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ABSTRACT

SUMMARY: Up to 30% of children with cleft palate will develop a severe speech disorder known as velopharyngeal insufficiency. Management of velopharyngeal insufficiency typically involves structural and functional assessment of the velum and pharynx by endoscopy and/or videofluoroscopy. These methods cannot provide direct evaluation of underlying velopharyngeal musculature. MR imaging offers an ideal imaging method, providing noninvasive, high-contrast, high-resolution imaging of soft-tissue anatomy. Furthermore, focused-speech MR imaging techniques can evaluate the function of the velum and pharynx during sustained speech production, providing critical physiologic information that supplements anatomic findings. The use of MR imaging for velopharyngeal evaluation is relatively novel, with limited literature describing its use in clinical radiology. Here we provide a practical approach to perform and interpret velopharyngeal MR imaging examinations. This article discusses the velopharyngeal MR imaging protocol, methods for interpreting velopharyngeal anatomy, and examples illustrating its clinical applications. This knowledge will provide radiologists with a new, noninvasive tool to offer to referring specialists.

ABBREVIATIONS: LVP = levator veli palatini; VPI = velopharyngeal insufficiency

The most common craniofacial anomaly is cleft palate and/or lip, occurring in 0.33 of every 1000 live births worldwide.[1] Although the timing of primary palatoplasty to repair the cleft of the palate varies across the globe, in the United States and Europe a one-stage repair is typically performed before 12 months of age.[2] One of the primary goals of cleft palate repair is to establish anatomy that will result in normal speech function. However, up to 30% of children[3,4] will continue to present with hypernasal speech and/or nasal air emission due to velopharyngeal insufficiency (VPI), which is a form of velopharyngeal dysfunction. In VPI, the velopharyngeal valve does not close completely and/or consistently during the production of oralized sounds.[5] The presence of hypernasal speech can limit a child's ability to effectively communicate with others and has been shown to negatively impact peer relationships and academic performance.[6] Management of VPI involves surgical intervention either seeking to restore the normal anatomy and physiology of the velopharyngeal mechanism or to narrow the velopharyngeal portal through use of a pharyngeal flap or sphincter pharyngoplasty, for example.[6] Surgical planning for patients with VPI includes a perceptual speech evaluation performed by a speech-language pathologist and direct and/or indirect instrumentation. Selection of the appropriate surgical procedure requires reliable imaging to depict each patient's specific velopharyngeal anatomy and physiology.

Nasopharyngoscopy and videofluoroscopy are common direct imaging tools used to examine VPI.[7,8] MR imaging is a relatively newer clinical imaging diagnostic tool in cleft care that is being introduced into cleft craniofacial care units, particularly in the United States.[9-11] The interest in velopharyngeal MR imaging is primarily due to the advantage of MR imaging in visualizing the velopharyngeal musculature, which is not possible using nasopharyngoscopy and videofluoroscopy.[9-11] Similar to videofluoroscopy, MR imaging can be used to accurately quantify key velopharyngeal structures with the added benefits of section specificity (eg, the ability to select a precise midsagittal section without head rotation) and lack of ionizing radiation, which is present, though minimal, in videofluoroscopy. The use of MR imaging in the clinical assessment process may be particularly important when muscle reconstruction is

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being considered to treat VPI[12] or following a failed VPI surgery.[13] In such cases, details related to the position of the primary velar muscle (levator veli palatini [LVP] muscle) relative to the posterior hard palate and/or cohesiveness of the LVP muscle can be provided using MR imaging and add value to the clinical process.[12] A recent survey sampling 80 cleft palate craniofacial centers across the United States demonstrated that 93.5% of respondents think that MR imaging brings value to clinical assessment; however, only 11% reported using velopharyngeal MR imaging in their clinical workflows.[11] A key challenge to the widespread clinical use of velopharyngeal MR imaging is the limited technical and interpretive training of key personnel.[14]

Previously published guidance in the use of MR imaging for VPI has not addressed a clinical radiology audience, instead focusing heavily on the feasibility and clinical interpretations of velopharyngeal MR imaging findings for the surgical team.[8,15-18] This article provides radiologists with a focused practical review of the MR imaging technique and interpretation for evaluating the velopharynx in patients with VPI. We will outline the velopharyngeal MR imaging protocol, explain the methods for anatomic interpretation, and provide examples of clinical applications from velopharyngeal MR imaging interpretations. Such increased training and support for radiologists in velopharyngeal MR imaging has the potential to optimize surgical planning and improve clinical care for patients with VPI.

