

A Simple Technique for Determining Velopharyngeal Status during Speech Production

Kate Bunton, Ph.D., CCC-SLP,¹ Jeannette D. Hoit, Ph.D., CCC-SLP,¹ and Keegan Gallagher¹

ABSTRACT

Clinical evaluation of velopharyngeal function relies heavily on auditory perceptual judgments that can be supported by instrumental examination of the velopharyngeal valve. Many of the current instrumental techniques are difficult to interpret, expensive, and/or unavailable to clinicians. Proposed in this report is a minimally invasive and inexpensive approach to evaluating velopharyngeal function that has been used successfully in our laboratory for several potentially difficult-to-test clients. The technique is an aeromechanical approach that involves the sensing of nasal ram pressure (N-RamP), a local pressure sensed at the anterior nares, using a two-pronged nasal cannula. By monitoring the N-RamP signal, it is possible to determine the status of the velopharyngeal port (open or closed) during speech production. Four case examples are presented to support its clinical value.

KEYWORDS: Velopharynx, evaluation

Objectives: As a result of this activity, the reader will be able to (1) identify techniques used to assess velopharyngeal function, and (2) discuss the advantages of the N-RamP technique as it applies to clinical populations.

Velopharyngeal closure is critical for production of vowels and oral consonants and thus has a profound impact on speech intelligibility. Several clinical populations, for example, children with a history of a cleft palate or individ-

uals with dysarthria, have impairments in velopharyngeal function that contribute to problems with speech production. Clinical evaluation of velopharyngeal function often relies heavily on the clinician's auditory perceptual

¹Department of Speech, Language, and Hearing Sciences, University of Arizona, Tucson, Arizona.

Address for correspondence and reprint requests: Kate Bunton, Ph.D., 1131 E. 2nd Street, P.O. Box 210071, Tucson, AZ 85721-0071 (e-mail: Bunton@u.arizona.edu).

Bridges between Speech Science and the Clinic: A Tribute to Thomas J. Hixon; Guest Editor, Jeannette D.

Hoit, Ph.D., CCC-SLP.

Semin Speech Lang 2011;32:69-80. Copyright © 2011 by Thieme Medical Publishers, Inc., 333 Seventh Avenue, New York, NY 10001, USA. Tel: +1(212) 584-4662.

DOI: <http://dx.doi.org/10.1055/s-0031-1271976>.
ISSN 0734-0478.

judgment. For example, a clinician might judge a client's speech to be hypernasal or hyponasal and assign a severity rating to it (e.g., mildly hypernasal). However, auditory perceptual judgments are known to be unreliable¹ and are not necessarily well correlated to velopharyngeal status.²⁻⁴ Therefore, auditory perceptual judgments of velopharyngeal function are often supplemented with instrumental evaluation. Instrumental approaches to understanding velopharyngeal function have proven to have both clinical and research value. Unfortunately, some of these are intrusive, difficult to interpret, expensive, and/or unavailable to clinicians. Proposed in this report is a simple, minimally invasive, and inexpensive approach to evaluating velopharyngeal function that has been successfully used for several potentially difficult-to-test clients.

INSTRUMENTAL APPROACHES TO EVALUATING VELOPHARYNGEAL FUNCTION DURING SPEECH PRODUCTION

There are many instrumental approaches to evaluating velopharyngeal function during speech production. The focus here is on those that are commonly used in clinical settings by speech-language pathologists and other clinical professionals and include selected acoustical, visual imaging, and aeromechanical approaches.

An acoustical approach to velopharyngeal evaluation is attractive because the data are generally easy to record, requiring only a microphone and a recording device. Analysis of the speech signal often involves spectrographic analysis with an emphasis on selected acoustic features: for example, formant bandwidth (coupling of the velopharyngeal-nasal pathway to the oral pathway is associated with wider bandwidths) and formant frequencies (coupling of the velopharyngeal-nasal pathway to the oral pathway usually introduces a low-frequency "nasal formant" into the spectrum). Nevertheless, this type of analysis can be difficult to carry out and interpret without substantial experience and expertise.

