ORIGINAL ARTICLE

The Association of 3-D Volume and 2-D Area of Post-swallow Pharyngeal Residue on CT Imaging

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Abstract

Pharyngeal residue, the material that remains in the pharynx after swallowing, is an important marker of impairments in swallowing and prandial aspiration risk. The goals of this study were to determine whether the 2D area of post-swallow residue accurately represents its 3D volume, and if the laterality of residue would affect this association. Thirteen patients with dysphagia due to brainstem stroke completed dynamic 320-detector row computed tomography while swallowing a trial of 10 ml honey-thick barium. 3D volumes of pharyngeal residue were compared to 2D lateral and anterior–posterior areas, and a laterality index for residue location was computed. Although the anteroposterior area of residue was larger than the lateral area, the two measures were positively correlated with one another and with residue volume. On separate bivariate regression analyses, residue volume was accurately predicted by both lateral ($R^2 = 0.91$) and anteroposterior ($R^2 = 0.88$) residue areas, with limited incidence of high residuals. Half of the sample demonstrated a majority of pharyngeal residue lateralized to one side of the pharynx, with no effect of laterality on the association between areas and volume. In conclusion, the area of post-swallow pharyngeal residue was associated with volume, with limitations in specific cases. Direct measurement of pharyngeal residue volume and swallowing physiology with 3D-CT can be used to validate results from standard 2D instrumentation.

Keywords Pharynx · Dynamic computed tomography · Brainstem stroke · Residue · Deglutition · Deglutition disorders

Introduction

Approximately 16 million people are treated for dysphagia in the United States annually [1, 2]. Dysphagia is associated with risk of aspiration pneumonia, malnutrition and dehydration, high morbidity and mortality of stroke patients, deterioration in quality of life, and increased healthcare costs [3–5]. Pharyngeal residue, the material that may remain in the pharynx after swallowing, is an important marker of impairments in swallowing and prandial aspiration risk. Residue may result from weak or uncoordinated oropharyngeal musculature during bolus propulsion, disrupted sensation, or limited opening of the upper esophageal sphincter (UES), and is associated with several etiologies, including brainstem stroke [6, 7]. Previous reports suggest that risk of aspiration is directly associated with the presence and amount of pharyngeal residue [8–10].

To date, pharyngeal residue has been assessed by perceptual, semi-quantitative, and quantitative methods. Perceptual measures categorize residue by its absence/presence,

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amount, and location as represented by binary or ordinal data points [11–14], and may be limited by low interjudge reliability [15]. Semi-quantitative measures estimate the percentage of anatomically defined space (e.g., vallecullae, pyriform sinuses) that is filled with post-swallow residue [9, 16, 17]. Quantitative measures have been developed to improve the reliability and precision of residue measurements, and include computer-based area estimation with drawing tools on videofluoroscopy [18, 19] and the ratio of residual isotope counts with respect to the initial count prior to swallowing on scintigraphy [20, 21].

In addition to subjective ratings, videofluoroscopic measures of pharyngeal residue are limited to imaging in two dimensions [22]. Videofluoroscopy (VFSS) captures images in the lateral projection or the anteroposterior projection, whereby the X-ray beam passes through 3-D structures and is projected onto a 2-D screen. On the lateral projection, the 2-D area of residual contrast medium does not reflect differences between the right and left sides of the pharynx. The laterality of residue can be assessed on anteroposterior view, though in this plane it is not possible to distinguish between residue that is in the anterior pharynx (e.g., close to the laryngeal vestibule) versus residue on the posterior pharyngeal wall. On fiberoptic endoscopic evaluation of swallowing (FEES), pharyngeal residue is assessed from a superior view of the pharynx and yields a 2-D image that does not represent the depth of residue in the pharynx. Although the presence or absence of pharyngeal can be detected by FEES and VFSS with similar results [23, 24], ratings of pharyngeal residue severity on simultaneous FEES and VFSS were found to be significantly different [14], suggesting that residue area viewed from one plane is not equivalent to the area viewed from another plane, though this hypothesis has not been directly tested. We would anticipate that the area of residue on lateral and anteroposterior views would be correlated due to a shared vertical dimension.

To overcome the limitations of 2-D imaging, swallowing has recently been assessed by a 320-row area detector computed tomography (320-ADCT) scanner to yield 3-D dynamic swallowing studies [25, 26]. The 320-ADCT instrumentation acquires data over a 16-cm region, spanning from the oral cavity to the upper esophagus, and yields multi-planar reconstruction (MPR) and three-dimensional computer tomography (3D-CT) images. Based on these isotropic images, quantitative volume data for coronal (x), sagittal (y), and axial (z) sections can be depicted at any arbitrary cross section and in any orientation (0.47 mm by 0.47 mm by 0.5 mm voxels).

