Cervical vertebral height approximates hyoid displacement in videofluoroscopic images of healthy adults

Abstract

Clinicians and researchers commonly judge the completeness of hyoid displacement from videofluoroscopic swallow study (VFSS) videos. Judgments made during the clinical exam are often subjective, and post-examination analysis reduces the measure's immediate value. This study aimed to determine the validity and feasibility of a visual, anatomically scaled benchmark for judging complete hyoid displacement during a VFSS. The third and fourth cervical vertebral bodies (C3 and C4) lie at roughly the same vertical position as the hyoid body and are strongly correlated with patient height. We hypothesized that anterior and superior displacement of the hyoid bone would approximate the height of one C3 or C4 body during safe swallows. Trained raters marked points of interest on C3, C4, and the hyoid body on 1414 swallows of adult patients with suspected dysphagia (n = 195) and 50 swallows of age matched healthy participants (n = 17), and rated Penetration Aspiration Scale scores. Results indicated that the mean displacements of the hyoid bone were greater than one C3 unit in the superior direction for all swallows from patient and healthy participants, though significantly and clinically greater in healthy participant swallows ($p < .001$, $d > .8$). The mean anterior and superior displacements from patient and healthy participant swallows were greater than one C4 unit. Results show preliminary evidence that use of the C3 and/or C4 anatomic scalars can add interpretive value to the immediate judgment of hyoid displacement during the conduct of a clinical VFSS examination.

Keywords: dysphagia; videofluoroscopy; swallow assessment; hyoid bone; deglutition

Introduction

Clinicians and researchers commonly judge swallowing kinematic impairments from videofluoroscopic swallow study (VFSS) videos [1]. One typical component of VFSS interpretations is the perceived completeness of anterior and superior hyoid displacement. The simultaneous bi-directional displacement pattern of the hyoid bone can be observed along two discernible axes of lateral-view VFSS images (i.e., anterior-posterior, and superior-inferior). This displacement reflects the summation of traction and other forces that occur during the pharyngeal phase of swallowing, which contribute to resultant hyolaryngeal displacement for airway protection, and upper esophageal opening for bolus passage [2, 3]. Subjective, quasi-objective, and objective measures have been used with some success to determine hyoid displacement in research studies and clinical work, though the literature reveals inconsistent norms and limited consideration for variation across individuals [4].

Many clinicians rely on experience and subjective estimations to determine the completeness of hyoid displacement during VFSS; however, making these judgements in real-time can lead to vague interpretive terms in reports like “reduced” or “limited” hyoid displacement [5]. Vague language in VFSS reports may result in unclear treatment rationale and unsubstantiated pre-treatment baseline measurements. Though the addition of post-examination frame-by-frame analysis might contribute to more accurate judgements of hyoid displacement, a recent survey of speech-language pathologists (SLPs) working in clinical dysphagia management indicated that 30% of the respondents never use frame-by-frame analysis, and 66% of the respondents only use it half of the time [6]. Post examination analysis does not allow the clinician to judge impairments and test the efficacy of compensations or other interventions

during the conduct of the VFSS examination, which may be one reason for low usage rates, and the dependency on real-time (i.e., during the examination) judgments of hyoid displacement.

The Modified Barium Swallow Impairment Profile (MBSImP) [7] is an example of a quasi-objective measure used to label degrees of anterior hyoid displacement during the VFSS exam. Clinicians judge the trajectory of anterior displacement with scores from zero (complete anterior hyoid displacement) to two (no anterior hyoid displacement), using the angle formed by the hyoid bone and thyroid cartilage as viewed on the VFSS image, as a guide. Potential limitations of this approach are approximations leading to subjectivity and broad rating categories, which may result in overlap between ratings among clinicians.