Velopharyngeal MR Imaging Protocol

Ninety-three percent of patients with surgical planning for VPI are between 4 and 8 years of age.[19] As a result, most patients scheduled for velopharyngeal MR imaging will typically be between these ages; however, velopharyngeal MR imaging has been demonstrated in VPI surgical planning for patients ranging in age from 3 to 39 years ($n = 113$ patients) at a single cleft craniofacial center in the United States.[10] Patients are required to be imaged both at rest and while producing and sustaining specific sounds. While typical MR imaging in young children is often performed with sedation or general anesthesia with use of a laryngeal mask airway to support the airway for breathing, successful velopharyngeal MR imaging requires that the patient be fully awake using a nonsedated protocol with no contrast or laryngeal mask airway. Because patients are fully awake for the entire MR imaging protocol and are imaged without contrast, patient and family preparation before MR imaging is critical to its overall success. The involvement of support staff such as a speech-language pathologist in such preparation is invaluable, as acknowledged in current protocols for speech videofluoroscopy and other fully awake, nonsedated, noncontrast MR imaging protocols.[20,21] Patients should receive anticipatory guidance about scanner noise, expectations (what to wear/bring, length of study, who will be with them in the scanner, and so forth), hearing protection, and use of a head coil. Multiple supplementary resources such as checklists, links to websites to be used with families and patients to prepare for the MR imaging, and protocol sheets have been published[12,22] and shown to facilitate patient preparation and improve results in >95% of cases.[22] Additionally hospital resources are published online and provide support for radiology staff in understanding the velopharyngeal anatomy and making measurements of key velopharyngeal variables (details available at https://cahs.ecu.edu/speechimaging/mri-resources-for-hospitals/).

Example MR imaging protocol and sequence parameters are outlined in the Online Supplemental Data. Unlike brain imaging, which localizes to the nasion, velopharyngeal MR imaging should be localized to the nose tip to place the ROI at the level of the speech mechanism. The imaging protocol starts in a neutral head position. For resting sequences, patients should keep their lips together and breathe through their nose; initially, a high-resolution anatomic imaging, 3D T2-weighted sequence, is performed of the whole head. Subsequent imaging consists of rapid thicker-section sagittal and oblique coronal images, with focused FOVs including the muscular structures associated with the velopharyngeal speech mechanism. Baseline resting sagittal TSE T2-weighted images consist of 4–8 slices, scanned from 1 lateral pharyngeal wall to the contralateral side. This procedure is followed by a TSE T2 oblique coronal image, obtained at rest, acquired at a 50°–60° angle to the plane of the cribriform plate and aligned with the spheno-occipital junction (Fig 1). The oblique coronal plane is selected to visualize the entire muscle body of the LVP, the key muscle involved in velar elevation during speech production. Setting the correct plane requires training, practice, and careful image review; online training and resources are also available.[23] The oblique coronal sequence should consist of 4–8 slices, scanning from the posterior aspect of the hard palate to the tip of the uvula.[15,24] Maximal viewing of the LVP in the oblique coronal plane is crucial. If the LVP cannot be visualized completely within this plane, the scan angle should be adjusted, and the sequence repeated before proceeding to scanning during phonation. Most frequently, the imaging plane needs to be rotated further clockwise into a more horizontal position.

