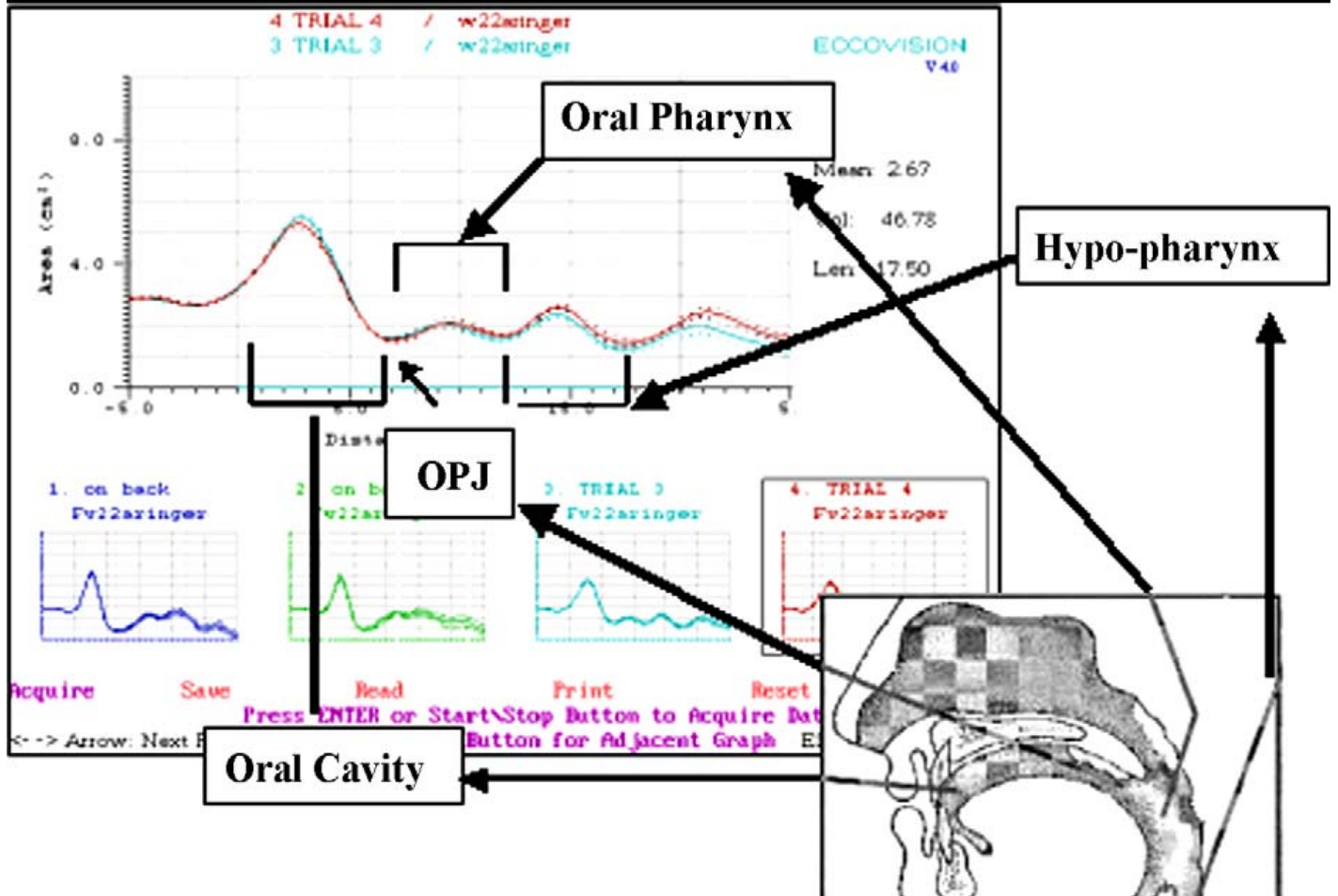
(OPJ that refers to the velum area demarcating oral cavity and pharyngeal cavity) of the mouth-breathing curve best matched the OPJ of the nose-breathing curve, and (b) the curve fluctuated with the smallest magnitude due to airflow changes. The resultant volume–distance relationships were divided into two sections by hand-marking to separate the oral cavity from the pharyngeal cavity as outlined by the manufacturer, using the following standard criteria: an oral region extending from the incisors to the anterior margin of OPJ and a pharyngeal region extending from the oral pharynx to the end of hypo-pharynx (the glottis) (Fig. 3). Six measured volume–distance curves were obtained for each participant: oral volume, pharyngeal volume, vocal tract volume (in cubic centimeters), oral length, pharyngeal length and vocal tract length (in centimeters).

2.3. Testing procedures

In accordance with manufacturer’s guidelines, each participant was tested three times using the following procedure:

1. All subjects were tested while sitting upright in a chair while demonstrating good postural control and head support during normal tidal breathing.
2. A new, sanitized mouthpiece was selected for each participant and sized for optimal fit to prevent air leakage. The wave tube was positioned so that it was positioned parallel to the ground, creating a straight line to the pharyngometer.
3. Subjects were asked to focus on a certain point in space, which was indicated by a picture the researcher attached to the wall. The researcher assisted the participant in sitting up straight and remaining still. The participant was then prompted to think silently of an ‘‘ooh’’ sound to relax the facial muscles, bring the tongue to a neutral position, and close the velum thereby preventing air leakage through the nasal cavity.
4. The clinician elicited three curves during normal mouth breathing. For those children who had difficulty of maintaining mouth breathing, the clinician would use index finger and thumb to approximate their nasal cavities towards the nasal septum to seal nasal breathing. The calculations of these curves were averaged for each participant across the six VT parameters. Note: For one participant, only one valid trial was obtained; consequently, the values for this participant were not based on an average of three trials.

Due to the difficulties of some participating Down syndrome children to follow the examiners’ directions of mouth breathing



during pharyngometric recording, the testing procedures were not exactly consistent across all participants. However, the investigation demonstrated that AR technology could be used for large scale comparative studies of vocal tract configurations when it is not feasible to use MRI and other conventional imaging technologies. The findings of the study motivated the speech pathologists to develop new therapies with the aim of enhancing the compromised mobility of the articulators within smaller oral cavities of Down syndrome children.

Fig. 3. Area–distance curve of vocal tract dimensions from a pharyngometer. Note: Pharyngeal cavity is calculated by combining oral pharynx and hypo-pharynx.