Using objective methods to measure hyoid displacement, such as plotting and tracking position and movement with image processing software, increases the chance for precision and reliability among clinicians. Unfortunately, objective measures of hyoid displacement are not feasible during online clinical decision-making, thus reducing the measures' immediate value. In clinical diagnostic work, many online judgments must be made during the VFSS so clinicians can describe patient function and impairments, contribute to diagnoses, and immediately formulate rationale for compensatory interventions as an initial treatment efficacy trial [8]. As a result, despite their facilitation in identifying appropriate treatment targets, the use of objective methods for measuring hyoid displacement is less common than subjective judgment in standard clinical practice [6].

Until recently, many objective hyoid displacement methods have used fixed objects of known length (e.g., a coin) to judge hyoid displacement in absolute linear measurements (i.e., millimeters) [9, 10]. This method resulted in measurements that were not corrected or scaled for patient size and individual variability. Molfenter and Steele [11] found a strong correlation

between participant height and the linear distance between the anterior-inferior aspect of the second cervical vertebral body (C2) and the anterior-inferior aspect of the fourth cervical vertebral body (C4). Their research indicated that previously reported sex differences in linear hyoid displacement are neutralized with the application of the "C2-C4" anatomical scalar. Using this scalar also robustly retains the known effects of bolus volume on hyoid displacement [4].

The introduction of the C2-C4 anatomical scalar has contributed substantively to dysphagia research to account for participant size differences; however, employing the scalar requires post-examination image processing. While post-examination of VFSS remains an essential component for most aspects of this instrumental exam, clinicians would benefit from a standard, anatomically scaled benchmark from which to judge the completeness of anterior and superior hyoid displacement *during* VFSS. Such a benchmark would enable immediate screening-level identification of impairments and an objective basis upon which to select and assess the efficacy of therapeutic probes.

The third and fourth cervical vertebral bodies (C3 and C4) lie at roughly the same vertical position as the hyoid body before, during, and after swallows on most lateral/sagittal-view VFSS frames in anatomically typical adults. While Molfenter and Steele [11] found that C2-C4 had the strongest correlation with patient height (r =0.83), their research also determined that C3 and C4 were strongly correlated (r = 0.69 and r = 0.75, respectively) [12, 13]. Subsequently, the aim of the current study was to determine the validity and feasibility of using the height of either C3 or C4 as a valid, visual, and anatomically scaled benchmark for determining complete hyoid displacement during a VFSS. We hypothesized that anterior and superior displacement of the body of the hyoid bone would each approximate the height of one C3 or C4 vertebral body (i.e.,

one C3 or C4 “unit”) during safe swallows (i.e., Penetration Aspiration Scale (PAS) = 1 or 2 [14, 15]).

Methods and Materials

Data Acquisition

The protocol for this study was approved by the Institutional Review Board at the University of Pittsburgh. All participants provided informed consent. One hundred and ninety adult patients (115 male; mean age 63.6 ± 14.3; 1414 swallows) with suspected dysphagia who were recommended for VFSS by an SLP, and 17 age-matched healthy community-dwelling adults (14 male; mean age 62.56 ± 7.56; 50 swallows) underwent an oropharyngeal swallowing assessment via VFSS at the University of Pittsburgh Medical Center (Pittsburgh, PA). The patient cohort was comprised of 36 individuals who had experienced a stroke, and 154 individuals of heterogeneous diagnoses unrelated to stroke. Healthy participants reported no history of head or neck surgery, neurological disorders, or swallowing difficulties.

Data were collected from patients during standard clinical care without interference in clinical decision-making during the VFSS. The assessment protocol, including bolus condition (i.e., spoon or cup), consistency, and swallowing maneuver, was modified by the SLP performing VFSS as clinically appropriate. This study analyzed swallows of Varibar thin liquid (Bracco Diagnostics Inc., Monroe Township, NJ). Boluses were administered by spoon (approximately 3mL) or by self-administered unmeasured-volume sips from a cup. Most patient swallows under both administration conditions were command swallows. Cup administered bolus volumes were not recorded for the patient cohort.