After collection of sagittal and oblique coronal images at rest, additional sequences mirroring these image parameters are obtained while the child sustains phonation of selected speech sounds. The angle of the oblique coronal image plane at rest should be copied over onto the subsequent speech sequences. The speech-language pathologist should predetermine the speech sounds required for the MR imaging study and indicate these to the radiology team. The speech pathologist should select sounds that the child is able to successfully produce and sustain for the duration of the 6- to 9-second MR imaging sequence. Ideally, the patient should practice these sounds with the speech language pathologist before the MR imaging procedure, to be familiar with the tasks that will be performed during the velopharyngeal MR imaging study.

While dynamic MR imaging using speech samples has been described,[25-28] these methods are not fully translated to all clinical MR imaging scanners. Clinical sites that have begun to use velopharyngeal MR imaging have, therefore, adopted the use of sustained phonation tasks, typically by using sustained phonation of /i/ ("eee" sound, as in "seek") and /s/ ("sss" sound, as in "hiss"). These sounds are commonly used for several reasons. First, most children at the typical age for VPI surgical evaluation (4–8 years of age)[19] are able to produce a sustained /i/ sound without error because this is a basic vowel sound that is acquired early in phonological development. This sound also represents a high back

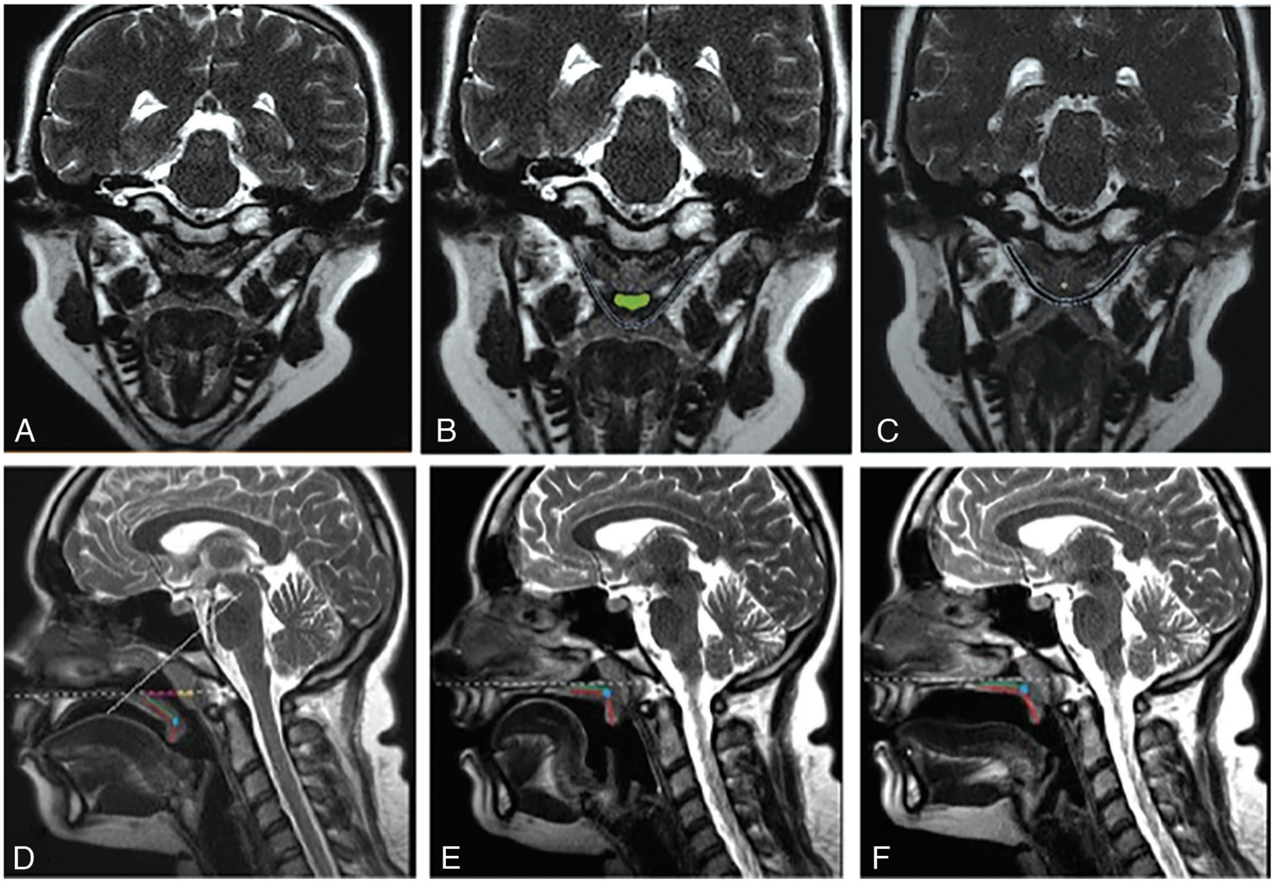

FIGURE. *A*, Coronal oblique T2 image along the plane of the LVP (*blue outline*, *B* and *C*) at the level of the velopharyngeal port during rest. The normal appearance of the LVP is T2-hypointense and intact along its length. *B*, Coronal oblique T2 with the velopharyngeal port appropriately open (*green outline*). *C*, Coronal oblique T2 during phonation with the velopharyngeal port appropriately closed. *D*, Sagittal midline T2 image through the head at rest showing the 50–60° coronal oblique plane (*solid white line*), effective length (*green line*), the total velar length (*red line*), and the palatal plane (*dotted line*). *E* and *F*, Sagittal midline T2 image during both i and s phonation, respectively. Note the appropriate elevation of the velum with closure of the velopharyngeal port as well as the tongue position.

vowel and has been shown to be a sound produced in individuals with normal velopharyngeal anatomy and physiology with the greatest degree of velar closure force.[29] The use of /s/ is often to assess the patient's ability to produce a consonant that can be easily sustained. The /s/ sound should be produced by the patient with an oral airflow. In many children with VPI, production of this sound may be in error with the sound being produced through the velopharynx, nasopharynx, and/or nasal passage.[5] This is referred to as a compensatory misarticulation. If the patient uses this type of error, the speech language pathologist should advise against the use of this sound. Other consonants that the child can produce with accuracy may be used, such as /f, v, z/, which can be typically sustained for the duration of the sequence.