Volumetric analysis with 3D-CT has been previously applied to head and neck tumors and craniofacial anatomy [27, 28], and may be applicable to the quantification of pharyngeal residue. Although the area of a simple shape can be converted to volume mathematically, the area of residue as measured from VFSS or FEES cannot be converted to volume due to the irregular, unpredictable shape of the residue, particularly in cases where there is a greater amount of residue on one side of the pharynx than on the other. 3D-CT provides isotropic voxel data across many thin slices with equal resolution on the x, y, and z planes, and volumes can be reconstructed and quantified in scanner software after data acquisition. It remains to be determined whether dynamic 3-D assessment of pharyngeal residue can provide a valid and reliable basis for the management of dysphagia and can supplement existing imaging methods [29–31].

The primary aims of this study were to quantify the volume of post-swallow pharyngeal residue using dynamic 320-ADCT, and to determine the association between 2-D areas and 3-D volumes of pharyngeal residue on the same swallow. First, we hypothesized that areas of pharyngeal residue as measured on lateral and anteroposterior images would be significantly correlated with the volume of pharyngeal residue for the same swallow. Next, we hypothesized that the 2-D areas of pharyngeal residue on the lateral and the anteroposterior projections for the same swallow would significantly differ due to the overlap of different structures in the two projections. Finally, we hypothesized that predicting residue volume based on residue area would be mediated by the degree of residue laterality as determined in the anteroposterior plane. This is the first study to directly measure pharyngeal residue volume with 3-D imaging.

Methods

Participants

In this exploratory study, 13 participants (6 females; 68.1 ± 8.5 years) with brainstem stroke and evidence of pharyngeal residue on VFSS were recruited. Inclusion was based on visible pharyngeal residue after the first swallow of a honey-thick bolus with no aspiration (to ensure safety during CT evaluation). Participants provided oral and written informed consent for the study based on protocols approved by the Institutional Review Board.

Procedure

Participants were seated in a semi-reclining position (45°) with a customized chair for CT examination of swallowing (Offset-Sliding CT Chair; eMedical Tokyo, Chuoku, Japan; Tomei Brace Co., Ltd., Seto, Japan) [26, 32]. This postural angle was required for CT imaging, as the chair must slide into the scanner with the gantry tilted to 22° [25, 26]. Although an upright position is not possible with CT instrumentation, a reclining posture has been suggested to reduce penetration and aspiration on VFSS in patients after

stroke, with no change in bolus transit times in comparison to an upright, 90° position [33].

Participants were trained to swallow on command. Each participant swallowed a trial of 10-ml honey-thick contrast medium (5% w/v barium; 460 mPa) presented via syringe. The viscosity was selected for a slower bolus transit [34, 35] that would optimize visualization and participant swallowing safety. Additionally, a higher viscosity bolus may increase the frequency of residue while decreasing the frequency of penetration and aspiration [36]. The concentration of barium (separate from viscosity), though different from that used during VFSS, was required for optimal CT imaging. A 320-row area detector computed tomography system (320-ADCT, Aquilion ONE; Canon Medical Systems) was used for image acquisition. Scanning duration was 3.3–4.4 s per trial at ten frames per second (highest obtainable frame rate with CT instrumentation). The scanning parameters were field of view = 240 mm and tube voltage/current = 120 kV/40 mA. The scanning range was 160 mm from the skull base to the upper esophagus. CT dose index for one swallow has been estimated as 34.7 mGy, with a dose length product of 554.9 mGy [37].

Data Analysis

Multi-planar reconstructed (MPR) images and 3D-CT images were generated at an interval of 0.10 s from thin axial slices with Aquilion software. MPR images were displayed with a window level of 100 HU and window width of 1000 HU. 3D-CT images of the head and neck bony structures, contrast medium ($\geq$ 300 HU), and upper aerodigestive tract ($\leq -$ 300 HU) were created via volume rendering (Fig. 1).

