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"A DAY IN THE LIFE OF THE FLUID BOLUS": AN INTRODUCTION TO FLUID MECHANICS OF THE OROPHARYNGEAL PHASE OF SWALLOWING WITH PARTICULAR FOCUS ON DYSPHAGIA

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ABSTRACT:
By following the path of a liquid bolus, from the oral preparatory phase to the esophagus, we show that a few fundamental concepts of fluid mechanics can be used to better understand and assess the importance of bolus viscosity during human swallowing, especially when considering dysfunctional swallowing (dysphagia) and how it can be mitigated. In particular, we highlight the important distinction between different flow regimes (i.e. viscosity controlled versus. inertia controlled flow). We also illustrate the difference between understanding bolus movements controlled by a constant force (or pressure) and those controlled by a constant displacement (or velocity). We limit our discussion to simple, Newtonian liquids where the viscosity does not depend on the speed of flow. Consideration of non-Newtonian effects (such as shear thinning or viscoelasticity), which we believe play an important part in human swallowing, requires a sound grasp of the fundamentals discussed here and warrants further consideration in its own right.

KEY WORDS:
Swallowing, dysphagia, deglutition, fluid mechanics, oral physiology

1 INTRODUCTION

The past two decades have seen an increase in the collaborative efforts of basic physical science and physiology in the field of dysphagia (swallowing disorders). For a basic introduction to the field of swallowing disorders, see e.g. [1]. Many clinicians and scientists are now aware that liquids used in the management of dysphagia need to be characterized and described more carefully than by the simplistic terms of thick and thin. Articles describing concepts such as viscosity, density, yield stress, shear rates, shear stress, Newtonian and non-Newtonian fluids are increasingly part of the discussion about thickened liquids in this context and appear in the research literature [2]. The field of rheology has provided insights into some of the factors (fluid composition, temperature, pressure) that influence fluid flow and deformation of liquid boluses. Typically, articles discussing thickened liquids have focused on measuring and describing the properties of these liquids without analyzing in detail how the bolus movement is affected by these properties. This is analogous to studying the viscosity of human blood and its relation to, for example, the concentration of red blood cells without considering the actual flow conditions inside the heart and blood vessels which are needed to assess the relative importance of any viscosity changes. Clearly, a sound understanding of the relative importance of viscosity in physiological flows requires at least a basic understanding of the nature of these flows.

The field of fluid mechanics provides insights into the motion of fluids. If we want to describe and predict what happens as the bolus moves over the tongue, through the pharynx and into the esophagus, fluid mechanics provides the basic laws relating forces and motions of liquids. To explore the use of fluid mechanics in describing the journey of the bolus during swallowing, this article aims to keep a healthy balance between (a) following key physiological features of the bolus journey and (b) introducing relevant fluid mechanical concepts at each stage of this journey without expecting significant fluid mechanics expertise by the reader. Kandel and Wurtz noted that “most of our impressions about the world and our memories of it are based on sight” [3, p. 492]. It is not surprising then that the assessment tools that dysphagia clinicians value most highly are imaging studies, such as videofluoroscopy or endoscopic evaluation of swallowing. These imaging studies allow us to observe the bolus on its journey. We can use frame-by-frame analysis to watch and track movements and image analysis software (e.g. ImageJ) to extract measurements of movement systematically.

We are accustomed to breaking down the physiology of the swallow in considerable detail. The same kind of detail can be used to describe the bolus, including the forces acting on the bolus and their controlling factors. This article synthesizes the physiology of the swallow with a more detailed understanding of the motion of the bolus. Capitalizing on our inherent vision of the oropharyngeal swallow, this article will provide some visual details about the bolus and how it interacts with the physiology of swallowing.