Another more widely used acoustical technique for evaluating velopharyngeal function is

nasometry. Nasometry requires the use of two microphones, one positioned in front of the lips and one positioned in front of the anterior nares. A cumbersome, horizontally oriented plate is positioned between the microphones to isolate the sound energy from the two sources. Nasometry allows for the calculation of nasalance, which is the quotient of nasal sound pressure level to nasal + oral sound pressure level. Although nasalance values have been found to be strongly associated with perceptual judgments of nasality (at least when specified cutoff scores are used), they have been found to be weakly correlated with estimated velopharyngeal orifice area.⁵ The weak correlation between nasalance values and velopharyngeal orifice size is likely due, at least in part, to the effects of variables such as turbulent nasal air flow and degree of mouth opening on nasalance.^{5,6}

Visual imaging is another common approach to evaluating velopharyngeal function in clinical practice. One type of imaging is videonasendoscopy, which involves passing a flexible endoscope posteriorly through the nasal pathways and viewing the velopharynx from above. Another type is videofluoroscopy, which involves the use of X-ray to view oral, nasal, pharyngeal, and laryngeal structures from both sagittal and coronal perspectives (though not simultaneously). These two imaging techniques permit direct observation of the velum and pharyngeal walls as they move in relation to one another during speaking and swallowing. A major motivation for using a visual imaging approach is to examine contributions of the velum and lateral and posterior pharyngeal walls to velopharyngeal closure, information that is often critical in planning medical management, including surgical and prosthetic interventions. Visual imaging can be expensive and invasive and poses safety risks and is, therefore, applied selectively.

Aeromechanical approaches are also used frequently to evaluate velopharyngeal function during speech production. Perhaps the most powerful aeromechanical method involves obtaining simultaneous measures of nasal airflow, oral air pressure, and nasal air pressure. By entering these measures into an equation developed by Warren and DuBois,⁷ it is possible

to estimate the size of the velopharyngeal port during running speech production. Knowing the size of the velopharyngeal port allows the clinician to determine if medical management is necessary or if behavioral management alone may be appropriate.

Perhaps the simplest aeromechanical technique currently in use involves the sensing of nasal airflow. A small mask is attached to a pneumotachometer and placed over the outer nose. The pneumotachometer is connected to a sensitive differential pressure transducer, and the signal is calibrated so that mass airflow exiting the nose can be measured. Nasal airflow is relatively well correlated to velopharyngeal port size, but only at small sizes⁸; the correlation decreases as velopharyngeal size increases. Nevertheless, nasal airflow provides an excellent means of determining if the velopharynx is open or closed during speech production. For example, if nasal airflow is detected during oral sound production, it can be inferred that the speaker has a velopharyngeal leak.

THE NASAL RAM PRESSURE TECHNIQUE

The motivation for creating a less cumbersome aeromechanical technique came from an interest in documenting velopharyngeal develop-

ment during sound production in infants. By the 1990s, Thomas Hixon and Jeannette Hoit, along with their coworkers, had conducted investigations of velopharyngeal function in healthy children as young as 3 years of age⁹ and in healthy adults as old as 97 years.⁶ For these earlier investigations, they had used the nasal airflow technique (described above) to determine if the velopharynx was open or closed during speech production. However, when they attempted to place a mask over an infant's nose, the infant moved his head and arms, tried to push the mask away, and cried most of the time. Hixon and Hoit explored other means of detecting nasal airflow in infants, including thermal imaging and nasal thermistors, but these presented their own challenges. Finally, they tested a technique involving the use of nasal ram pressure (N-RamP) and found it to be successful with infants.

The N-RamP technique requires the use of a two-pronged nasal cannula, such as that shown in Fig. 1. This is the same type of nasal cannula that is used to deliver oxygen to sick infants. The two probes that insert into the anterior nares are sometimes cut short so that the distal ends do not touch the nasal membranes. To detect pressure change, the other end of the nasal cannula is connected to a sensitive differential pressure transducer (with a ± 2 cm

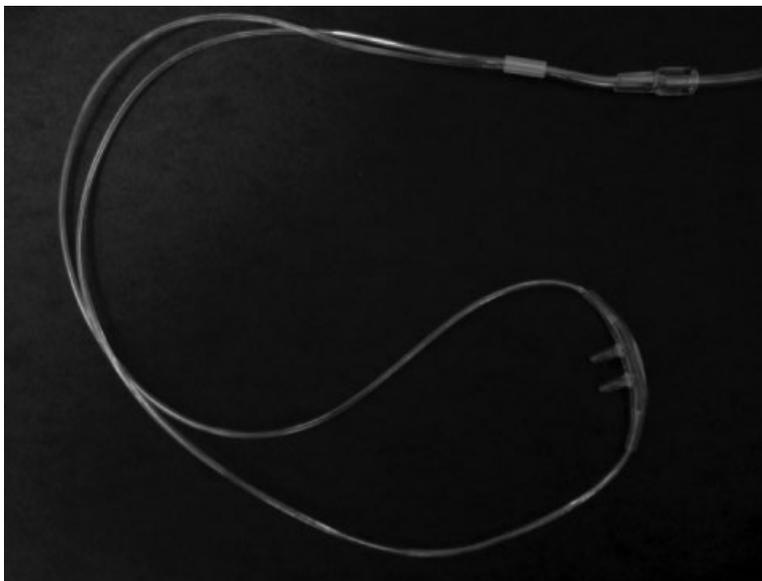


Figure 1 A nasal cannula.

