Published in final edited form as:

Neurogastroenterol Motil. 2019 January ; 31(1): e13465. doi:10.1111/nmo.13465.

Derivation and Measurement Consistency of a Novel Biofluid Dynamics Measure of Deglutitive Bolus-Driving Function - Pharyngeal Swallowing Power

Dr. Isaac Sia,

Department of Rehabilitation, National University Hospital, 5 Lower Kent Ridge Road, Singapore 119074, Singapore, isaac_sia@nuhs.edu.sg, Fax: +65 6779 7740, Tel: +65 9694 3929

Michael A. Crary,

Swallowing Research Laboratory, University of Central Florida, Orlando, Florida

John Kairalla,

Department of Biostatistics, University of Florida, Gainesville, Florida

Giselle D. Carnaby,

Swallowing Research Laboratory, University of Central Florida, Orlando, Florida

Mark Sheplak, and

Department of Mechanical and Aerospace Engineering and Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida

Dr. Timothy McCulloch

Division of Otolaryngology–Head and Neck Surgery, University of Wisconsin-Madison, Madison, Wisconsin

Abstract

Background—The primary function of the pharyngeal swallowing mechanism is to drive ingested materials into the esophagus. Currently, a definitive measure of pharyngeal bolus-driving function that accounts for bolus movement remains lacking. The primary objectives of this study were to describe the derivation of a novel biofluid dynamics measure of deglutition – i.e.

-
- Author Contributions
 - IS - study concept and design; acquisition of data; analysis and interpretation of data; drafting of the manuscript; critical revision of the manuscript for important intellectual content; statistical analysis
 - MC - study concept and design; critical revision of the manuscript for important intellectual content
 - JK - study concept and design; analysis and interpretation of data
 - GC - study concept and design; critical revision of the manuscript for important intellectual content
 - MS - study concept and design; critical revision of the manuscript for important intellectual content
 - TM - study concept and design; technical and material support; study supervision; critical revision of the manuscript for important intellectual content

Disclosures

No competing interests declared

pharyngeal swallowing power (PSP) – and to demonstrate the consistency of PSP in normal swallowing.

Methods—The pharyngeal swallowing mechanism was conceptualized as a hydraulic power system with the upper esophageal sphincter (UES) as a conduit. PSP was calculated as the product of bolus pressure and flow across the UES.

34 young healthy subjects swallowed materials consisting of two bolus volumes (10 mL, 20 mL) and four bolus viscosities (thin liquid, nectar-thick liquid, honey-thick liquid, pudding). High-resolution impedance manometry was used for data collection. The consistency of PSP across specific bolus conditions was evaluated using standardized Cronbach coefficient alpha.

Key Results—Standardized Cronbach coefficient alphas in specific bolus conditions ranged between .85 and .93. Fisher weighted mean Cronbach coefficient alphas for swallow trials across bolus volumes and across bolus viscosities ranged from .86 to .90. Fisher weighted mean Cronbach coefficient alpha for overall consistency of PSP across all swallow trials was 0.88.

Conclusions & Inferences—PSP estimates the output power of the pharyngeal bolus-driving mechanism during deglutition. PSP's high consistency indicates that it to be a useful biofluid dynamics measure of pharyngeal bolus-driving function. Current results also demonstrate that consistency in pharyngeal bolus propulsion is an important physiological target for the pharyngeal swallowing mechanism.

Abbreviated abstract:

Pharyngeal swallowing power (PSP) estimates the output power of the pharyngeal bolus-driving mechanism during deglutition. PSP's high consistency indicates that it to be a useful biofluid dynamics measure of pharyngeal bolus-driving function. Current results also demonstrate that consistency in pharyngeal bolus propulsion is an important physiological target for the pharyngeal swallowing mechanism.

Keywords

Deglutition; Swallowing Power; Consistency; High-resolution manometry; Multichannel intraluminal impedance

Introduction

The primary function of the pharyngeal swallowing mechanism is to drive ingested materials into the esophagus. Early literature on pharyngeal swallowing primarily designated the pharyngeal walls as pressure generators in the form peristaltic waves responsible for bolus passage ^{1,2,3,4}. However, unlike other regions of the gastrointestinal tract where the luminal walls are the only source of pressure generation, pharyngeal pressures have a number of potential pressure generating sources including the tongue, palate and larynx ². As such the theory of peristaltic bolus propulsion was inadequate and inappropriate to explain pharyngeal swallowing. Understanding of pharyngeal swallowing pressure phenomena reached a milestone with the advent of manometry techniques (i.e. pressure measurement). By combining data concurrently obtained from manometry and fluoroscopy, McConnel was the first to demonstrate using empirical data that the tongue driving pressure and the partial

vacuum developed in upper esophageal sphincter (UES) opening are more important for bolus transit than the peristaltic-like pressure applied by the pharyngeal constrictors⁵. Building on McConnel's work, Cerenko et al. proposed that bolus transit relies on synergistic action of two pumps – the oropharyngeal propulsion pump and the hypopharyngeal suction pump - which together contributes to the pharyngeal pressure gradient responsible for bolus transport⁶. These authors used pharyngeal pressure-time integrals as proxies for bolus-driving forces as it was not possible to ascertain the surface area on which pharyngeal pressures act. However, pressure-time integrals remain inadequate for describing and quantifying the bolus-driving function of the pharyngeal swallowing mechanism. Specifically, different amplitude of bolus-driving forces acting on boluses of different sizes (e.g. different bolus volumes) may result in similar pressure-time integrals due to differences in surfaces in contact with pressure-generating sources. Furthermore, how variations in such pressure-time integrals ultimately impact bolus propulsion cannot be determined. Moreover, the synergistic pumps theory of bolus propulsion does not take into consideration additional influences such as the impact of gravity and bolus viscosity (i.e. friction) on bolus movement. Hence, a definitive measure of deglutitive pharyngeal bolus-driving function that takes bolus dynamics into account has yet to be found.

In recent years, high-resolution manometry (HRM) has found its way from gastroenterology into the field of deglutition. HRM, with up to 15 circumferential sensors located within the pharynx⁷, addresses issues associated with traditional pharyngeal manometry such as limited spatial and temporal resolution and radial asymmetry. Thus, HRM allows better quantification of the pharyngeal pressures involved during bolus transit. Currently, application of HRM has been largely limited to the research setting due not only to technical barriers, but more significantly, to uncertainties pertaining to which measures are clinically relevant or significant⁸. Because of the persisting uncertainty in contact areas and difficulty in estimating bolus-driving forces, HRM studies of pharyngeal swallowing physiology have continued to focus on peak pressures characteristics at various locations (e.g., velopharynx, base of tongue and hypopharynx). Other common parameters that have been reported include pressure rise time (to peak pressure), pressure drop time, and pressure change duration^{9,10,11,12,13}. However, such measures do not provide any information about how the behavior of the pharyngeal swallowing mechanism is impacting bolus movement. Furthermore, as Cerenko et al. had shown, peak manometric pressures occur during pharyngeal bolus clearance, after the majority of the bolus has passed through the upper esophageal sphincter⁶. Moreover, due to asymmetry of the pharyngeal space and asymmetrical bolus flow through the pharyngeal space, pharyngeal peak pressures may also be due to direct pharyngeal contact with manometric sensors rather than reflecting bolus-driving force. Some researchers sought to overcome this limitation by reporting on intrabolus pressure, i.e. the pressure recorded as the bolus passes over the manometric sensor^{14,15,16}. However, intrabolus pressure similarly does not contain information about the motion of the bolus from pharyngeal bolus propulsion. In other words, a measure that quantifies the bolus dynamics resulting from pharyngeal bolus-driving function remains lacking.