Healthy participants swallowed five 3mL boluses of Varibar thin liquid from a spoon using a command swallow paradigm, and five individual, spontaneous, self-selected volume sips from a

cup containing 60mL of thin liquid. The mean bolus volume by cup was 18.44 mL across healthy participants.

VFSS for patients was conducted in the lateral plane using an Ultimax system (Toshiba, Tustin, CA) with a pulse rate of 30 pulses per second (pps) and frame resolution of H1008*W792. Due to hospital equipment upgrades during research, the Precision 500D system (GE Healthcare, LLC, Waukesha, WI) with a pulse rate of 30 pps and frame resolution of H1024*W1280 was used for healthy participants. Prior to data analyses, we verified that differences in spatial image resolution between the two acquisition systems did not affect the reliability and accuracy of the ratings in a blinded internal analysis. Inter-rater reliability for identical, randomly ordered videos sampled at both video resolutions was at .99 or above, as measured by intraclass correlation coefficients (ICC) [16]. VFSS output stream was captured via an AccuStream Express HD video card (Foresight Imaging, Chelmsford, MA) and digitized with a sampling rate higher than or equal to 60 frames per second (fps) [17], then down sampled to 30 fps to remove duplicate frames. The digital video stream was saved to a hard disk using LabView's Signal Express (National Instruments, Austin, Texas).

Image Analysis

Patient and healthy participant swallows were de-identified and randomized for kinematic measurements. Swallows were segmented in ImageJ open-source software [18] by trained raters as previously described [19, 20]. The onset of a swallow segment was defined as the frame at which the bolus head reached the posterior border of the ramus of the mandible. The offset of the swallow segment was defined as the frame at which the hyoid bone completed motion associated with swallowing-related pharyngeal activity with clearance of bolus tail from the video image. Trained raters, independent of those segmenting swallows, observed VFSS videos and scored the

patients' and participants' levels of airway protection using the PAS to classify the "safe" (PAS = 1 or 2) from "unsafe" (PAS = 3 – 8) swallows. Only "safe" swallows with a PAS score of one or two were included in the analyses.

Raters trained in kinematic swallowing analysis used a custom application developed in MATLAB (R2015b, The MathWorks, Inc., Natick, MA, USA) to mark the following anatomical points of interest on each frame for each swallow: the anterior-inferior corner of the C2 vertebral body, the anterior-superior and anterior inferior corners of the C3 and C4 vertebral bodies, and the anterior-inferior and posterior-superior corners of the body of the hyoid bone (Figure 1). For the purposes of this preliminary paper, we report results based on displacement of the anterior-inferior portion of the hyoid body, which aligns with work published by Molfenter & Steele [11]. Raters maintained ongoing inter- and intra-rater reliability with ICCs of over .99 for all ratings and measurements in this study, indicating a high level of agreement.

The anterior and superior displacements of the anterior-inferior landmark of the hyoid bone, and the height of the C3 and the C4 vertebral bodies were calculated in pixels using the landmarks labeled by judges. The ratios of superior and anterior displacements of the hyoid bone landmark to C3 and C4 heights were calculated as relative measures of hyoid displacement with respect to the static anatomical structures (i.e., vertebral height measures).

Head movement is common during VFSS due to patient movement and clinician-directed maneuvers. To control for this variable and to avoid a biased estimation of hyoid bone movement, a head movement compensation algorithm, aligned with the "remapping" methods of Dengel et al. [21], was applied to anatomical landmarks in each frame of each swallow. The segment between the anterior-inferior corner of C2 vertebral body and the anterior-inferior corner of the C4 vertebral body was marked in the first frame of each swallow and used as an anatomical referent to calibrate

for subsequent head movement. For each additional frame, the C2-C4 segment was marked and compared to the C2-C4 segment from the first frame. Any rotation and/or translational displacement that occurred between frames were detected through this comparison. Translational displacement was defined as the displacement of the anterior-inferior corner of the C4 vertebral body between frames. The rotational angle was defined as the angle between C2-C4 segments of the current and the first frame. A linear transformation using these two parameters was applied to orient the frame, using the first frame as a referent to correct for motion artifact. See Figure 2.