H₂O diaphragm, such as is often used to detect airflow during speech production). As shown in Fig. 2, the probes of the cannula are inserted into the anterior nares and the tubing is taped to the cheeks. In addition, a small microphone is taped to the forehead. The resultant air pressure signal and acoustic signal are each amplified, displayed on an oscilloscope for online monitoring, and recorded on a multichannel digital recorder for later analysis. The infant is also videotaped at close range (with the audio signal from the microphone routed into the video camera). The purpose of the video is to have a record of mouth status and body movements (discussed later), as well as documentation of the communication situation.

In this context, the nasal air pressure signal reflects a ram pressure; that is, the local average pressure in the probe tube. This is akin to the ram pressure that is used to measure aircraft speed. This local pressure is directly related to the local airflow within the tube, but it is not necessarily related to the mass airflow from the nose (because air escapes around the probe tubes). For this reason, Hixon and Hoit decided that it was not useful to attempt to calibrate the pressure signal, as it would not provide meaningful information. What it did provide, however, was critical information that could be used to determine if the velopharynx

was open or closed. Specifically, the signal could be interpreted as follows: (1) negative pressure = inspiration through the nasal airway, (2) positive pressure = expiration through the nasal airway, and (3) pressure at zero (atmospheric) = no airflow (breath holding) or a closed velopharynx during inspiration or expiration. Thus, during vocalization (which almost always occurs during expiration), positive pressure indicates an open velopharynx and pressure at zero indicates a closed velopharynx. It is also important to determine if the mouth is open or closed. If the mouth is closed, nasal pressure is necessarily positive during vocalization (except in the case of instantaneous mouth closure for /p/ and /b/). Thus, the vocalizations that are of greatest interest are those produced with the mouth open.

One of the major advantages of the N-RamP technique over nasal airflow is that most head or body movements do not affect the N-RamP signal. This is because the sensing probes are free to move within the nasal vestibules and are not sealed airtight into the anterior nares. Thus, they are part of an open system and are not sensitive to the types of artifacts that often prevail in closed aeromechanical systems (such as a nasal mask coupled to the face). The only major exception that we have encountered is when a child bounces vertically in his chair or when a baby is bounced on a parent's knee. Despite its relative immunity to movement artifacts, the N-RamP signal is very sensitive to local pressure changes that are associated with velopharyngeal opening and closing.^a

The N-RamP technique was first applied to the study of velopharyngeal function during vocalization in a longitudinal study of six infants (from age 2 to 6 months) conducted by Thom and colleagues.¹⁰ All six infants tolerated the nasal cannula and the vast majority of vocalizations recorded from them were nondistress (i.e., "happy") vocalizations. The results of this study indicated that the frequency of velopharyngeal closure generally increases with age, but that consistent closure for oral sound production is not yet achieved by 6 months. These



Figure 2 An infant seated in a high chair with a microphone taped to her forehead and a nasal cannula in place.

^aThe rainbow passage has been shown to contain a mixture of oral and nasal consonants equivalent to that found in conversational speech, and normative data are available.²¹

findings challenged previously published acoustic and perceptual data that suggested that velopharyngeal closure occurs by ~4 months of age.^{11,12}

CASE EXAMPLES

We have had the opportunity to use the N-RamP technique to evaluate velopharyngeal function in a variety of individuals. Here, we offer descriptions of four case examples that illustrate the ease and value of the N-RamP technique: a healthy infant, a school-aged child with a speech sound disorder, a teenager with an orofacial syndrome, and an adult with amyotrophic lateral sclerosis.

Healthy Infant

Z was a healthy male infant who was seen in our laboratory once a month beginning at age 6.5 months and continuing until age 19 months. Z was a typically developing infant, as determined by data collected at each visit using the Brigance Diagnostic Inventory of Early Development (gross and fine motor subtests),¹³ the MacArthur Communicative Development Inventory,¹⁴ and the Vocal Development Checklist.¹⁵ During his first visit, Z was producing

primarily vowel-like productions. He proceeded through the expected phases of babble, proto-words, and real words. At 20 months of age he had an expressive vocabulary of roughly 100 words, was producing two- to three-word utterances spontaneously, and could imitate utterances cued by the investigator. His utterances were analyzed by breath group (between inspirations) and were classified as being open throughout the breath group, closed throughout the breath group, or closed during part of the breath group.