Concurrent pressure and impedance measurements (i.e. high-resolution manometry with impedance, HRIM) has allowed for an evaluation of the relationship between esophageal

motility and luminal flow¹⁷. Applied to pharyngeal swallowing, HRIM enables the systematic evaluation of relationships among pharyngeal pressure, pressure wave velocity or coordination, and the effectiveness of bolus transport and bolus clearance. For example, Omari et al. used HRIM to demonstrate that intraluminal impedance patterns in the pharynx are far more complex than those in the esophagus¹⁷. Pharyngeal residues and prolonged mucosal contact post swallow from pharyngeal constriction mean that multichannel intraluminal impedance (MII) is not able to provide accurate information about the relation of pharyngeal bolus flow with regards to onset and offset of pharyngeal pressures. Although it is not possible to measure pharyngeal bolus transit times using MII, Omari et al. has shown that bolus transit across the UES, being closed at rest (similar to the collapsed esophagus), can be accurately identified by MII since the issues of residues and prolonged mucosal contact do not apply. As such, MII may be used for assessing bolus transit across the UES and HRIM can potentially be exploited for evaluation of pharyngeal bolus-driving function and its direct impact on bolus dynamics.

The objectives of this study were to first introduce and describe the derivation of a novel biofluid dynamics measure of deglutitive bolus-driving function using data obtained from HRIM, and then to demonstrate its consistency across repeated trials in normal deglutition.

Materials and Methods

A) Introduction and Derivation of Pharyngeal Swallowing Power

Fluid dynamics (i.e. fluid flow) is the natural science of liquids and gases in motion. Fluid dynamics may be applied to the study of pharyngeal bolus movement by treating swallowed boluses as biofluids^{18,19,20}. Biofluid dynamics (i.e. the science of fluid flow in biological fluids) have already facilitated the understanding of human circulatory, respiratory and digestive systems²¹. Hence, the application of biofluid dynamics for studying pharyngeal swallowing follows precedents in other fields of human physiology.

Physiological hydraulic power systems are an important application of biofluid dynamics. In hydraulic power systems, liquids under pressure control and transmit power. For example, the cardiovascular system is a hydraulic power system with the heart acting as a pump. Hydraulic power (as a function of time) is calculated as the product of pressure and volumetric flow rate (Equation 1).

$$\text{Hydraulic power, } P(t) = p(t)Q(t) \quad (\text{Equation 1})$$

where p is pressure in pascals (Pa, where $\text{Pa} = \text{N/m}^2$) and Q is volumetric flow rate in m^3/s measured at time t respectively. In the cardiovascular system, cardiac power can be measured as the product of mean arterial pressure and cardiac output (or cardiac index) from the pulmonary artery²² or as the product of blood pressure and flow in the proximal aorta²³.

The pharyngeal phase of swallowing is a pressure-driven event that is similar to cardiac systole, with material propulsion occurring by means of the action of an anatomical pump.

Harvey was one of the first to note that the rapid sequence of events that occur during swallowing resembles that of the cardiac cycle²⁴. McConnel, in a seminal paper identifying tongue driving pressure and the partial vacuum developed in UES opening as primary mechanisms for pharyngeal bolus transit, also compared the rapid events of the pharyngeal phase to the cardiac cycle⁵. Indeed, the coupling of the heart with the pulmonary artery and aorta during the cardiac cycle is analogous to the coupling of the pharynx with the open UES during the pharyngeal phase of swallowing (Figure 1 and 2). In the pharynx, mechanical power is converted into hydraulic power as rapid movements within the swallowing mechanism synergistically propel the bolus through the UES and into the proximal esophagus. Thus, the pharyngeal swallowing mechanism is also a physiological hydraulic power system with the pharyngeal swallowing mechanism acting as a propulsion pump to drive the bolus into the UES and esophagus. As such, a novel biofluid dynamics measure of pharyngeal swallowing function, pharyngeal swallowing power (PSP) (as a function of time), may be derived by taking the product of UES bolus pressure (p_{bolus}) and flow (Q_{bolus}) during deglutition (Equation 2), where

$$\text{Pharyngeal swallowing power, } PSP(t) = p_{bolus}(t)Q_{bolus}(t) \quad (\text{Equation 2})$$

where p_{bolus} is pressure in pascals (Pa, where Pa = N/m²) and Q_{bolus} is volumetric flow rate in m³/s measured at time t respectively.

B) Determining the Measurement Consistency of PSP

Study participants—The study recruited young healthy volunteers aged 21 – 40 years. Potential subjects were screened via standard questionnaire to exclude any history of swallowing disorder, food allergies, or allergy to topical anesthetic. The local Institutional Review Board (IRB) reviewed and approved the study. All subjects signed an approved informed consent form.

Equipment—A solid-state high-resolution impedance manometry (HRIM) catheter was used with the ManoScan™ 360 High-Resolution Manometry (HRM) System (Given Imaging, Atlanta, GA). The catheter had an outer diameter of 4.2 mm, consisting of 36 circumferential pressure sensors at 1 cm intervals and 18 impedance segments at 2 cm intervals. Each pressure sensor spanned 2.5 mm and received input from 12 circumferential sectors. Calibration was completed prior to each data collection to measure pressure against atmospheric pressure between –20 and 600 mmHg, with fidelity of 2 mmHg. Pressure from each sensor was recorded at a sampling rate of 50 Hz. However, as the system response capability of ManoScan is 100 Hz, the software automatically imputes data for output at 100 Hz.

Test materials—Test materials were prepared 60 minutes before scheduled data collection sessions by following a standard procedure and formula in order to maintain consistency and to minimize variability between subjects. A 10 % NaCl saline solution was first prepared by mixing 11.8 g of NaCl (table salt) into 4 Oz (118 mL) of distilled water. A 1 qt. bottle (32 Oz (946 mL)) of Lemon Lime Gatorade Thirst Quencher (The Gatorade Co., Chicago, IL)

(used to improve palatability) was added to the saline solution to obtain a Gatorade-saline mixture composed of approximately 1 % NaCl. An 8 Oz portion of the Gatorade-saline mixture was then set aside for use as thin liquid test material. Following manufacturer-provided formula, 2 tablespoons (9 g), 3 tablespoons (13 g), and 4 tablespoons (18 g) of a commercially available food thickener (THICK & EASY® Instant Food & Beverage Thickener, Hormel Health Labs, Savannah, GA) were then added to three additional 8 Oz portions of Gatorade-saline mixture to make nectar-thick liquid, honey-thick liquid and pudding test materials respectively. Detailed rheological analyses (including apparent viscosity, density, Bostwick consistency, and texture) established clear rheological differentiation between test materials. Apparent viscosity tested at a spindle revolution rate of 100 rpm using a Brookfield DV-II PRO Viscometer (Brookfield Engineering Labs, Inc., Middleboro, MA) with different spindles used for thin liquid, nectar-thick liquid, honey-thick liquid and pudding, were 13 cP, 301 cP, 2360 cP, and 11260 cP respectively. Luer-Lok™ tip syringes (BD, Franklin Lakes, NJ) were filled and set-aside for 45 min to allow for the viscosity of test materials to reach stability before data collection ²⁵.