Statistical Analysis

R (R Foundation for Statistical Computing) was used for all statistical analyses, with a significance level set at $\alpha < .05$. Descriptive statistics of patients and healthy participants' maximum anterior and superior relative displacements of the hyoid bone were performed based on the bolus condition (i.e., spoon or cup). Analysis of variance (ANOVA) was performed on the maximum anterior and superior relative displacement of the anterior-inferior aspect of the hyoid bone corner against the controlling parameter (i.e., bolus condition) followed by Tukey Honestly Significant Differences (Tukey HSD) test for pairwise comparisons. An independent t-test was performed to determine whether significant differences existed between the maximum hyoid displacements in swallows of patients and healthy participants. Effect size for differences between sub-groups was calculated via Cohen's *d*.

Results

Mean Overall Hyoid Displacements in Terms of C3 and C4 Units

Table 1 shows the mean anterior and superior hyoid displacements of the hyoid bone in patients and healthy participants, in terms of C3 and C4 units. In Table 2, the mean anterior and superior hyoid displacements are displayed according to bolus condition (i.e., spoon or cup) in

patients and healthy participants, in terms of C3 and C4 units. Both tables depict statistical and clinical significance between patient and healthy participant data, as well as within group significance for directional displacements and bolus conditions.

The C3 unit

The mean displacement of the hyoid bone was greater than one C3 unit in the superior direction for all swallows from patient and healthy participants. Superior displacements were significantly greater in healthy participant swallows than patient swallows p (p <.001) with a large effect size (d >.8). Superior displacements were significantly greater than anterior displacements in both groups. The mean anterior displacement was greater than one C3 unit in healthy participants, but less than one C3 unit in patients (0.78 ± 0.28). Anterior displacements were significantly greater in healthy participant swallows than patient swallows (p <.001), with a large effect size (d >1.0).

In healthy participants, there was a significant effect of volume on hyoid displacement, and the mean anterior and superior displacements for both bolus conditions (i.e., spoon and cup) were greater than one C3 unit. Superior displacements were significantly greater in the cup condition for this group. In patients, the mean superior displacement was greater than one C3 unit in the cup condition and approached one C3 unit in the spoon condition (0.99±0.37). The anterior displacement of the hyoid bone in patients was less than one C3 unit in both the spoon condition (0.75 ± 0.257) and cup conditions (0.80 ± 0.289). Healthy participant swallow displacements were significantly greater than patient swallow displacements for both bolus conditions (p ≤ .001), with large effects sizes (d ≥.8).

The C4 unit

The mean anterior and superior displacements of the hyoid bone from patient and healthy participant swallows were greater than one C4 unit. The mean anterior displacement was significantly greater in healthy participant swallows than patient swallows (p <.05), but the effect size was small (d = .2). Superior displacements were significantly greater than anterior displacements in both groups.

Patient and healthy participants had mean displacements greater than one C4 unit in the superior and anterior directions for both bolus conditions. Healthy participant swallows had significantly greater superior displacements in the cup condition than the spoon condition. Anterior displacement in the patient group approached one C4 unit in the spoon condition (0.98 ± 0.426). The superior displacements were significantly greater in healthy participants than in patients in the spoon condition (p <.01), with small to medium effect sizes ($d \leq .5$).