When we look at a liquid, we do not usually consider that it is made up of many microscopic molecules, which when observed on a microscopic scale would seem to move in an apparently random fashion where rapid thermal motions are superimposed onto larger scale collective movements. In practice, we are usually interested in the average behavior of macroscopic regions of fluid, well above the molecular scale. These regions of fluid need to move and slide around relative to one another and, as we shall see, there are a different ways in which this can occur. When these packets of fluid are moving slowly relative to one another, layers slide smoothly over one another when the bolus flows and macroscopic gradients of velocity occur between stagnant and fast moving regions. These gradients are the manifestation of viscosity, which can be thought of as friction between adjacent fluid layers (Figure 1). If we were to observe a liquid flowing slowly through a pipe, e.g. by following small tracer particles inside a transparent viscous liquid, we would see that the layers in the center of the liquid flow faster than the layers at the outside edges with a continuous transition from fast to slow, similar to traffic flow in different lanes on a freeway, where fast, medium and slow lanes exist. If the fluid moves faster, it turns out that at some stage, movements of the fluid packets become more uniform over large parts of the fluid (macroscopic velocity differences are concentrated in smaller regions) as well as increasingly irregular and eventually turbulent locally[1]. The underlying reasons for this instability are complex and will not concern us here; the point to note is that the inertia related to the mass of the fluid packets becomes increasingly important relative to the viscosity until it changes the observed flow pattern. Figure 1 schematically illustrates this, by plotting the paths of several fluid particles from their initial positions. Once again the freeway analogy is applicable. In this case, we assume high traffic density, and many vehicles rapidly changing lanes in order to find the fastest stream. All lanes will end up moving at about the same average speed for the same underlying reasons that they do in fluid flow. An interesting consequence of this analogy is that elements of fluid mechanical theory and analysis have found their way into the analysis and planning of road transports – a concrete example being reduced speed limits during rush hours in an attempt to maintain a stable traffic flow [4].

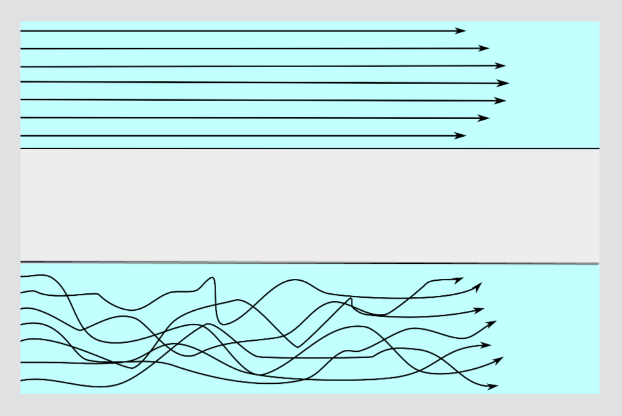

Figure 1: Visualizations of the microscopic differences between laminar (low Re) and turbulent (high Re) flows. The arrows follow the trajectories of the fluid as it flows along the channel after starting from different initial positions on the left hand side. In laminar flow (top) the flow is well organised and regular such that the initial vertical position is maintained. In the turbulent flow case (bottom) there is irregular vertical motion causing a chaotic (convective) vertical mixing.

To summarize, depending on the speed of a fluid flow, the physical effects that control the flow can be different. In the case of slow flow, the viscosity of the fluid is extremely important, but, in the case of fast flow, the density of the fluid will matter more (returning to the traffic analogy, heavy trucks can adapt less quickly than bicycles). From a clinical perspective, one may imagine that adapting the viscosity of a liquid bolus would only be a useful intervention in cases of slow flow. Having established our motivation, we will now define what slow flow actually means quantitatively. Once this is established, we will discuss the various stages of the bolus journey from this perspective.

A ratio of inertial to viscous forces might be a useful indicator for what is a slow or a fast flow. In fluid mechanics, this ratio is called the Reynolds number (abbreviated by the symbol *Re*) and is defined as the ratio of inertial to viscous stresses,

$$Re = \frac{\rho U^2}{\eta \dot{\gamma}} = \frac{\rho U L}{\eta} \tag{1}$$

The first expression characterizes the kinetic energy per unit volume (i.e. the potential of a fluid part to accelerate other parts of the surrounding fluid) relative to the viscous stress (force per unit area) that is required to move a fluid part relative to another against internal friction. This stress is equal to the product of viscosity and shear rate (i.e. the velocity gradient). The second relation is obtained by recognizing that a shear rate (velocity gradient) equals the change of velocity U over a certain distance L and then simplifying the equation. There are other conceptual ways to derive this relation and the reader will usually find the Reynolds number defined as in the second relation in most physics and engineering literature. Returning one more time to our traffic analogy, one could view the Reynolds number as the fluid mechanical equivalent of stopping distance (mass of vehicle/efficiency of brakes).