Data Collection—Subjects were instructed not to eat for 4 hours or drink for 2 hours before presenting for data collection in order to minimize the risk of gastric reflux and any confounding effect of satiety ^{7,14}. To optimize subject comfort, transnasal catheter placement proceeded after application of topical 2% viscous lidocaine hydrochloride to the nasal passages using a cotton swab. The effect of a small quantity of viscous lidocaine (less than 1 cc) on swallowing has been shown to be negligible ^{7,26,27}. Viscous lidocaine was also applied to the tip of the catheter as an anesthetic and lubricant to facilitate passage through the nasal cavity and pharynx.

Subjects were familiarized with the data collection process by taking in distilled water from a syringe while they acclimatized to the catheter in situ. Sitting upright for the study, subjects were instructed to close their lips around the tip of the syringe and water was deposited at a steady rate. Subjects were asked to hold the water bolus on their tongue and not to allow the bolus to go under their tongue when swallowing (i.e. tipper swallow) ²⁸. Subjects were then instructed to swallow the bolus in a single attempt on the command “Swallow” (i.e. cued volitional swallowing).

Data collection commenced upon completion of two practice (water) boluses. Subjects were presented with five trials of eight bolus types (40 boluses in total): 10 mL and 20 mL thin liquid, nectar-thick liquid, honey-thick liquid, and pudding test materials. The order of presentation was partially counterbalanced for volume and viscosity across trials such that the order began and ended with different bolus volumes and viscosities across trials one to five. A 10 second pause was given after each swallow to minimize potential carryover effect and subjects were offered sips of water after each trial (i.e. after swallowing eight boluses). Data collection concluded when all 40 test boluses have been presented, typically within 20 minutes.

Data Extraction—Data collected were reviewed offline using ManoScan. Settings were adjusted to concurrently display pressure and impedance data on the spatiotemporal plot, and to display pressure data from –10 mmHg to 300 mmHg on pressure line plots for all

sensors. The location of the UES high-pressure zone (UESHPZ) can be identified on the spatiotemporal plot as the band of warm colors (e.g. red and yellow) sandwiched between cold colors (e.g. blue) associated with the pharynx proximally, and the esophagus distally (Figure 2). Cursors on the linear sensor locator were aligned with the location of individual pressure sensors within and surrounding the UEHPZ to allow examination of pressures registered at individual sensors. The pressure sensor registering the highest pressure in the UESHPZ approximated the location of the cricopharyngeus muscle responsible for the UES resting (baseline) pressure (Figure 3). As the UES is known to displace rostrally during swallowing²⁹, the sensor recording the highest pressure prior to swallow-related reduction in pressure was identified for measurement of UES intrabolus pressure (Figure 3). Confirmation of UES location during the swallow was achieved by examining the high-pressure peak indicating UES closure following the swallow. All impedance and manometric measures were completed in MATLAB (The MathWorks, Inc., Natick, MA).

Measures

a) Bolus flow interval: Bolus flow measures were assessed at the intraluminal impedance channel co-located with the pressure sensor identified for measuring UES intrabolus pressure (Figure 3).

Pharyngeal bolus transit time can be estimated most reliably by MII using a criteria of 50% drop of impedance from baseline to indicate bolus entry, and recovery to 25% of baseline to indicate bolus clearance¹⁷. These criteria had been shown to detect bolus entry and clearance of semisolid (i.e. pudding consistency) boluses within the UES reliably when compared with measurements taken using videofluoroscopy (entry: $r = 0.737$, $P < 0.0001$; clearance: $r = 0.761$, $P < 0.0001$). Although Omari et al. had reported that the reliability of detecting liquid entry into the pharynx may be reduced due to the presence of air trapped within the moving bolus¹⁷, this is less problematic for detecting bolus entry into the UES since the UES is typically occluded and bolus entry occurs rapidly after UES opening. Furthermore, even though absolute impedance values may differ depending on catheter characteristics (e.g. electrode width, diameter and spacing), relative drop in impedance (i.e. percent change) due to bolus contact is likely to remain the same³⁰. Therefore, in this study, UES bolus flow interval (FI), T, was measured as the time interval between bolus entry and clearance with a 50% impedance drop from baseline indicating bolus entry, and recovery to 25% of baseline indicating bolus clearance (Figure 4). UES bolus flow interval was measured in seconds (s).

b) Volume flow rate: Volume flow rate (VFR), Q, was calculated by dividing bolus volume (V) by bolus flow interval (T) (Equation 3). This provided a mean flow rate that assumed bolus flow at a constant rate through the UES. VFR was measured in mLs⁻¹ and converted to cubic meters per second (m³s⁻¹) for calculating pharyngeal swallowing power.

$$Q = V/T \quad (\text{Equation 3})$$

c) Intrabolus pressure: Pressure assessed at the time point corresponding to nadir UES impedance indicated peak UES intrabolus pressure (pIBP), $P^{31,32}$ (Figure 5). Omari et al. have shown that nadir impedance during bolus swallow identifies the center of a swallowed bolus in both time and space. Hence the pressure at nadir impedance corresponds to the pressure during passage of the bolus center^{31,32}. An offset in manometric and impedance signal timings was noted during Manoscan review of the data collected. Although bench tests confirmed that this technical issue did not negatively impact data quality, pIBP measurements had to be taken at 11 data points before the time point of nadir UES impedance to account for the timing offset between onset of pressure and impedance signals. pIBP was measured in millimeter mercury (mmHg) and converted to pascal (Pa) for calculating pharyngeal swallowing power.

d) Pharyngeal swallowing power: To ascertain pharyngeal swallowing power (PSP), the UES was conceptualized as a conduit for the pressurized bolus. PSP was calculated as the product of pIBP and VFR (Equation 4) and measured in milliwatts (mW).

$$PSP(t) = pIBP(t) (P) \times VFR(t) (Q) \quad (\text{Equation 4})$$

where $pIBP$ is peak UES intrabolus pressure in pascals (Pa) and VFR is volumetric flow rate in cubic meters per second (m^3s^{-1}) measured at time t respectively.

Statistical Analyses—Descriptive statistics were used to provide of an overview of all extracted and calculated data (i.e. bolus flow interval (FI), volume flow rate (VFR), intrabolus pressure (pIBP) and pharyngeal swallowing power (PSP)). Cronbach coefficient alpha was then used for evaluating consistency of PSP across five repeated swallow trials in each specific bolus condition. Cronbach's coefficient alpha estimates consistency by determining the average correlation of PSP measurements across trials³³. Cronbach's alpha is equivalent to using intraclass correlation coefficient (ICC) to assess reliability of a mean or sum of measurements per subject. However, Cronbach's alpha is preferred over ICC when parallelism of observations (i.e. constancy of the measurement across time) is not assumed³⁴. Fisher z normalizing transformation was used to estimate 95% confidence intervals for coefficient alphas. The Fisher method has been shown to be a conservative approach for confidence interval estimation³⁵. Fisher transformation was also applied to estimate weighted mean coefficient alphas across bolus volumes and bolus viscosities. Similarly, Fisher transformation was used to estimate a weighted mean coefficient alpha for an overall estimate of consistency for PSP across all bolus conditions³⁶.