Fig. 3 shows the percentage of nondistress mouth-open utterances that Z produced at each monthly visit wherein his velopharynx was either closed throughout (N-RamP = 0) or closed during part of the breath group (N-RamP = 0 for part and N-RamP = positive for part). His nondistress utterances included raspberries, syllable utterances (e.g., vowel productions of long or short duration, consonant-vowel combinations produced in isolation or in multiples, and reduplicated and variegated babbling), protowords, and words.

Results show that Z obtained velopharyngeal closure for nearly all vowel-like and babble utterances containing oral consonants at 8 months of age (91% were closed throughout or closed during part). This percentage

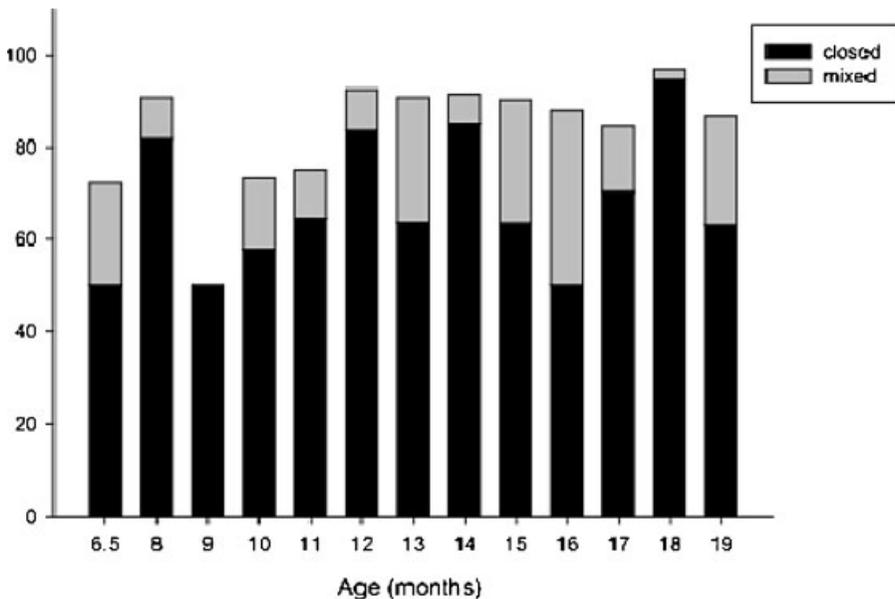


Figure 3 Longitudinal data for Z shown as percentage of breath groups containing nondistress utterances produced with the velopharynx either closed throughout (closed) or closed during part (mixed).

decreased at 9, 10, and 11 months of age (range 50 to 75%) but was consistently over 85% for all subsequent months. During the period from 9 to 11 months, Z's consonant inventory increased from two to eight consonants being produced at least twice during a recording session. It is unclear if this increase relates to the lower percentage of utterances being produced with the velopharynx closed. It is clear, however, that the N-RamP technique can be successfully applied to the study of velopharyngeal development in very young children.

School-Aged Child with Speech Sound Disorder

B, a 6-year-old boy, was referred for an evaluation of his velopharyngeal function. According to his school speech-language pathologist, B was "struggling to produce certain high-pressure consonants," which generated a concern that he might have a velopharyngeal leak. He was diagnosed with a moderate-severe speech sound disorder, mild motor programming deficit, and severe tongue thrust. Upon oral examination, a slightly asymmetric elevation of the uvula was noted. An audiometric screening indicated that his hearing sensitivity was within normal limits (20 dB HL¹⁶), and a language screening indicated that his receptive and expressive language were within normal limits (Clinical Evaluation of Language Fundamentals 4th ed. [CELF-4] screening¹⁷).

Velopharyngeal function during speech production was evaluated using the N-RamP technique. The speech tasks included imitation of nonsense words imbedded in a carrier phrase (e.g., "Say /isi/ again"), imitation of high-pressure consonant-loaded sentences (e.g., "The puppy was playing with a rope"), picture naming using the Iowa Pressure Articulation Test (IPAT¹⁸), and conversational speech.