Discussion

In this study, we sought to determine whether the height of the C3 or C4 vertebral bodies could be used as valid, visual, and anatomically scaled benchmarks for estimating completeness of superior and anterior hyoid displacement during the administration of a VFSS. This estimation is often a subjective judgment made by clinicians despite research reporting that perceptual judgments of hyoid excursion are unreliable [22]. Clinicians would benefit from an objective, "real-time" method of judging hyoid displacement during VFSS that is calibrated to patient height and does not require extensive training or additional time to perform. We hypothesized that the height of the C3 and/or C4 vertebral unit(s) would offer individual-referenced comparisons from which to judge hyoid displacement. The results indicated that "safe" swallows (i.e., normal airway protection) in patients and healthy participants generally had anterior and superior hyoid displacements that approximated or exceeded the height of the C3 and C4

vertebrae. Greater differences were seen between patient and healthy participant anterior hyoid displacements when using C3 as a comparison, but this requires verification with a larger data set of healthy participant swallows.

Other researchers have investigated C3 as an anatomical scalar from which to judge hyoid displacement but assigned the vertebra a fixed measure of 15mm for all participants [23, 24], or scaled to a fixed object like a coin [9, 25], thereby discounting individual height differences. The C2-C4 distance is shown to be a reliable scalar for hyoid displacement, taking individual size into account, but judging hyoid displacement based on this distance is impractical for use in real-time VFSS sessions. In clinical work, on-line interpretation is often expected and the C2-C4 scalar requires post-examination analyses, contributing to our decision to investigate C3 and C4 as alternatives.

Molfenter and Steele (2014) reported that complete superior hyoid displacement correlated with the C2-C4 scalar in a sample of healthy participants. Our research showed that mean superior hyoid displacements for healthy participants and patients were roughly one C3 or C4 unit and, consistent with extant research, significantly greater than anterior displacement [26, 27]. These results suggest that superior displacement of the hyoid relative to C3 or C4 units can be used as valid and reliable alternatives to the validated C2-C4 scalar, though anterior displacement requires further analyses.

In agreement with prior research [4, 11, 27, 28], our study found significant differences in hyoid displacements between smaller and larger bolus volumes, particularly in the superior direction, both within and between participant groups. For healthy participant swallows, the mean superior and anterior hyoid displacements were one C3 or C4 unit or greater, regardless of volume. Healthy participant swallows had clinically and statistically significantly greater

displacements than patient swallows, particularly when using the C3 unit scalar. Interestingly, this was true despite patient swallows being "safe" (PAS one or two) and having hyoid displacement greater than or equal to one C3 unit. Translated to impact on clinical practice, these results suggest that using these anatomic scalars to judge hyoid displacement may improve identification of subtle, largely asymptomatic increments of decompensation. Such subtle decompensation is common in the progression of dysphagia in several clinical scenarios, such as neurodegenerative diagnoses, post-radiation dysphagia, and others. Clinicians may be able to detect subclinical reductions in hyoid displacement before the airway is compromised, thus guiding preventive treatment planning.

In contrast to the healthy cohort, anterior displacements for patients did not reach one C3 unit despite being "safe" swallows (i.e., PAS scores of one or two). This finding may indicate the use of physiologic compensations, independent of hyolaryngeal displacement, that enable complete laryngeal closure and UES opening. Some literature suggests that reduced superior hyoid displacement threatens airway protection [23, 29], while reduced anterior displacement may contribute to pharyngeal residue [23, 30]. According to these theories, the patient swallows in our study may be considered safe from an airway protection standpoint because of their adequate superior hyoid displacement but are still atypical due to incomplete anterior displacement. Our methods analyzed hyoid displacement and PAS scores but did not consider other aspects of impaired swallowing physiology, such as those leading to pharyngeal residue. These will be considered in future investigations. Still, other research suggests that limited anterior displacement is more likely to be associated with or even to predict an elevated "risk" of penetration and/or aspiration [4, 31, 32]. As mentioned previously, the C3 and C4 scalars are reliable alternatives to the C2-C4 scalar in the superior direction, but future studies are required

to determine the individual relationships of anterior hyoid displacement with the C3 and C4 scalars.