Three different benchmark scales for qualitative characterization of agreement (originally developed for Kappa coefficients)^{37,38,39} were used to help interpret the strength of agreement from Cronbach coefficient alpha statistics. As there is no consensus on the threshold consistency level that marks a clinical measure as being useful^{40,41,42}, two levels were adopted in this study as references to assist in the interpretation of consistency estimates obtained for PSP. An initial reference level of .70 was adopted based on recommendations of Nunnally and Bernstein that modest consistency in the early stages of predictive or construct validation research may be adequate^{43,44}. Subsequently, consistency

estimates were evaluated at the reference level of .90 on the recommendations of Portney and Watkins to ensure validity and reproducibility in clinical measurements ⁴⁵.

Results

Subjects

Swallow studies were successfully completed in 34 subjects (18 female: mean age 22.9 years, SD 2.4 years, range 21 – 28 years; 16 male: mean age 27.2 years, SD 5.5 years, range 21 – 39 years).

Final Dataset

Analyses were completed for 1289 swallow trials obtained across subjects (95 % of all possible data). Trials in which subjects did not swallow or were omitted due to subject request (e.g. 20 mL pudding trials were difficult for some subjects) were treated as missing data. Trials in which two or more swallow attempts were made precluded the calculation of volume flow rate (VFR) for individual swallows and were also treated as missing data. The proportion of missing data in specific bolus conditions ranged from 1 % to 17 % (Mean 5.2 % SD 5.4 %). 83 % of the missing data were from 20 mL volume condition. 51 % of the missing data were from pudding viscosity condition. 20 ml pudding viscosity bolus condition accounted for most missing data (41 %). Two subjects contributed to 42 % of the missing data.

Descriptive Statistics

Mean bolus flow interval (FI) across all subjects and bolus conditions was 0.54 s (SD 0.17 s) (Table 1). Mean volume flow rate (VFR) was 29.1 mLs⁻¹ (SD 14.4 mLs⁻¹) and was smaller (i.e. slower) in the 10 mL bolus condition than in the 20 mL bolus condition (Table 1). Mean peak intrabolus pressure (pIBP) was 19.9 mmHg (SD 9.75 mmHg) (Table 1). Mean PSP was 78.8 mW (SD 54.9 mW). Mean PSP was greater in the 20 mL bolus condition than in the 10 mL bolus condition and increased with increasing bolus viscosity (Table 1).

Consistency of Pharyngeal Swallowing Power across Repeated Evaluations

Standardized Cronbach coefficient alphas providing estimates of PSP consistency across five repeated swallow trials in specific bolus conditions ranged between .85 and .93 (Table 2). Standardized Cronbach coefficient alphas were used as an adjustment for unequal variances across trials ⁴⁶. Fisher weighted mean Cronbach coefficient alphas for trials across both bolus volumes and across all bolus viscosities ranged from .86 to .90 (Table 3). Fisher weighted mean Cronbach coefficient alpha for overall consistency of PSP across all swallow trials was 0.88.

Discussion

Pharyngeal swallowing power (PSP) is a novel biofluid dynamics measure of deglutitive bolus-driving function. PSP is derived from UES bolus flow interval (FI), volume flow rate (VFR) and peak intrabolus pressure (pIBP). This study explained how PSP is analogous to cardiac power and demonstrated how data obtained from high-resolution impedance

manometry (HRIM) may be used to calculate PSP. PSP showed high levels of measurement consistency over repeated trials across a variety of bolus conditions in normal deglutition, indicating a potential for future clinical and research applications.

This study described the theoretical basis and derivation of PSP from UES bolus FI, VFR and pIBP – measures that are obtainable from HRIM. Current results complemented the advances made by Omari and colleagues in the application of MII and HRIM to pharyngeal swallowing. Omari et al. were the first to study pharyngeal pressure-flow in normal swallowing and swallowing in patients with dysphagia using HRIM^{14,15,17,31,32,47,48,49,50,51,52}. Omari et al. found that different pressure-flow variables were affected when post swallow pharyngeal residue was present in healthy individuals (e.g., increased pharyngeal intrabolus pressure) vs. dysphagia patients (e.g., prolonged UES relaxation interval)³². As such, it is not feasible to use any single pressure-flow measure to differentiate normal and abnormal swallowing. For this reason, the value of individual pressure-flow measures for assessing dysphagia severity and predicting swallowing and clinical outcomes may also be limited. Nevertheless, Omari et al. derived a mathematical swallow risk index (SRI) that included a reduced set of pressure-flow measures obtained from superimposed pressure-impedance time plots (e.g., flow interval, pressure at nadir impedance, hypopharyngeal intrabolus pressure)^{31,50}. However, although the SRI has shown promise in clinical applications (i.e. identifying aspiration and pharyngeal residue), it is fundamentally a risk measure and not a direct measure of the physical function of the pharyngeal swallowing mechanism. To obtain such a measure, a return to the fundamental concepts commonly used to evaluate other aspects of human performance (e.g., force, velocity, power) is necessary.

PSP uses bolus pressure and flow to estimate an important physical property of the bolus - i.e. fluid power - during deglutition. In normal swallowing, the UES is pulled open by the action of the suprahyoid muscle complex prior to the arrival of the bolus head. The bolus transits from the hypopharynx into the open UES with minimal downstream resistance. Thus, PSP is an estimate of the output power of the pharyngeal bolus-driving mechanism during deglutition. Any factor that leads to a reduction in VFR or pIBP (e.g., reduced pharyngeal bolus propulsion) may result in reduced PSP. Conversely, high PSP may not necessarily indicate a normal swallowing mechanism. For example, normal pharyngeal bolus propulsion in the presence of reduced UES opening may lead to elevated pIBP and result in high PSP. Rather, normal swallowing function may be associated with a PSP that is constrained within a normative range. These hypotheses will need to be verified in future clinical studies that may include the application of both HRIM and videofluoroscopy (e.g., to assess UES opening).

Results in this study indicated that the pharyngeal mechanism swallows boluses of a larger volume and/or greater viscosity with greater power than when swallowing smaller, less viscous boluses. These bolus-related changes in bolus dynamics may have resulted directly from the physical characteristics of different bolus themselves, or indirectly as a result of physiological bolus accommodation of the pharyngeal mechanism that is associated with swallowing different bolus types. Future in-depth analyses of the variation of VFR and pIBP

across bolus types are already planned and are expected to provide greater insight to the cause of variation in PSP associated with different bolus volumes and viscosities.

Current results demonstrated that PSP is highly consistent across repeated evaluations for all bolus volume and viscosity conditions. All consistency estimates met the criteria for the greatest strength of agreement for the three benchmark scales of agreement referenced ^{37,38,39}. All consistency estimates also exceeded the critical reference level of .70 used to indicate adequate consistency across measurements in preliminary research. Reliability and validity are key characteristics of measurements and measuring instruments. However, the upper limit of a measurement's validity has been shown to be a function of reliability ⁵³. Current results show that reliability of PSP is unlikely to be a significant limitation for validity. Furthermore, overall consistency of PSP and average consistency across bolus volume and viscosities either approximated or met the reference level of .90 for ensuring validity and reproducibility in clinical measurements ⁴⁵. Average consistency differed minimally across bolus volume and bolus viscosity conditions (.86 - .90), indicating that PSP to be a reliable measure of pharyngeal bolus-driving function regardless of the characteristics of the swallowed bolus.