It is critically important to run the sequence exactly when the cue is given to the child to start sound production to ensure that the child is phonating during the entire sequence. Additionally, progressing from 1 sequence to the next as fast as possible prevents movement and improves the likelihood of obtaining the velopharyngeal muscles in each of the oblique coronal sequences. Because it can be challenging during image review to distinguish between voluntary failure to phonate and paralysis of the palate muscles, the MR imaging technician should also listen carefully to confirm phonation during the entire image sequence. Only images collected with sustained phonation throughout the entire sequence should be accepted and saved for radiologist interpretation.

If a patient is unable to sustain phonation for 8 full seconds, sagittal sequences can be reduced to cover only the midsagittal region, and oblique coronal images can be reduced to the region representing the long axis of the LVP muscle into the velum. While these changes may limit the scope of information collected, these scans can still often provide sufficient information to inform surgical decision-making while reducing the time of the scanning substantially.

Interpreting Velopharyngeal Anatomy

LVP. Normal resonance during speech involves the coordination of several velopharyngeal muscles. The LVP is primarily responsible for elevation and posterior movement of the velum (Online Supplemental Data).[30,31] Qualitative evaluation of LVP muscle integrity (eg, relative size, position, and cohesiveness) can be determined via oblique coronal T2-weighted sequences during rest and phonation scans (Fig 1*A–C*). Comparisons between rest (Fig 1*A*)

Table 1: The definitions for pertinent measurements for quantitatively examining VPI[a,44]

Variable	Description
Pharyngeal depth	Linear distance (mm) from PNS to PPW or adenoid pad as seen on the midsagittal image
Velar length	Curvilinear distance (mm) from the posterior nasal spine to the tip of the uvula as seen on the midsagittal image
VP ratio	Calculation obtained from the dividing velar length by pharyngeal depth
Effective velar length	Linear distance (mm) from the posterior border of the hard palate to the point of levator muscle insertion into the velum as seen on the midsagittal image
EVP ratio	Calculation obtained from dividing effective velar length by the pharyngeal depth
Adenoid depth	Linear distance (mm) along the palatal plane from the adenoid pad to the posterior end of the adenoid