In this investigation, our data revealed similar anterior displacements across patient and healthy participant swallows using the C4 scalar but, as mentioned, showed significantly and clinically reduced anterior displacements in patient swallows when using the C3 scalar. This data suggests that C3 may be a more sensitive indicator of hyoid displacement characteristic of patient populations, perhaps due to deconditioning, fatigue, or disease processes. The results also suggest three alternate hypotheses: 1) using the C4 as a scalar for complete hyoid displacement is sufficient because although displacements were different, all swallows were considered "safe" (albeit atypical), 2) using C3 as a scalar is more appropriate because results could indicate that the swallow may be safe, but not healthy, and 3) "complete" hyoid displacement is not necessary for a safe swallow. Further investigations replicating these methods using patient swallows with inadequate airway protection can help differentiate "healthy" versus "safe" swallows and what qualifies as adequate hyoid displacements for each.

The C2-C4 height has been widely used as an anatomic scalar for post-examination measurements with image processing software. We sought to determine whether the C3 or C4 height could serve as a convenient immediate visual estimate of anterior and superior hyoid displacement and not to determine whether C3 or C4 height is a surrogate for C2-C4 height in measurements. Until more questions are answered about the C3 and C4 units, the C2-C4 height should continue to be preferred by researchers conducting investigations of swallow kinematics in the clinical setting and should support impressions of the completeness of hyoid displacement during the VFSS study. Nevertheless, the results of this study strongly suggest that use of the C3

and/or C4 anatomic scalars can add interpretive value to the immediate judgment of hyoid displacement during the conduct of a clinical VFSS examination.

Limitations and directions for future research

A limitation of this study was the lack of a younger cohort. Swallowing physiology, including hyoid displacement, changes with age [4, 23]. Brates and colleagues [4] found that when comparing anatomically scaled hyoid displacements between older and younger groups, older group measures were inflated, possibly due to age-related cervical anatomical changes. The authors, therefore, cautioned against comparing older to younger age groups; however, if a study of a healthy younger cohort shows displacements equal to or greater than one C3 or C4 unit, the currently investigated method would still stand.

Additionally, in this study, patient data was collected during routine clinical care, so specific bolus volumes were not measured for patients. We do not expect that patients referred for swallowing difficulties swallowed the same average bolus volume as our healthy participants. The inclusion of self-selected cup volumes in research and clinical work is in part designed to account for some of these differences by enabling participant/patient self-determination of "comfortable" bolus volumes.

Considering the preliminary nature of this study, a variety of avenues can be pursued to strengthen the argument that the C3 and/or C4 vertebral units can be used to determine completeness of hyoid displacement during a VFSS. Along with possibilities already addressed, the C3 and C4 units should be examined across bolus consistencies, given the role that bolus viscosity plays in hyoid displacement [28]. The scalars should also be verified with the vector, or hypotenuse of hyoid displacement [11]. And finally, more research is required to establish whether human judges can reliably visually discriminate between the difference of one or less

than one C3 or C4 unit of hyoid displacement. With continued research, the C3 and C4 units could potentially offer more objectivity to ordinal rating scales, such as the MBSImP. For example, the C3 or C4 scalar may assist clinicians in differentiating between a score of zero (complete anterior movement) and one (partial anterior movement) on Component 9 ("Anterior Hyoid Excursion") of the MBSImP.

Conclusion

Literature shows that measures of hyoid displacement must be scaled to the height of the person swallowing. We have demonstrated initial feasibility of using the height of the C3 and C4 vertebral heights as quick, visual, anatomic scalars to make preliminary and more accurate estimations of hyoid displacement during a VFSS. Healthy participant swallows reliably have maximum superior and anterior displacements of more than one C3 and C4 unit, though it remains uncertain whether this generalizes to "healthy" patient swallows. Further investigation is warranted to establish whether human judges can visually discriminate between one and less than one C3 or C4 units of hyoid displacement in both a post-hoc analysis and during live data collection.

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