PSP consistency is high although variability in swallowing physiology for healthy individuals has been well-documented ^{54,55}. For example, Söder and Miller found that durational aspects of tongue movement varied considerably during swallowing ⁵⁵. Similarly, Stephen et al. reported that bolus position at the point of pharyngeal swallow onset (i.e. triggering of involuntary swallow reflex) could vary substantially from trial to trial within an individual. Stephen et al. concluded that the triggering of swallowing depends on multiple influences and not merely the location of the bolus ⁵⁶. Physiological variability in swallowing may not be surprising given that multiple cortical and sub-cortical activations and interactions are associated with swallowing, ^{57,58,59,60}. In addition, swallowing has been shown to be a submaximal task, particularly with respect to pressure generation ^{61,62,63}. As such, there is considerable potential for swallowing physiology to be influenced by factors such as fatigue and fluctuations in the test environment or cognitive state (e.g. attention to task and level of anxiety). Taken together, swallowing behavior appears to be a highly adaptive with potential for significant trial-to-trial variability. As such, variability in PSP may also have been expected. However, our results showed that PSP is highly consistent across bolus conditions within individuals. This corroborates findings of Molfenter and Steele that the degree of variability differs across different measures of swallowing physiology ⁶⁴. High PSP consistency across trials indicates that pharyngeal bolus propulsion is a relatively stable function in contrast to high variability in other aspects of swallowing physiology. According to the minimal intervention principle of motor control, the sensorimotor system preferentially controls task-relevant parameters while allowing task-irrelevant ones to fluctuate in order to meet task demands while minimizing control effort ⁶⁵. As swallowing and respiration functions both require utilization of a common pharyngeal space, high PSP consistency appear to demonstrate that consistent pharyngeal bolus propulsion is necessary for intricate coordination with respiratory function to ensure airway protection. Therefore, pharyngeal bolus propulsion may be prioritized over other aspects of swallowing physiology in order to ensure safe and efficient bolus transition into the esophagus and prevent pulmonary aspiration.

High PSP consistency may be an indicator of normal swallowing function in healthy individuals. Studies of motor function in cognitive aging have associated reduced consistency in movement production with functional decline and aging ⁶⁶. Hausdorff, Rios and Edelberg reported increased variability in stride time in elderly community-living, ambulatory individuals who subsequently fell during the 12-month follow-up period ⁶⁷. Similarly, Krampe, Mayr and Kliegl reported increased timing variabilities for complex sequence tasks in healthy older adults ⁶⁸. In the swallowing literature, reduced consistency of swallowing physiology has similarly been found in 'at risk' patient and elderly populations. White et al. reported that consistency of orolingual swallowing pressure were lower in newly diagnosed head and neck cancer patients compared to controls ⁶⁹. On the other hand, Adams found lower consistency in tongue strength for elderly vs. young adults when assessed using the Iowa Oral Performance Instrument ⁷⁰. Hence, consistency of swallow physiology may be lower in individuals with swallowing dysfunction or pre-clinical functional decline. Since current results showed that consistency of PSP in healthy individuals is high, a reduction of PSP consistency across trials may indicate a decline in swallowing function. Future studies of PSP in subjects with known swallowing dysfunction and in the elderly population will be needed to substantiate this hypothesis.

A limitation of PSP is that it is dependent on the bolus being swallowed completely. PSP cannot be determined when the bolus is swallowed piecemeal or if there is reduced clearance with oral or pharyngeal residue. However, in individuals who can swallow at least specific bolus types completely (e.g. only small, viscous boluses), PSP may be useful as a measure for quantifying physiological change. These individuals may include patients with mild or moderate dysphagia who are undergoing swallowing rehabilitation, as well as patients in early and mid-stages of neurodegenerative diseases (e.g. Parkinson Disease ⁷³), or pre-clinical populations whose swallowing are broadly functional but may be deteriorating (e.g. elderly or pre-clinical Parkinson Disease ^{71,72}). Nevertheless, the utility of PSP for measuring physiological change in patients with dysphagia and pre-clinical populations remain to be properly evaluated.

Wide standard deviation in PSP in our results indicates variability across individuals among the healthy population. As PSP did not differ between female and male participants, it is less likely that this variability is associated with anatomical (size) differences of the pharyngeal swallowing mechanism, and more likely to do with physiological differences and/or behavioral preferences. Variability of PSP across healthy individuals increases the possibility of overlap between the ranges of PSP in healthy individuals and clinical populations with swallowing dysfunction. The underlying cause for PSP variation between healthy individuals as well as in individuals with dysphagia will need to be further evaluated. If significant overlap in PSP truly exists between healthy and patient populations, the underlying factors and the clinical significance of such an overlap should also be examined.

PSP measures the output power of the pharyngeal swallowing mechanism, but other possible measures of output power can also be derived using MII and HRIM metrics. PSP is specifically an estimate of fluid power at the center of a swallowed bolus during UES transit. Other possible measures of output power, including average and peak fluid power, may have their scientific and clinical merits, but may be more complex in terms of their computation.

The value of the various measures of pharyngeal output power may be enhanced also if their physiological sources within the pharyngeal swallowing mechanism and their relative contributions can be established in future studies.

Before PSP can be utilized as a measure of swallowing physiology, further evaluation for measurement adequacy should be done pertaining to its accuracy, precision, validity and interrater consistency^{74,75}. The quality and usefulness of PSP as a measure can also be improved by examining the degree of uncertainty in PSP (i.e. the range of the values that could reasonably be attributed to the measured PSP)⁷⁶. Detailed uncertainty analysis will identify sources of uncertainty (e.g. instrumentation, test environment, measurement process and evaluator skill), determine their relative impact on the measurement of PSP, and enable the reduction of uncertainty in PSP estimation.

In conclusion, PSP is a novel biofluid dynamics measure of deglutitive bolus-driving function derived from UES bolus flow interval, volume flow rate and peak intrabolus pressure. PSP is advantageous for assessing pharyngeal bolus-driving function over measures of pharyngeal pressures and their derivatives because pharyngeal pressures have primarily a pharyngeal bolus-clearing function rather than a bolus-driving function. PSP is an estimate of a fundamental physical property of the moving bolus resulting directly from the pharyngeal bolus-driving function. Current results revealed high PSP consistency over repeated evaluations, demonstrating its potential as a useful measure of pharyngeal bolus-driving function. Systematic psychometric evaluation and detailed uncertainty analyses are priorities for future studies as prerequisites of clinical utility for this new measure.

Acknowledgements

The authors wish to thank Corinne Jones and Suzan Abdelhalim for their generous technical and administrative support provided throughout the study.

Funding

- This study was jointly funded by a University of Wisconsin-Madison Department of Surgery grant (to TM) and a National Institutes of Health (NIH) R21/R33 Phased Innovation Award (to TM).
- IS was jointly funded by a Singapore Ministry of Health Allied Health Postgraduate Scholarship and a National University Hospital (Singapore) Talent Development Award.