Note:—PNS indicates posterior nasal spine; PPW, posterior pharyngeal wall; VP, velopharyngeal; EVP, effective VP.
[a] Adapted with permission from Perry JL, Kotlarek KJ, Sutton BP, et al. Variations in velopharyngeal structure in adults with repaired cleft palate. Cleft Palate Craniofac J 2018;55:1409-18.

Table 2: The mean (SD) of pertinent variables for quantitively examining VPI and results of analysis of variance[a,b,31]

Variable	Infants (4–23 mo.)	Children (4–9 yr)	Adolescents (10–19 yr)	Adults (20+ yr)
Pharyngeal depth	11.43 (4.46)	17.80 (4.79)	21.45 (4.62)	20.92 (4.14)
Velar length	20.27 (3.32)	27.63 (4.17)	30.98 (5.10)	34.85 (4.79)
VP ratio	2.08 (0.94)	1.70 (0.69)	1.51 (0.42)	1.73 (0.42)
Effective velar length	8.58 (1.46)	12.07 (2.43)	13.12 (3.32)	13.72 (3.46)
EVP ratio	0.89 (0.43)	0.74 (0.30)	0.63 (0.19)	0.67 (0.19)
Adenoid depth	11.36 (4.38)	9.66 (5.49)	9.96 (5.49)	5.18 (3.88)

Note:— EVP indicates effective velopharyngeal; VP, velopharyngeal.
[a] Measurements are listed in millimeters with the exception of VP ratio measures.
[b] Adapted from Haenssler et al.[31] Table 3 which is copyrighted material and included here with the permission of the American Speech-Language-Hearing Association (ASHA).

and phonation (Fig 1*B*–*C*) oblique coronal images can also provide insight into the function of the LVP muscle (ie, amount of muscle shortening/contraction).

Pharyngeal Adenoidal Tissue. The pharyngeal adenoidal tissue ("fat pad") contributes to creating a functional seal for appropriate sound production, particularly in patients with typical velar-to-adenoid contact. This tissue can vary in size; a small fat pad has a concave outer border, whereas a medium-sized fat pad has a relatively straight oblique line, and a large fat pad has a convex border extending into the nasopharynx (Online Supplemental Data).[14] Adenoid tissue depth can be measured by drawing a line from the oropharynx side of the velum posteriorly and superiorly to the point where the palatal plane intersects the adenoids. In many cases, the adenoids are not measured because they rest above the level of the palatal plane and thereby play no role in velopharyngeal closure.

The Palate. The palatal plane is approximated by the anterior and posterior nasal spines, important anatomic landmarks of the hard palate. The velum is measured in the midsagittal plane at rest by adding the distance from the posterior nasal spine or posterior palate to the LVP and the distance from the LVP to the posterior tip of the velum (Fig 1*D*).[31] The intersection of the palatal plane with the posterior wall of the pharynx defines the typical point of closure for children and separates the nasopharynx from the oropharynx. Pharyngeal port depth is measured in the midsagittal plane at rest from the posterior region of the hard palate to the posterior pharyngeal wall along the palatal plane reference line.[31] Although it is rarely a point of velar contact,[32] some patients may attempt velopharyngeal contact along a Passavant ridge. This is a muscular projection that extends as a muscle band anteriorly off the posterior pharyngeal wall during speech. If this is present and appears to be the point of attempted contact, the pharyngeal port depth should be drawn to the anterior region of this ridge. The portion of the velum that provides the closure of the velopharyngeal port is called the effective velar length. Effective velar length is measured from the posterior hard palate along the velum to the middle of the horizontal portion of the LVP, which lies within the body of the velum (Fig 1*D*).[31] The length of the velum at rest should be in excess of the pharyngeal port depth to achieve closure of the velum against the posterior pharyngeal wall.[31,33] Relevant definitions, as well as normal anatomic measurements/ratios of the velum, velopharyngeal port, and LVP, are summarized in Tables 1 and 2.