The last frame of each dynamic MPR sequence (when all structures had returned to baseline) was used to measure 2-D areas and 3-D volume of residual contrast in the pharynx after swallowing. The 2-D measurements were made on layered maximum intensity projection (MIP) images to simulate VFSS imaging in the lateral and anteroposterior planes. A simulation of VFSS was used due to the differing frame rates between CT and VFSS, as well as different positioning. Similar to the lateral view on videofluoroscopy, CT can yield midsagittal radiographic images with clear distinction of the oropharyngeal structures and tracking of physiology and bolus transit during swallowing [25]. The region of the pharynx was demarcated by the posterior nasal spine anteriorly and the bottom of the pyriform sinus inferiorly. A digital image-measurement tool was used to directly circumscribe regions representing residue in Aquilion software. 3-D residue volume was depicted (window length > 250) and calculated with an automated digital-measurement tool. All area and volume measurements were completed by two raters;

differences in judgement were reviewed and resolved by consensus.

The laterality of residue was measured from the frontal, anteroposterior view of 3-D CT images. The image of the pharynx was divided into left and right by a line passing through three landmarks: the posterior nasal spine, the pyriform sinus incisura, and the posterior aspect of the true vocal folds (Fig. 2). The volumes of residue in the left and right portions of the pharynx were measured separately with the Aquilion digital-measurement tool. Laterality was quantified by the formula:

Laterality Index $= |(V_L/V_T) - (V_R/V_T)|$, where $V_L =$ volume of residue in the left hemi-pharynx, $V_R =$ volume of residue in the right hemi-pharynx, and $V_T =$ total volume of residue. This formula was designed to set a conservative cut-off, such that high laterality was defined as > 75% of the total residue being present in one side of the pharynx, and yielded a scale from 0 to 1. The degree of laterality was classified as low if the laterality index was $\leq$ 0.5 (< 75% of total residue on one side), and as high if the index was > 0.5 (> 75% of total residue on one side).

Statistical Analysis

Normality assessment by Shapiro–Wilk tests indicated that the values for anteroposterior area and volume were not normally distributed, though lateral area was normally distributed. The associations between 2-D lateral and anteroposterior areas and 3-D volume were assessed with Spearman correlations. Anteroposterior and lateral areas were compared by Wilcoxon signed-rank test, and their association was tested with Spearman correlation. The degree to which observed residue areas could predict residue volume for the same swallow was assessed by bivariate linear regression modeling with analysis of residuals. To assess laterality, Spearman correlations between lateral area and volume of residue were calculated for participants in the low and high laterality groups. The Z scores of the correlation coefficients for each laterality group were then analyzed by t test. Laterality index scores were plotted against the residuals from the bivariate linear regression models for lateral and anteroposterior areas. The level of statistical significance was set at $p < 0.05$. All data analysis was conducted using SPSS Statistics 19 (IBM, Japan).