Abbreviations

PSP	Pharyngeal swallowing power
UES	Upper esophageal sphincter
HRM	High-resolution manometry
HRIM	High-resolution manometry with impedance
MII	Multichannel intraluminal impedance
IRB	Institutional Review Board
P(t)	Hydraulic power as a function of time

p	Symbol for UES bolus pressure
Q	UES bolus flow or symbol for volume flow rate
FI	Bolus flow interval
VFR	Volume flow rate
V	Bolus volume
T	Bolus flow interval
P	Symbol for UES intrabolus pressure
pIBP	Peak UES intrabolus pressure
t	Time
ICC	intraclass correlation coefficient
SRI	Swallow risk index

References

1. Atkinson M, Kramer P, Wyman SM, Ingelfinger FJ. The dynamics of swallowing. I. Normal pharyngeal mechanisms. *Journal of Clinical Investigation*. 1957;36(4):581. [PubMed: 13416388]
2. Orlowski J, Dodds WJ, Lineman JH, Dent J, Hogan WJ, Arndorfer RC. Requirements for accurate manometric recording of pharyngeal and esophageal peristaltic pressure waves. *Investigative radiology*. 1982;17(6):567–571. [PubMed: 7152861]
3. Cook I, Dodds W, Dantas R, et al. Opening mechanisms of the human upper esophageal sphincter. *Am J Physiol*. 11 1989;257(5 Pt 1):G748–759. [PubMed: 2596608]
4. Donner MW, Bosma JF, Robertson DL. Anatomy and physiology of the pharynx. *Gastrointest Radiol*. 1985;10(3):196–212. [PubMed: 4029536]
5. McConnel FM. Analysis of pressure generation and bolus transit during pharyngeal swallowing. *Laryngoscope*. 1 1988;98(1):71–78. [PubMed: 3336265]
6. Cerenko D, McConnel FM, Jackson RT. Quantitative assessment of pharyngeal bolus driving forces. *Otolaryngol Head Neck Surg*. 1 1989;100(1):57–63. [PubMed: 2493617]
7. Hoffman MR, Mielens JD, Ciucci MR, Jones CA, Jiang JJ, McCulloch TM. High-Resolution Manometry of Pharyngeal Swallow Pressure Events Associated with Effortful Swallow and the Mendelsohn Maneuver. *Dysphagia*. 1 2012.
8. Cook IJ. Combined Pharyngeal Impedance-Manometry: Has It Finally Come of Age? *Clinical Gastroenterology and Hepatology*. 2011;9(10):813–815. [PubMed: 21723235]
9. Hoffman MR, Ciucci MR, Mielens JD, Jiang JJ, McCulloch TM. Pharyngeal swallow adaptations to bolus volume measured with high-resolution manometry. *Laryngoscope*. 12 2010;120(12):2367–2373. [PubMed: 21108425]
10. Geng Z, Hoffman MR, Jones CA, McCulloch TM, Jiang JJ. Three-Dimensional Analysis of Pharyngeal High-Resolution Manometry Data. *The Laryngoscope*. 2013;123(7):1746–1753. [PubMed: 23417441]
11. Takasaki K, Umeki H, Hara M, Kumagami H, Takahashi H. Influence of Effortful Swallow on Pharyngeal Pressure: Evaluation Using a High-Resolution Manometry. *Otolaryngology -- Head and Neck Surgery*. 2011;144(1):16–20. [PubMed: 21493381]
12. McCulloch TM, Hoffman MR, Ciucci MR. High-resolution manometry of pharyngeal swallow pressure events associated with head turn and chin tuck. *Ann Otol Rhinol Laryngol*. 6 2010;119(6):369–376. [PubMed: 20583734]

13. Ghosh SK, Pandolfino JE, Zhang Q, Jarosz A, Kahrilas PJ. Deglutitive upper esophageal sphincter relaxation: a study of 75 volunteer subjects using solid-state high-resolution manometry. *Am J Physiol Gastrointest Liver Physiol*. 9 2006;291(3):G525–531. [PubMed: 16645162]
14. Omari TI, Kritas S, Cock C, et al. Swallowing dysfunction in healthy older people using pharyngeal pressure-flow analysis. *Neurogastroenterol Motil*. 1 2014;26(1):59–68. [PubMed: 24011430]
15. Omari T, Dejaeger E, Tack J, Beckevoort D, Rommel N. Effect of Bolus Volume and Viscosity on Pharyngeal Automated Impedance Manometry Variables Derived for Broad Dysphagia Patients. *Dysphagia*. 2013/6/01 2013;28(2):146–152. [PubMed: 22986957]
16. Nativ-Zeltzer N, Kahrilas P, Logemann J. Manofluorography in the Evaluation of Oropharyngeal Dysphagia. *Dysphagia*. 2012/6/01 2012;27(2):151–161. [PubMed: 22527220]
17. Omari TI, Rommel N, Szczesniak MM, et al. Assessment of intraluminal impedance for the detection of pharyngeal bolus flow during swallowing in healthy adults. *American Journal of Physiology-Gastrointestinal and Liver Physiology*. 2006;290(1):G183–G188. [PubMed: 16141366]
18. Tripathi D A mathematical model for the movement of food bolus of varying viscosities through the esophagus. *Acta Astronautica*. 2011/9/01/ 2011;69(7):429–439.
19. Misra JC, Maiti S. Peristaltic transport of rheological fluid: model for movement of food bolus through esophagus. *Applied Mathematics and Mechanics*. 2012/3/01 2012;33(3):315–332.
20. Misra JC, Pandey SK. A mathematical model for oesophageal swallowing of a food-bolus. *Mathematical and Computer Modelling*. 2001/4/01/ 2001;33(8):997–1009.
21. Goyal MR. *Biofluid Dynamics of Human Body Systems*. Vol 1: CRC Press; 2013.
22. Fincke R, Hochman JS, Lowe AM, et al. Cardiac power is the strongest hemodynamic correlate of mortality in cardiogenic shock: A report from the SHOCK trial registry. *Journal of the American College of Cardiology*. 2004;44(2):340–348. [PubMed: 15261929]
23. Rimehaug AE, Lyng O, Nordhaug DO, Løvstakken L, Aadahl P, Kirkeby-Garstad I. Cardiac power integral: a new method for monitoring cardiovascular performance. *Physiological reports*. 2013;1(6).
24. Harvey W *Exercitatio anatomica de motu cordis et sanguinis in animalibus*. Frankfurt am Main. 1928;1628.
25. O'Leary M, Hanson B, Smith CH. Variation of the apparent viscosity of thickened drinks. *International Journal of Language & Communication Disorders*. 2011;46(1):17–29. [PubMed: 20565232]
26. Jones CA, Hammer MJ, Hoffman MR, McCulloch TM. Quantifying contributions of the cricopharyngeus to upper esophageal sphincter pressure changes by means of intramuscular electromyography and high-resolution manometry. *Ann Otol Rhinol Laryngol*. 3 2014;123(3):174–182. [PubMed: 24633943]
27. Hammer MJ, Jones CA, Mielens JD, Kim CH, McCulloch TM. Evaluating the tongue-hold maneuver using high-resolution manometry and electromyography. *Dysphagia*. 10 2014;29(5):564–570. [PubMed: 24969727]
28. Dodds WJ, Taylor AJ, Stewart ET, Kern MK, Logemann JA, Cook IJ. Tipper and dipper types of oral swallows. *AJR Am J Roentgenol*. 12 1989;153(6):1197–1199. [PubMed: 2816632]
29. McCulloch TM, Hoffman MR, Ciucci MR. High resolution manometry of pharyngeal swallow pressure events associated with head turn and chin tuck. *The Annals of otology, rhinology, and laryngology*. 2010;119(6):369.
30. Szczesniak MM, Rommel N, Dinning PG, Fuentealba SE, Cook IJ, Omari TI. Optimal criteria for detecting bolus passage across the pharyngo-oesophageal segment during the normal swallow using intraluminal impedance recording. *Neurogastroenterology & Motility*. 2008;20(5):440–447. [PubMed: 18179611]
31. Omari TI, Dejaeger E, van Beckevoort D, et al. A method to objectively assess swallow function in adults with suspected aspiration. *Gastroenterology*. 2011;140(5):1454–1463. [PubMed: 21354152]
32. Omari TI, Dejaeger E, Van Beckevoort D, et al. A novel method for the nonradiological assessment of ineffective swallowing. *Am J Gastroenterol*. 10 2011;106(10):1796–1802. [PubMed: 21556039]
33. Cronbach L Coefficient alpha and the internal structure of tests. *Psychometrika*. 1951/9/01 1951;16(3):297–334.