The protocol was designed to determine the percentage of high-pressure consonants produced with a closed velopharynx. However, due to his tongue thrust and speech sound disorder, many of the targeted high-pressure consonants were substituted with a /θ/ or another off-target consonant. Because of this, it was not possible to calculate quantitative data as originally intended. Nevertheless, it was

possible to make certain qualitative observations. For example, we found that when B attempted to produce a high-pressure consonant in the context of an upcoming nasal consonant, he often generated a large nasal pressure pulse during the pressure consonant. This is illustrated in Fig. 4 during the production of /k/ (which he substituted for /g/) in "again." The large positive pressure spike associated with the /k/ indicated that his velopharynx was open momentarily. Fig. 5 also shows a large positive pressure spike during the production of a fricative consonant that preceded a nasal consonant when producing the name "Sean." Apparently, B opened the velopharynx inappropriately early in anticipation of the upcoming nasal consonant. It is important to note that this pattern was not consistent; there were many instances in which B produced similar utterances with appropriate velopharyngeal closure.

We concluded that B did exhibit a velopharyngeal leak during what should have been oral sound productions, but that the velopharyngeal leak was inconsistent and not attributable to a structural or peripheral neural impairment. The inappropriate velopharyngeal opening was concerning, although it appeared to be inconsistent and had less impact on his speech output than the pervasive tongue thrust. A report of the findings was sent to his school speech-language pathologist so that treatment could be tailored to include strategies such as biofeedback to address the unusual velopharyngeal pattern.

Young Adult with Goldenhar Syndrome

S, a 21-year-old male with hemifacial microsomia (Goldenhar syndrome), referred himself to the University of Arizona Clinic for Adult Communication Disorders for an evaluation 12 months after he had undergone a Le Fort I osteotomy. This is a surgical procedure wherein the maxillary bone and hard palate are separated from the skull and repositioned; the procedure is designed to move the maxillary bone forward for better alignment with the mandible. S stated his primary complaint as follows: "I have had VPI since the surgery. It was worse right after the surgery but it

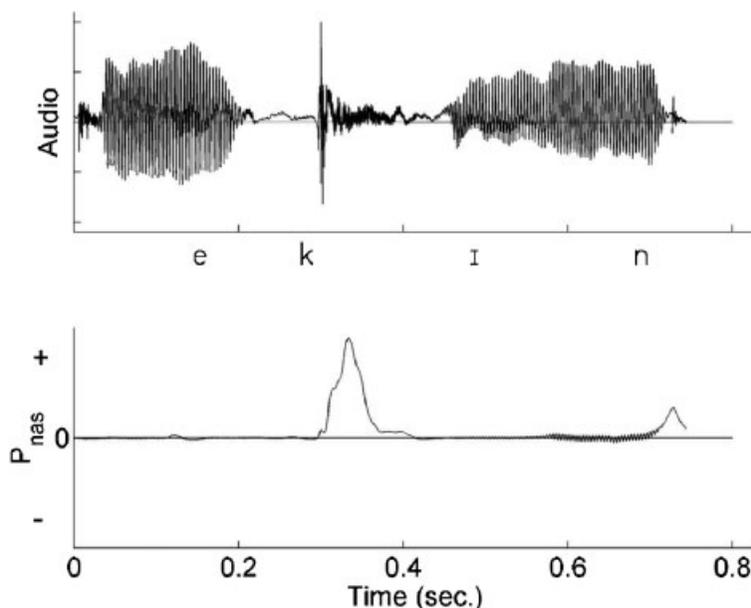


Figure 4 Glottal waveform and nasal pressure (P_{nas}) signal for the target utterance “again” produced by S. Note that the transcription in the figure is based on S’s actual production and that it does not match the target “again.” A positive P_{nas} peak can be seen near the release for the stop consonant /k/.

improved after about 2 to 3 months. People would ask me to repeat what I said. It has continued to get better but I still don’t sound like I did before the surgery.” His parents gave a similar account.

A full clinical evaluation was completed that included an oral mechanism examination, intelligibility testing, nasometry (Nasometer; Kay Elemetrics, Lincoln Park, NJ), an aeromechanical assessment (PERCI-SARS;