Preoperative Applications of Velopharyngeal MR Imaging

Anatomic and physiologic MR imaging findings are key in surgical decision-making. VPI surgery aims to facilitate closure of the velopharyngeal port during speech production via palatal or pharyngeal approaches.[6] Palate operations include LVP reconstruction and/or soft-palate lengthening; the integrity of the LVP and the length of the velum with respect to the size of the velopharyngeal port are, therefore, of central importance. In contrast, pharyngeal operations seek to narrow or partially obstruct the velopharyngeal port. When planning these operations, measurements of adenoid pad size, the contribution of lateral pharyngeal wall movement, the posterior pharyngeal wall movement, the amount of velar excursion, and the velopharyngeal closure pattern are important. For example, the use of a pharyngeal flap assumes that the patient has adequate lateral pharyngeal wall movement to close off the lateral ports that are otherwise open for breathing and nasal sound productions. Thus, describing the degree of lateral pharyngeal wall movement during the velopharyngeal MR imaging is valuable information for the cleft craniofacial team. Surgeons may also use velopharyngeal MR imaging data related to the size and length of the velum, LVP integrity (cohesiveness), the size of the adenoid pad, and the velopharyngeal closure pattern to determine VPI surgical strategy.

Velum Assessment. A short velum may be unable to reach the posterior pharyngeal wall to achieve velopharyngeal closure necessary for speech production, leading the surgeon to pursue a palatal lengthening operation (Online Supplemental Data).[34] Poor elevation of the velum on i or s phonation or failure of the LVP to shorten during phonation can suggest a hypodynamic LVP. This is often difficult to correct, potentially resulting in narrowing the overall size of the velopharyngeal cavity (Online Supplemental Data) via a pharyngeal flap or sphincter pharyngoplasty.[35]

LVP Integrity. Discontinuity of the LVP within the velum is identified as an interruption in the T2-hypointense band of tissue running along the velar portion of the muscular sling, visualized in coronal oblique scans (Online Supplemental Data). When discontinuity is identified on MR imaging, LVP muscle reconstruction will be required.

Closure Pattern. Specific velopharyngeal closure patterns seen on oblique coronal imaging can also play an important role in surgical decision-making. There are 3 primary variants of velopharyngeal closure morphology: circular, coronal, and sagittal (Online Supplemental Data).[36-38] Velopharyngeal closure can include any degree of velar excursion, lateral pharyngeal wall movement, and posterior pharyngeal wall movement. The degree of involvement of these structures in velopharyngeal closure determines the type of closure pattern observed. While closure pattern alone cannot be used to determine the surgical type, it can provide valuable insight when considering whether to perform a pharyngeal flap (generally more ideal in sagittal closure pattern types when there is ample lateral pharyngeal wall movement) or sphincter pharyngoplasty (generally ideal when there is a coronal closure pattern type evident by good velar movement but limited lateral pharyngeal wall involvement). While it is conceptually distinct, assigning a specific closure pattern can be difficult, particularly when there is incomplete velopharyngeal closure or when there is limited motion of both the velum and pharynx.[39]

Postoperative Applications of Velopharyngeal MR Imaging

Velopharyngeal MR imaging is also used to examine anatomic and functional changes following VPI surgery. While the protocol of postoperative imaging is identical to that of preoperative imaging, there are several key differences in interpretation. An adequate surgical and clinical history is paramount to allow appropriate interpretation by the radiologist.

Without a consensus guide for the surgical approach to VPI treatment, selection is traditionally based on a multimodality evaluation of patient mechanics and speech production.[35] Four common procedures for repair of VPI are revisional palatoplasty, palate lengthening with buccal myomucosal flaps, a pharyngeal flap, and sphincter pharyngoplasty.[34,35,40,41] The common goal of these procedures is to improve the closure of the velopharyngeal port by creating a tight seal between the velum and pharyngeal walls during speech production. While surgical preferences should not be discounted, the descriptions contained within the Online Supplemental Data provide a general guide for radiologists on the 4 most common surgical approaches for VPI repair.