Results

Participant demographics, location of stroke, and descriptive measures of residue are reported in Table 1. There was a strong linear correlation between anteroposterior area and volume of pharyngeal residue ($r = 0.94$, $p < 0.001$) and
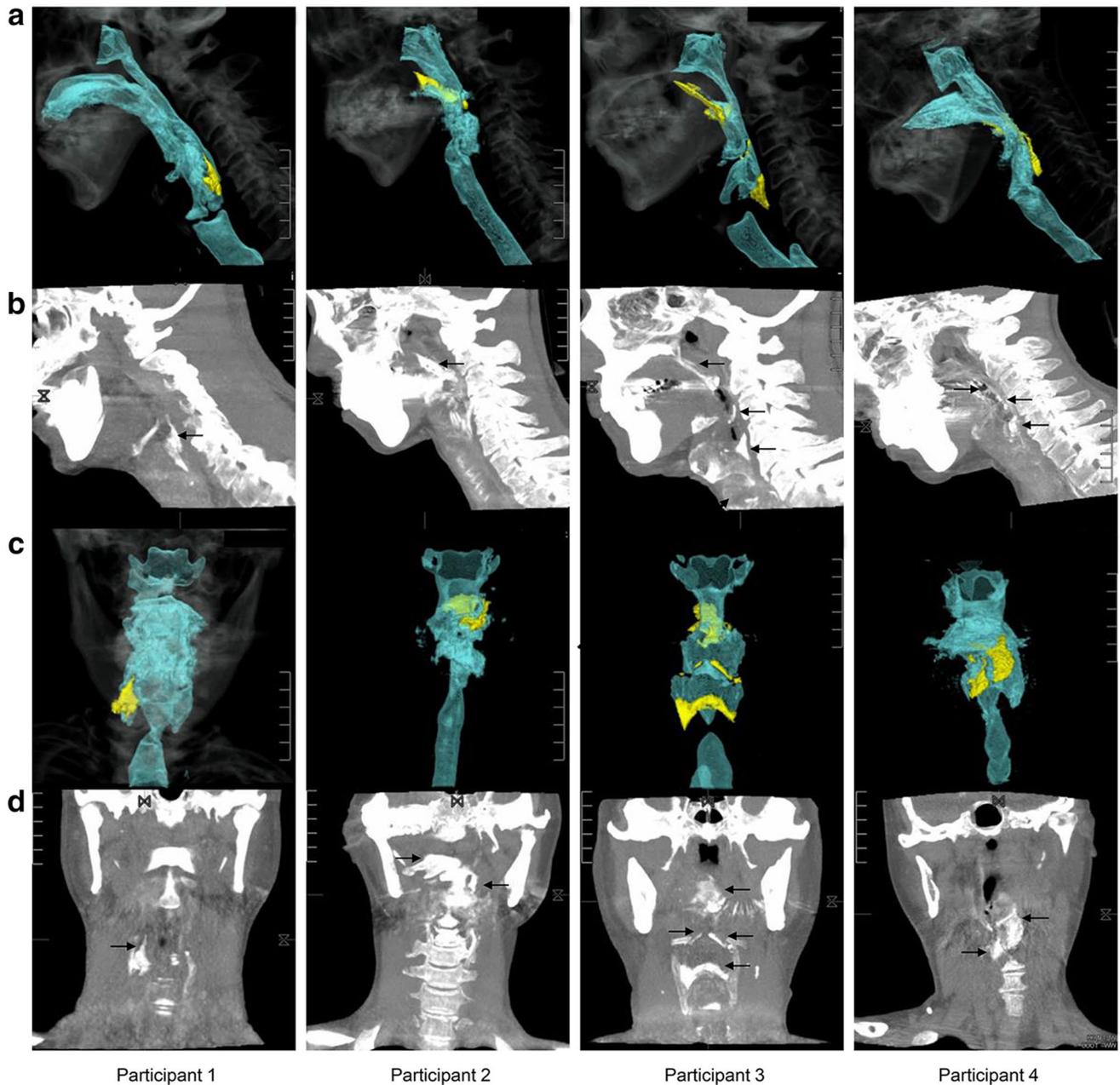
Fig. 1 Three-dimensional CT images of residue after swallowing in a sample of four participants representing various locations and amounts of pharyngeal residue (indicated by arrows). Images are presented in the lateral (**a**) and anteroposterior (**c**) views, with visible air surface (blue) and barium (yellow). Midsagittal (**b**) and coronal (**d**) images of swallowing in the same participants

between lateral area and volume ($r = 0.96$, $p < 0.001$). Anteroposterior area was significantly larger than lateral area of pharyngeal residue ($Z = 2.83$, $p < 0.05$), though the two areas were significantly correlated ($r = 0.94$, $p < 0.05$).

Linear regression analysis of area and volume yielded the following prediction equations:

$$\text{Volume} = 0.50 * \text{anteroposterior area} - 0.20$$

$$\text{Volume} = 1.24 * \text{lateral area} - 0.63.$$

Anteroposterior area significantly predicted volume ($\beta = 0.94$, $p < 0.001$), accounting for 88% of the explained variance in volume with adjusted $R^2 = 0.88$. The model for lateral area was also statistically significant ($\beta = 0.96$, $p < 0.001$), with lateral area accounting for 91% of the explained variability in volume with adjusted $R^2 = 0.91$. The calculated statistical residuals, based on the model presented, ranged from -1.25 to 0.73 cm^3 for lateral area and -0.81 to 1.56 cm^3 for AP area. Most of the calculated

Anterior nasal spine- posterior nasal spine
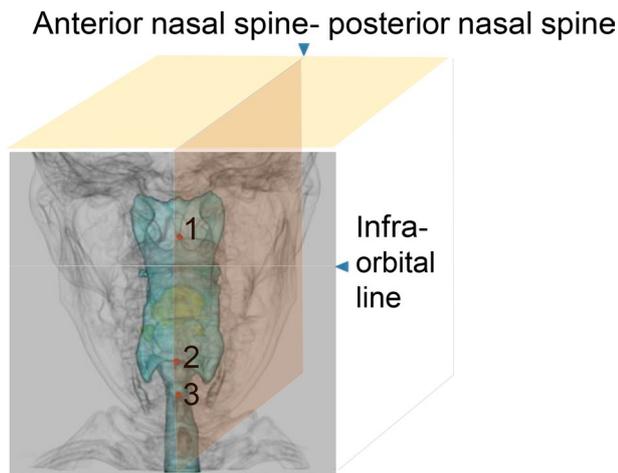
Fig. 2 Anteroposterior image depicting the division of the pharynx into left and right volumes by an infraorbital line passing through three landmarks: 1. posterior nasal spine, 2. pyriform sinus incisura, and 3. posterior aspect of the true vocal folds

statistical residuals were < 0.5 cm^3, indicating model accuracy (Fig. 3); only a few of the residuals were high (up to 76% of the actual volume), indicating a low frequency of error or unexplained variability.