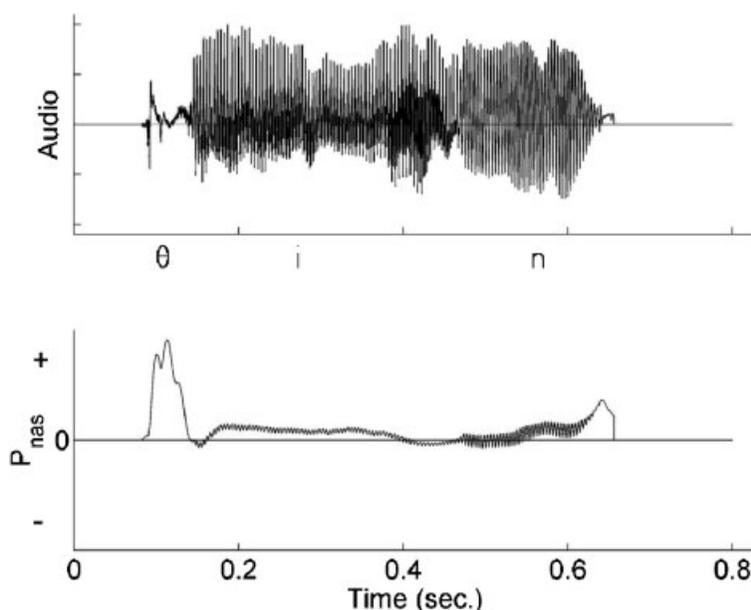


Figure 5 Glottal waveform and nasal pressure (P_{nas}) signal for the target utterance “Sean” produced by S. Note that the transcription in the figure is based on the S’ actual production and that it does not match the target utterance. A positive P_{nas} peak can be seen during production of the fricative.

Chapel Hill, NC), as well as data collection to assess velopharyngeal status using the N-RamP technique described in this article. The speech protocol consisted of three productions each of plosive consonants (p, b, t, d, k, g) and fricative consonants (s, z, ʃ, ʒ) in syllable initial, final, and medial positions combined with the vowels /i/ and /ɑ/. In addition, sentence reading (GOS.SP.ASS sentences¹⁹), passage reading (Rainbow Passage²⁰), and conversational speech samples were recorded.

Table 1 shows the percentage of breath groups produced with the velopharynx closed throughout and closed during part. Note that the reading passage^b and conversational speech samples contained a mixture of oral and nasal consonants; therefore, the number of breath groups that were closed during part were expected to be higher than if only breath groups containing oral consonants were analyzed. This analysis approach was selected because it was judged to be more directly comparable to the analysis approach typically used for nasometry data (for which mean nasalance values are calculated across speech samples containing both oral and nasal sounds). The N-RamP data indicated that S achieved velopharyngeal

Table 1 Speech Tasks Produced by S and Percentage of Utterances Identified as Being Produced with the Velopharynx Closed Throughout and Closed during Part of the Breath Group

Speech Task	Closed Throughout (%)	Closed During Part (%)
/b/	84	0
/p/	82	0
/d/	88	0
/t/	90	0
/g/	67	0
/k/	72	0
/s/	25	32
/z/	31	15
/ʃ/	37	24
Reading (Rainbow Passage)	76	14
Conversational speech (across all consonants)	72	17

closure on the majority (67 to 90%) of syllable utterances (consonant-vowel [CV], vowel-consonant-vowel [VCV], and vowel-consonant [VC]) in which the consonant was a stop. By contrast, he achieved closure on only a minority of the syllable utterances (25 to 37% were closed throughout, and 15 to 34% were closed during part) in which the consonant was a fricative.

To compare data from different instrumental techniques used during the same session for S, a correlation was computed to determine level of agreement for the N-RamP data (closed throughout only) and the nasometer data. Three correlations were computed. These included the pooled syllable data (CV, VCV, VC) data ($r = -.78$), passage reading ($r = -.84$), and conversational speech sample ($r = -.89$). In all cases, the correlation was negative because a high mean nasalance score (reflecting the fact that there is considerable acoustic energy emanating from the nose) corresponded to a small percentage of utterances produced with the velopharynx closed, and a low mean nasalance corresponded to a high percentage of utterances produced with the velopharynx closed. Although we do not expect a perfect correlation because nasometry has been shown to be susceptible to variations in oral acoustic impedance,²¹ our correlations suggest that there is a reasonable level of agreement between the two techniques. Direct comparison of the data from the PERCI-SARS was not completed because S had a severely deviated nasal septum and results differed when the placement of the nasal flow and nasal pressure transducers were switched. In general, larger velopharyngeal port openings were found for utterances containing fricative consonants compared with those with stop consonants. This is consistent with both the nasometry and N-RamP findings. We concluded that S might benefit from a period of trial behavioral therapy, with an emphasis on achieving velopharyngeal closure in fricative consonant contexts. We recommended that the N-RamP signal be used for visual biofeedback so that S could monitor his velopharyngeal closure on line.

^bThe Rainbow passage has been shown to contain a mixture of oral and nasal consonants equivalent to that found in conversational speech and normative data are available.²¹

Adult with Amyotrophic Lateral Sclerosis

C, a 57-year-old male diagnosed with amyotrophic lateral sclerosis (ALS), came to the clinic for a speech evaluation to determine if he would be a candidate for augmentative and alternative communication. His speech was slow, effortful, and of abnormally low loudness. Velopharyngeal function was assessed using the N-RamP technique while he produced the nonword and sentence repetition tasks described in the previous two cases.