34. Bravo G, Potvin L. Estimating the reliability of continuous measures with Cronbach's alpha or the intraclass correlation coefficient: toward the integration of two traditions. *J Clin Epidemiol*. 1991;44(4-5):381-390. [PubMed: 2010781]
35. Kromrey JD, Romano J, Hibbard ST. ALPHA_CI: A SAS® macro for computing confidence intervals for coefficient alpha. *matrix*. 2008;2(2):2.
36. Faller AJ. An average correlation coefficient. *Journal of Applied Meteorology*. 1981;20(2):203-205.
37. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics*. 3 1977;33(1):159-174. [PubMed: 843571]
38. Altman DG. *Practical statistics for medical research*. CRC press; 1990.
39. Fleiss JL. The measurement of interrater agreement. *Statistical methods for rates and proportions*. 1981;2:212-236.
40. Cleophas TJM, Zwinderman AH, Cleophas TF, Cleophas EP. *Statistics applied to clinical trials*. Springer; 2006.
41. Bruton A, Conway JH, Holgate ST. Reliability: What is it, and how is it measured? *Physiotherapy*. 86(2):94-99.
42. Chinn S *Statistics in respiratory medicine*. 2. Repeatability and method comparison. *Thorax*. 1991;46(6):454-456. [PubMed: 1858087]
43. Nunnally JC, Bernstein IH, Berge JMFt. *Psychometric theory*. Vol 226: McGraw-Hill New York; 1967.
44. Iacobucci D, Duhachek A. Advancing alpha: Measuring reliability with confidence. *Journal of consumer psychology*. 2003;13(4):478-487.
45. Portney LG, Watkins MP. *Foundations of clinical research: applications to practice Vol 2*: Prentice Hall Upper Saddle River, NJ; 2000.
46. Falk CF, Savalei V. The relationship between unstandardized and standardized alpha, true reliability, and the underlying measurement model. *J Pers Assess*. Sep-Oct 2011;93(5):445-453. [PubMed: 21859284]
47. Hoffman MR, Mielens JD, Omari TI, Rommel N, Jiang JJ, McCulloch TM. Artificial neural network classification of pharyngeal high-resolution manometry with impedance data. *Laryngoscope*. 3 2013;123(3):713-720. [PubMed: 23070810]
48. Omari TI, Dejaeger E, Tack J, Vanbeekevoort D, Rommel N. An impedance-manometry based method for non-radiological detection of pharyngeal postswallow residue. *Neurogastroenterology & Motility*. 2012;24(7):e277-e284. [PubMed: 22594606]
49. Szczesniak MM, Rommel N, Dinning PG, Fuentealba SE, Cook IJ, Omari TI. Intraluminal impedance detects failure of pharyngeal bolus clearance during swallowing: a validation study in adults with dysphagia. *Neurogastroenterology & Motility*. 2009;21(3):244-252. [PubMed: 18761629]
50. Noll L, Rommel N, Davidson GP, Omari TI. Pharyngeal flow interval: a novel impedance-based parameter correlating with aspiration. *Neurogastroenterol Motil*. 6 2011;23(6):551-e206. [PubMed: 21143556]
51. Omari TI, Papanthanasopoulos A, Dejaeger E, et al. Reproducibility and agreement of pharyngeal automated impedance manometry with videofluoroscopy. *Clin Gastroenterol Hepatol*. 10 2011;9(10):862-867. [PubMed: 21699810]
52. Omari TI, Ferris L, Dejaeger E, Tack J, Vanbeekevoort D, Rommel N. Upper esophageal sphincter impedance as a marker of sphincter opening diameter. *American Journal of Physiology-Gastrointestinal and Liver Physiology*. 2012;302(9):G909-G913. [PubMed: 22323128]
53. Lord FM, Novick MR, Birnbaum A. *Statistical theories of mental test scores*. 1968.
54. Gay T, Rendell JK, Spiro J. Oral and laryngeal muscle coordination during swallowing. *The Laryngoscope*. 1994;104(3):341-349. [PubMed: 8127193]
55. Söder N, Miller N. Using Ultrasound to Investigate Intrapersonal Variability in Durational Aspects of Tongue Movement During Swallowing. *Dysphagia*. 2002/12/01 2002;17(4):288-297. [PubMed: 12355144]

56. Stephen J, Taves D, Smith R, Martin R. Bolus Location at the Initiation of the Pharyngeal Stage of Swallowing in Healthy Older Adults. *Dysphagia*. 2005/10/01 2005;20(4):266–272. [PubMed: 16633870]
57. Lang I Brain Stem Control of the Phases of Swallowing. *Dysphagia*. 2009/9/01 2009;24(3):333–348. [PubMed: 19399555]
58. Michou E, Hamdy S. Cortical input in control of swallowing. *Current Opinion in Otolaryngology & Head and Neck Surgery*. 2009;17(3).
59. Paine PA, Hamdy S, Chitnis X, et al. Modulation of activity in swallowing motor cortex following esophageal acidification: a functional magnetic resonance imaging study. *Dysphagia*. 6 2008;23(2):146–154. [PubMed: 17955290]
60. Lowell SY, Poletto CJ, Knorr-Chung BR, Reynolds RC, Simonyan K, Ludlow CL. Sensory stimulation activates both motor and sensory components of the swallowing system. *Neuroimage*. 2008;42(1):285–295. [PubMed: 18515150]
61. Robbins J, Levine R, Wood J, Roecker EB, Luschei E. Age effects on lingual pressure generation as a risk factor for dysphagia. *J Gerontol A Biol Sci Med Sci*. 9 1995;50(5):M257–262. [PubMed: 7671027]
62. Nicosia MA, Hind JA, Roecker EB, et al. Age effects on the temporal evolution of isometric and swallowing pressure. *J Gerontol A Biol Sci Med Sci*. 11 2000;55(11):M634–640. [PubMed: 11078092]
63. Fei T, Polacco RC, Hori SE, et al. Age-related Differences in Tongue-Palate Pressures for Strength and Swallowing Tasks. *Dysphagia*. Vol 28 Boston2013:575–581. [PubMed: 23677389]
64. Molfenter S, Steele C. Temporal Variability in the Deglutition Literature. *Dysphagia* 2012/6/01 2012;27(2):162–177. [PubMed: 22366761]
65. Valero-Cuevas FJ, Venkadesan M, Todorov E. Structured Variability of Muscle Activations Supports the Minimal Intervention Principle of Motor Control. *Journal of Neurophysiology*. 2009;102(1):59–68. [PubMed: 19369362]
66. Krampe RT. Aging, expertise and fine motor movement. *Neuroscience & Biobehavioral Reviews*. 11// 2002;26(7):769–776. [PubMed: 12470688]
67. Hausdorff JM, Rios DA, Edelberg HK. Gait variability and fall risk in community-living older adults: A 1-year prospective study. *Archives of Physical Medicine and Rehabilitation*. 8// 2001;82(8):1050–1056. [PubMed: 11494184]
68. Krampe RT, Mayr U, Kliegl R. Timing, sequencing, and executive control in repetitive movement production. *J Exp Psychol Hum Percept Perform*. 6 2005;31(3):379–397. [PubMed: 15982121]
69. White R, Cotton SM, Hind J, Robbins J, Perry A. A comparison of the reliability and stability of oro-lingual swallowing pressures in patients with head and neck cancer and healthy adults. *Dysphagia*. 2009;24(2):137–144. [PubMed: 18956230]
70. Adams VJ. Reliability of the Iowa Oral Performance Instrument: Measuring tongue and handgrip strength and endurance in young and elderly adults. 2014.
71. Siderowf A, Lang Anthony E. Premotor Parkinson's disease: Concepts and definitions. *Movement Disorders*. 2012/4/15 2012;27(5):608–616. [PubMed: 22508279]
72. Wu Y, Le W, Jankovic J. Preclinical biomarkers of parkinson disease. *Archives of Neurology*. 2011;68(1):22–30. [PubMed: 21220674]
73. Jones CA, Ciucci MR. Multimodal swallowing evaluation with high-resolution manometry reveals subtle swallowing changes in early and mid-stage Parkinson disease. *Journal of Parkinson's disease*. 2016;6(1):197–208.
74. Trajkovi G Measurement: Accuracy and Precision, Reliability and ValidityMeasurement: accuracy and precision, reliability and validity. In: Kirch W, ed. *Encyclopedia of Public Health*: Springer Netherlands; 2008:888–892.
75. Myers JB, Oyama S, Wassinger CA, et al. Reliability, precision, accuracy, and validity of posterior shoulder tightness assessment in overhead athletes. *Am J Sports Med*. 11 2007;35(11):1922–1930. [PubMed: 17609529]
76. Coleman HW, Steele WG. Experimentation, validation, and uncertainty analysis for engineers. John Wiley & Sons; 2009.