Based on the formula for laterality, seven participants had more than 75% of residue localized to one side of the pharynx. There was no significant difference in the correlation between lateral area and volume of residue between the low and high laterality groups. In addition, there was no effect of laterality on statistical residuals.

Discussion

This study presents the first report of volumetric measurement of pharyngeal residue after swallowing using 320-ADCT. Our image-based analysis of the two- vs. three-dimensional properties of pharyngeal residue highlights two key points. First, there were strong correlations between 2D anteroposterior and lateral areas and 3D volume. The predictive capacity of area for volume was also high in most cases, with a few exceptions. Nonetheless, a large difference was found in some calculations of statistical residuals representing variance not explained by the statistical model. Detailed investigation of these outliers revealed that pharyngeal residue was dispersed laterally, anteroposteriorly, and superoinferiorly. Thus, this model inaccuracy may be explained by the shape of the barium residue seen; the more complex the shape, the more unexplained variance or error of the model. Second, the associations between area and volume were not significantly influenced by the laterality of pharyngeal residue. Our results validate the use of area to quantify the amount of pharyngeal residue in the case that the error rate is acceptably low.

The results of this study indicate that pharyngeal residue in approximately half of participants with brainstem stroke evidenced a high degree of laterality. Larger amounts of residue on one side in comparison to the other may be related to differences in strength of muscle contraction and sensation during swallowing. Although many health individuals evidence comparable bolus flow through both sides of the pharynx, a study of VFSS found that 35% of all participants were noted to have more contrast on the right, and 7% on the

Table 1 Participant demographics, location of stroke, and measures of pharyngeal residue

ID	Sex	Age	Location of stroke	Residue volume (cm^3)	Residue lateral area (cm^2)	Residue anteroposterior area (cm^2)	Residue laterality index
1	M	65	Left lateral medulla	0.40	0.95	1.40	1.00
2	F	80	Left brainstem	4.40	3.47	10.78	− 0.27
3	F	70	Left lateral medulla	1.70	1.83	4.65	0.53
4	F	65	Right lateral medulla	1.80	1.98	3.76	− 0.78
5	M	79	Left lateral medulla	2.30	2.39	4.86	− 0.04
6	M	76	Right lateral medulla	0.60	1.51	1.71	− 0.67
7	M	56	Cerebellum and right medulla	0.40	0.61	1.28	0.50
8	M	71	Right medulla	0.30	0.32	0.61	0.33
9	F	67	Right pons medulla	5.90	5.24	9.04	− 0.60
10	M	71	Right medulla and pons	1.10	2.41	1.71	− 0.45
11	F	74	Left lateral medulla	0.60	0.93	2.23	− 1.00
12	F	62	Right medulla	1.00	1.25	2.65	− 0.40
13	M	49	Right lateral medulla	3.10	2.78	7.51	0.42