Results indicated that he closed his velopharynx during only 26% of his high-pressure consonant productions (11.1% were closed throughout the production; 14.8% were closed during part of the production). Table 2 contains the results for each of the target sounds tested.

Although our focus was on the status of the velopharynx during high-pressure consonant productions, the N-RamP waveforms provided us with other valuable information about velopharyngeal behavior. For example, we noted several instances wherein N-RamP was positive (indicating an open velopharynx) during productions of vowels that surrounded the high-pressure consonants, one of which is illustrated in Fig. 6. This figure contains two consecutive productions of “Say /isi/ again” in which the velopharynx was closed during the /s/ segment in both; however, the second production (on the right) shows that the velopharynx was open during the /i/ that preceded the /s/ and the /i/ that followed the /s/. This velopharyngeal opening was not perceptible to the ear.

Although C produced the majority of the high-pressure consonants with his velopharynx open, we noticed that several of these productions sounded as if they had been produced with the velopharynx closed. To investigate this further, we conducted an informal perceptual study with two speech-language pathology graduate students and two certified speech-language pathologists serving as listeners.

The listeners were presented with the speech samples (auditory only) and were asked to indicate “whether the velopharynx is open or closed” during the target sound productions.

Table 2 Target Sounds Produced by C and Percentage of Utterances Identified as Being Produced with the Velopharynx Closed Throughout and Closed during Part of the Breath Group

Target Sound	Closed Throughout (%)	Closed during Part (%)
/p/	40	10
/b/	0	0
/t/	20	0
/d/	0	0
/k/	16	33
/g/	0	0
/v/	0	0
/f/	33	50
/s/	50	16
/z/	0	20
/θ/	0	50
/ð/	0	0
/j/	0	40
/æ/	0	0
/tʃ/	0	25
/j/	0	0

A signal-to-noise ratio (SNR) of the N-RamP signal was determined by measuring the peak pressure (in arbitrary digital units) of three consecutive inspirations produced by an adult and computing their mean value. Then, using the same data acquisition settings, a sample was recorded while the pressure tube was held in free space. The mean of this recorded pressure (again in arbitrary digital units) served as the noise floor signal. The SNR was calculated as the mean peak pressure divided by the mean noise pressure and then converted to a decibel scale. The SNR for the system was found to be 71.4 dB.

The two graduate students identified the velopharynx as closed when it was open on 54% and 55.8% of the productions. The two speech-language pathologists identified the velopharynx as closed when it was open on 16% and 28.4% of the productions. These findings suggest that the ear is not always a good judge of velopharyngeal status and that velopharyngeal function may be impaired before it is detected in clients with ALS.

CONCLUSIONS

The N-RamP technique has been used successfully in our laboratory to evaluate clients with a variety of etiologies, as well as to track velopharyngeal development in healthy infants and young children. We see N-RamP

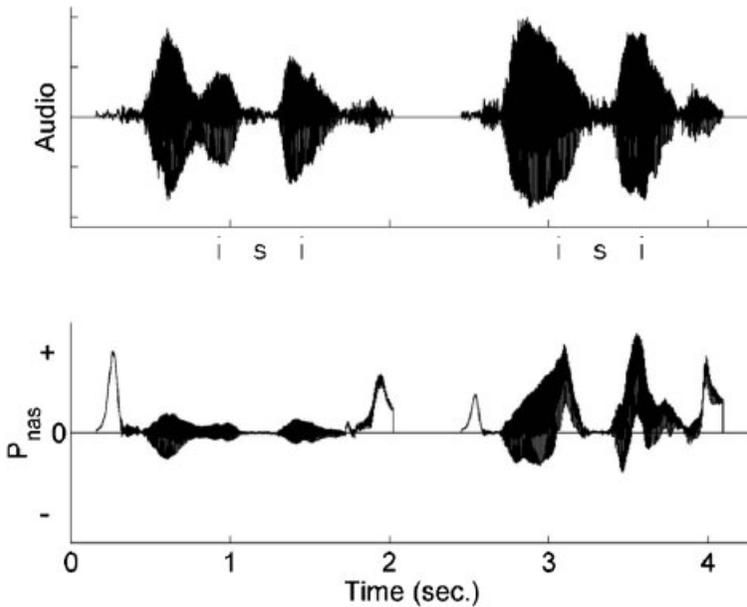


Figure 6 Glottal waveform and nasal pressure (P_{nas}) signal for two repetitions of the target utterance "Say /isi/ again" produced by C. The first production (left) of the utterance indicates a closed velopharynx during the "/isi/" ($P_{nas} = 0$). During the second production of "/isi/" (right), P_{nas} is positive during the vowels that precede and follow the consonant, indicating an open velopharynx.