Potential Imaging Pitfalls

Determining the optimal angular position of the oblique coronal section for visualization of the LVP is a common challenge when performing velopharyngeal MR imaging. The imaging plane should sit at 50°–60° with respect to a line drawn through the cribriform plate. If not performed correctly, the LVP will not be visualized well on a single section; this issue can lead to misdiagnosis of LVP discontinuity in midline.

Another common issue in velopharyngeal MR imaging arises in cuing the patient to produce the desired sounds during the phonation sequences. If the timing of phonation and scanning is not synchronized, a false appearance of an incomplete closure of the velopharyngeal port can be observed. Observation of tongue position is crucial to confirm appropriate phonation. During /i/ sound production, the tongue should have a convex upper margin along the superficial surface at the midportion. The tip of the tongue should also be posterior to the mandibular central incisors. During /s/ sound production, the tongue should be flattened, while the tip of the tongue protrudes just beyond the mandibular central incisors. Anecdotally, the best way to remember these positions is to make the /i/ and /s/ sounds yourself, noting the position of your own tongue (Fig 1*E*, -*F*). An incorrect tongue position can also result in a falsely closed velopharyngeal port. Careful assessment of the posterior aspect of the tongue may reveal compensatory elevation of the velum by the tongue itself.

Another limitation of the protocol outlined within this study is that the stimuli used are limited to sustained phonation tasks. There are, however, key clinical biomarkers that are best derived from static MR imaging, including levator muscle cohesiveness, length, relative position to hard palate, pharyngeal depth, velar length, adenoid involvement and size, and pharyngeal flap position.[12] These variables would be difficult to obtain using current dynamic MR imaging methods. Because speech is a dynamic event, it is important that MR imaging technologies expand to also include dynamic speech at word-, phrase-, and sentence-level productions as described by Perry and colleagues.[42] These developments are already underway to support the translation of dynamic protocols into clinical scanners,[43] which will require an update to these outlined protocols. However, it is likely that sustained phonation tasks will still be of value, given the aforementioned reasons. Until such developments are available to cleft craniofacial clinics, the use of MR imaging may supplement dynamic methods of nasoendoscopy and videofluoroscopy, particularly when dynamic speech data and muscle imaging are a priority to the surgical planning.

Last, a limitation of this study surrounds issues related to access of MR imaging resources to cleft craniofacial teams throughout the world. While reports have published costs of MR imaging similar to those of other imaging methods (nasopharyngoscopy and videofluoroscopy) in the United States,[12] these costs are not universal. Many regions of the world do not have access to MR imaging for clinical use and/or costs are not realistic for patient care currently. Additionally, hospitals may not have access to training resources on site to develop and implement velopharyngeal MR imaging, and costs associated with personnel and such resources may not be feasible. Therefore, while velopharyngeal MR imaging may be actualized in some regions of the world, it may not be globally accessible, which is true for other direct and indirect imaging tools used in cleft care.

CONCLUSIONS

The combination of higher contrast anatomic detail and rapid dynamic techniques of MR imaging allow new, innovative techniques in the assessment of VPI. Particularly attractive is the elimination of ionizing radiation, which was previously standard of care with fluoroscopic examinations. MR imaging is also noninvasive and hence much better tolerated than nasopharyngoscopy. Additionally, MR imaging provides the clinician with information on LVP muscle continuity, position, and contraction, which is not available with the currently used imaging methods of nasopharyngoscopy or multiview videofluoroscopy. Discussion and feedback among radiologists and clinicians can ensure optimal study results. Although the use of MR imaging is currently supplemental to direct visualization, continued technologic advancement and further experience may soon negate the need for other invasive techniques.

Disclosure forms provided by the authors are available with the full text and PDF of this article at www.ajnr.org.

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