Participant 1
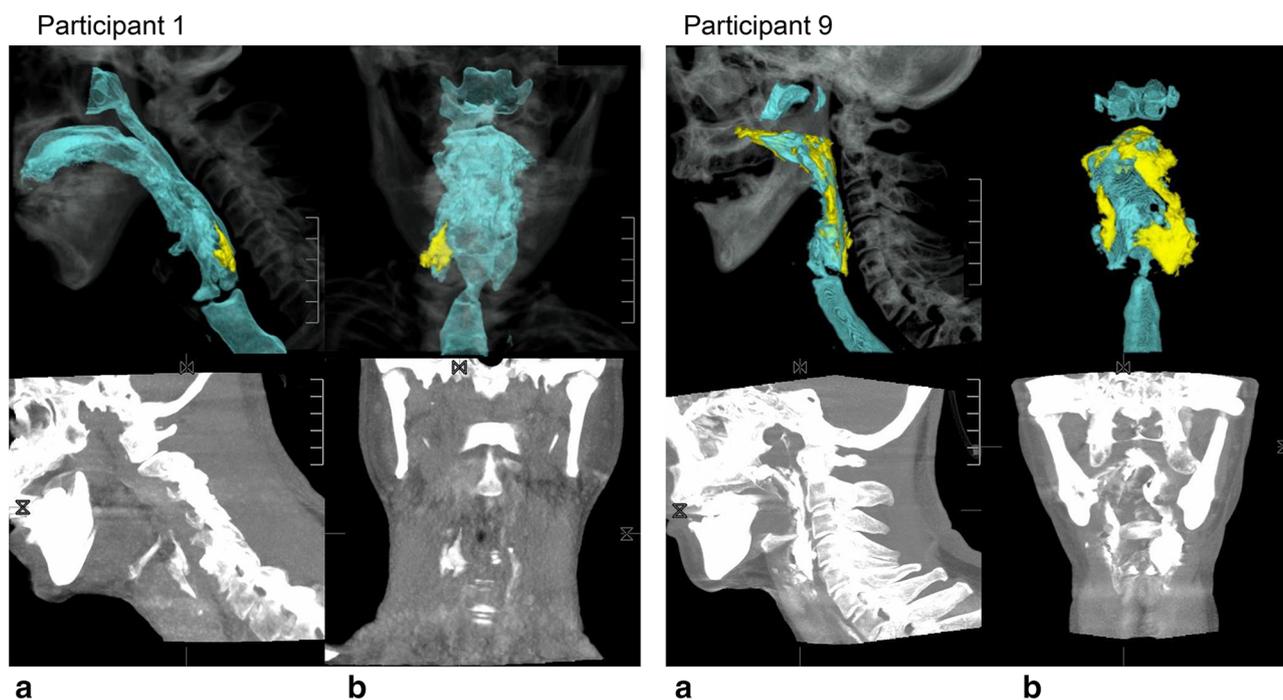
Participant 9

Fig. 3 CT images of residue after swallowing from two participants in the lateral/midsagittal (**a**) and anteroposterior/coronal (**b**) views. Participant 1 is an example of a case in which pharyngeal residue volume was accurately predicted based on pharyngeal residue area, whereas Participant 9 represents a case in which measured volume was higher than the predicted volume due to unequal amounts of residue on the right and left sides in anteroposterior view that were masked in the lateral view

left, which increased to 71% in older males [38]. On anteroposterior VFSS imaging, Kim et al. reported that stroke patients evidenced wider columns of contrast in the right UES than the left, regardless of lesion site [38], though Yang et al. reported the reverse [39]. In another study, the passage of contrast through the UES in medullary stroke patients was observed to be bilateral, lateralized to the affected side, lateralized to the non-affected side, or absent, with similar frequency, with more frequent hypopharyngeal passage bilaterally or through the affected side [40]. Although bolus flow and residue laterality may be independent, the mechanism, frequency, and effect of lateralized bolus flow and residue remain to be determined.

This methodology could be used to assess the association between aspiration risk and pharyngeal residue, and to determine the effect of therapy. Compensatory strategies such as ipsilateral rotation and contralateral tilting of the neck have demonstrated potential utility in reducing aspiration [41, 42]. In addition, a head-raising exercise has been shown to improve UES opening and reduce the height and width of pharyngeal residue, within a sample including patients with brainstem stroke [43]. Precise measurement of changes in pharyngeal residue could inform dysphagia rehabilitation.

Limitations

Our sample was limited in size and included participants who presented with pharyngeal residue after brainstem stroke; thus, the findings may not generalize to the other patient populations or presentations of dysphagia. The instrumentation required a semi-reclined position (45°), which has been used with some patients [32, 44], but is not the conventional positioning for instrumental evaluation in all countries; future systematic comparison of swallowing outcomes in different positions is required. The number of trials was limited by consideration for radiation exposure, and the results may not be generalizable to other volumes and consistencies. Future studies exploring these factors would deepen our understanding of pharyngeal motility. When assessing for inter-rater reliability, one study found that temporal measures of swallowing events and bolus transit on CT were highly reliable [45], though future work is necessary to assess reliability specific to the quantification of bolus residue.

Conclusion

The lateral and anteroposterior areas of post-swallow residue view are highly correlated with 3-D volume. The area of residue can predict volume, though, in some cases, there may be errors due to the distribution of residue throughout the pharynx. Precise measurement with 320-ADCT can validate morphologic and kinematic analyses of swallowing with conventional instrumental methodologies.

Compliance with Ethical Standards

Conflict of interest No conflict of interest declared.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

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