as a powerful clinical tool for several reasons: (1) it is minimally invasive and comfortable and does not interfere with speech production; (2) it is inexpensive and accessible and does not require much training or experience to use; (3) its data collection and interpretation/measurement procedures are relatively quick; (4) it can be used with clients of any age with neural, structural, or functional disorders; (5) it reveals information about velopharyngeal function that is not easily detected in the acoustic signal; and (6) it has potential as a biofeedback tool for behavioral management of velopharyngeal dysfunction.

ACKNOWLEDGMENT

This work was supported by NIH/NIDCD R01 DC010140.

REFERENCES

- Bradford LJ, Brooks AR, Shelton RL. Clinical judgments of hypernasality in cleft palate children. *Cleft Palate J* 1964;1:329-335
- Mayo R, Dalston RM, Warren DW. Perceptual assessment of resonance distortion in unoperated clefts of the secondary palate. *Cleft Palate Craniofac J* 1993;30(4):397-400
- Warren DW, Dalston RM, Mayo R. Hypernasality and velopharyngeal impairment. *Cleft Palate Craniofac J* 1994;31(4):257-262
- Watterson T, Emanuel F. Observed effects of velopharyngeal orifice size on vowel identification and vowel nasality. *Cleft Palate J* 1981;18(4):271-278
- Dalston RM, Warren DW, Dalston ET. Use of nasometry as a diagnostic tool for identifying patients with velopharyngeal impairment. *Cleft Palate Craniofac J* 1991;28(2):184-188; discussion 188-189
- Hoit JD, Watson PJ, Hixon KE, McMahon P, Johnson CL. Age and velopharyngeal function during speech production. *J Speech Hear Res* 1994;37(2):295-302
- Warren DW, Dubois AB. A pressure-flow technique for measuring velopharyngeal orifice area during continuous speech. *Cleft Palate J* 1964;16:52-71
- Warren DW. Nasal emission of air and velopharyngeal function. *Cleft Palate J* 1967;4(2):148-155
- Thompson AE, Hixon TJ. Nasal air flow during normal speech production. *Cleft Palate J* 1979; 16(4):412-420

10. Thom S, Hoit J, Hixon T, Smith A. Velopharyngeal development in infants. *Cleft Palate Craniofac J* 2006;43:539–546
11. Buhr RD. The emergence of vowels in an infant. *J Speech Hear Res* 1980;23(1):73–94
12. Kent RD, Murray AD. Acoustic features of infant vocalic utterances at 3, 6, and 9 months. *J Acoust Soc Am* 1982;72(2):353–365
13. Brigance A. *Brigance Diagnostic Inventories: Inventory of Early Development II*. North Billerica, MA: Curriculum Associates; 2004
14. Fenson L, Dale P, Reznick J et al. *MacArthur Communicative Development Inventories: User's Guide and Technical Manual*. San Diego, CA: Singular; 1993
15. Velleman S. *Childhood Apraxia of Speech Resource Guide*. Clifton Park, NY: Thomson Delmar Learning; 2003
16. American-Speech-language-Hearing Association Panel of Audiologic Assessment. *Guidelines for Audiologic Screening*. Rockville, MD 1997
17. Semel E, Wiig EH, Secord WA. *Clinical Evaluation of Language Fundamentals*. 4th ed. Screening Test. San Antonio, TX: Harcourt Assessment; 2004
18. Templin MC, Darley FL. *Iowa Pressure Articulation Test*. 2nd ed. (IPAT). Iowa City, IA: University of Iowa; 1969
19. Seaver EJ, Dalston RM, Leeper HA, Adams LE. A study of nasometric values for normal nasal resonance. *J Speech Hear Res* 1991;34(4):715–721
20. Fairbanks G. *Voice and Articulation Drillbook*, 2nd ed. New York, NY: Harper and Row; 1960
21. Seaver EJ, Dalston RM, Leeper HA, Adams LE. A study of nasometric values for normal nasal resonance. *J Speech Hear Res* 1991;34(4):715–721
22. Karnell MP, Schultz K, Canady J. Investigations of a pressure-sensitive theory of marginal velopharyngeal inadequacy. *Cleft Palate Craniofac J* 2001;38(4):346–357