Key Points

- A definitive measure of pharyngeal bolus-driving function that accounts for bolus movement remains lacking. The primary objectives of this study were to describe the derivation of a novel biofluid dynamics measure of deglutition – i.e. pharyngeal swallowing power (PSP) – and to demonstrate the consistency of PSP in normal swallowing.
- PSP is derived by conceptualizing the pharyngeal swallowing mechanism as a hydraulic power system. PSP showed high levels of measurement consistency over repeated trials across a variety of bolus conditions in normal deglutition.
- High PSP consistency over repeated evaluations demonstrates its potential as a useful measure of pharyngeal bolus-driving function. Current results also demonstrate that consistency in pharyngeal bolus propulsion may be an important physiological target for the swallowing mechanism so as to ensure safe and efficient bolus propulsion into the esophagus.

Figure 1.
Schematic representation of (a) cardiac power system (top) and (b) pharyngeal power system (bottom)

Figure 2. Spatiotemporal plot showing the UES high-pressure zone, swallowing event with UES relaxation, and bolus flow (purple shading)

Swallow Event

Manometric traces from multiple sensors within the pharynx (top traces), UES (middle traces), and proximal esophagus (bottom traces) across a 5-second window with a swallow event marked out within bold dotted vertical lines. This permits identification of (a) the UES high-pressure zone at rest (dotted circles), (b) the sensor registering UES resting pressure (downward arrow), and (c) high pre and post swallow pressures (bold circles) locating the UES during the swallow event and the sensor to be used for UES intrabolus pressure measurements. Values on the left-hand side of the figure are instantaneous pressure readings for each sensor at the time point marked by the thin dotted vertical line.

Figure 4. Impedance trace of single swallow event illustrating the UES bolus flow interval (FI).

Figure 5. Impedance and pressure traces of single swallow event illustrating how peak UES intrabolus pressure (pIBP) is assessed at nadir UES impedance.

Table 1.

Summary statistics for bolus flow interval (FI), volume flow rate (VFR), peak intrabolus pressure (pIBP) and pharyngeal swallowing power (PSP)

Variable	Condition	Mean	Standard Deviation
Bolus Flow Interval, FI (s)	Overall	0.54	0.17
	Female	0.56	0.16
	Male	0.52	0.18
	10 mL	0.50	0.13
	20 mL	0.59	0.20
	Thin Liquid	0.53	0.14
	Nectar-Thick Liquid	0.55	0.12
	Honey-Thick Liquid	0.53	0.14
	Pudding	0.55	0.26
Volume Flow Rate, VFR (mLs ⁻¹)	Overall	29.1	14.4
	Female	27.1	9.14
	Male	31.3	18.3
	10 mL	22.1	13.0
	20 mL	36.7	11.9
	Thin Liquid	31.6	21.2
	Nectar-Thick Liquid	27.8	13.1
	Honey-Thick Liquid	28.7	9.92
	Pudding	28.3	10.0
Peak Intrabolus Pressure, pIBP (mmHg)	Overall	19.9	9.75
	Female	21.1	9.74
	Male	18.7	9.61
	10 mL	16.9	7.28
	20 mL	23.2	10.9
	Thin Liquid	14.8	7.21
	Nectar-Thick Liquid	17.1	8.20
	Honey-Thick Liquid	21.6	8.30
	Pudding	26.7	10.7
Pharyngeal Swallowing Power, PSP (mW)	Overall	78.8	54.9
	Female	79.7	51.7
	Male	77.8	58.1
	10 mL	48.5	27.7
	20 mL	111.0	58.1

Variable	Condition	Mean	Standard Deviation
	Thin Liquid	63.4	49.4
	Nectar-Thick Liquid	65.0	46.6
	Honey-Thick Liquid	84.7	48.0
	Pudding	104.0	64.6

Table 2.

Consistency of pharyngeal swallowing power (PSP) across trials

Bolus Condition	Standardized Cronbach Coefficient Alpha	95 % CI	Landis and Koch Scale ³⁷	Strength of Agreement	Fleiss Scale ³⁹
10 mL Thin Liquid	.87	.75 - .93	Almost perfect	Very good	Excellent
10 mL Nectar-Thick Liquid	.88	.77 - .94	Almost perfect	Very good	Excellent
10 mL Honey-Thick Liquid	.93	.85 - .96	Almost perfect	Very good	Excellent
10 mL Pudding	.86	.73 - .93	Almost perfect	Very good	Excellent
			Almost perfect	Very good	Excellent
20 mL Thin Liquid	.85	.71 - .93	Almost perfect	Very good	Excellent
20 mL Nectar-Thick Liquid	.92	.82 - .96	Almost perfect	Very good	Excellent
20 mL Honey-Thick Liquid	.86	.71 - .93	Almost perfect	Very good	Excellent
20 mL Pudding	.89	.75 - .96	Almost perfect	Very good	Excellent

Table 3.
Average consistency of pharyngeal swallowing power (PSP) across bolus conditions

Bolus Condition	Fisher Weighted Mean Cronbach Coefficient Alpha	95 % CI	Landis and Koch Scale ³⁷	Strength of Agreement	Fleiss Scale ³⁹
Overall	.88	.81 - .93	Almost perfect	Very good	Excellent
10 mL	.89	.81 - .94	Almost perfect	Very good	Excellent
20 mL	.88	.80 - .93	Almost perfect	Very good	Excellent
Thin Liquid	.86	.83 - .88	Almost perfect	Very good	Excellent
Nectar-Thick Liquid	.90	.84 - .94	Almost perfect	Very good	Excellent
Honey-Thick Liquid	.90	.75 - .96	Almost perfect	Very good	Excellent
Pudding	.88	.83 - .82	Almost perfect	Very good	Excellent