Traditionally, engineers use the symbols ρ for density, U for velocity and η for viscosity, but frequently μ is also used for viscosity. Reynolds numbers are dimensionless (a stress divided by another stress has no dimension or physical unit, i.e. a ratio). A high Reynolds number (>> 1) indicates that inertial forces are much larger than viscous forces, whilst a low Reynolds (<< 1) number means that viscous forces dominate[2]. When inertial forces are dominant, large fluctuations in velocity can result in complex three-dimensional flow patterns with chaotic eddies and vortices (i.e.,turbulent flow). Flows at a low Re, where viscous forces are dominant, always show laminar flow with macroscopically smooth, constant motions of the liquid. The Reynolds number as an indicator (or diagnostic) of flow regime has value for engineers to model or predict flow behavior and to know how to design specific flow systems. The oropharynx and esophagus, however, already impose a uniquely designed flow system, which has previously been described as a series of pumps and valves [1]. We could say that these pumps and valves work with a series of special pipes in which viscous or inertially dominated flow may occur, depending on the properties of a liquid bolus. Figure 2 illustrates the basic anatomy of the human swallowing machinery.

Liquids can be described rheologically as Newtonian or non-Newtonian. For non-Newtonian liquids, viscosity varies depending on the shear rate or speed of flow. To introduce key concepts of fluid mechanics, this article will focus on Newtonian liquids alone. Note that such Newtonian liquids can be thin like water or thick like syrup or treacle, but always have a constant viscosity regardless of the specific type of flow. The key advantage of this simplification is that the fluid properties in this case have little or no effect on the kinematics (velocity patterns) of the flow as long as Re does not vary much (i.e. we do not change from a laminar to a turbulent regime). This facilitates the discussion of the bolus journey by removing some of the complexity that arises due to fluid rheology (e.g. properties such as shear thinning, viscoelasticity, or thixotropy). Despite this simplification, there will be many interesting questions to answer, which remain relevant even in the context of swallowing complex fluids. Consideration of non-Newtonian liquids in the future will further improve our understanding of bolus transport and its consequences on swallowing safety and efficiency.

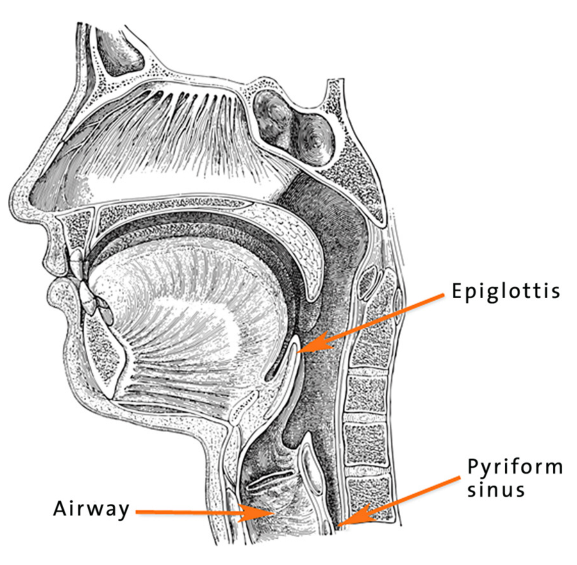

Figure 2: Basic anatomy of the human swallowing apparatus.

2 CONCEPTUAL STAGES OF SWALLOWING

2.1 BOLUS CONTAINMENT AND BALANCING THE BOLUS ON THE TONGUE

In standardized assessments of swallowing, boluses of 1, 5, and 20 ml are often used, although average natural sip volumes are reported to range from 6 – 34 ml, depending on participant age and task instruction [5, 6]. Let's consider a bolus of ~20 ml of water, representing a typical sip size during natural drinking [6]. The bolus is taken into the mouth and the tongue adjusts its shape inferiorly, anteriorly, and posteriorly to accommodate it. Anteriorly, and through the mid-section, the tongue cups the liquid [7 – 9]. Posteriorly, the tongue base is raised as a mechanical barrier to prevent the bolus from spilling into the pharynx prematurely. A fairly gentle, slow motion allows collection of the bolus onto the cupped tongue.

Once the bolus has been cupped on the tongue, the objective is to balance the bolus until the swallow is ready to be initiated. The tongue presumably activates small motions in order to stop the bolus from spilling over before initiating a swallow [10], somewhat like movements we might make in trying to balance an egg on a spoon. The magnitude of the corresponding stress-

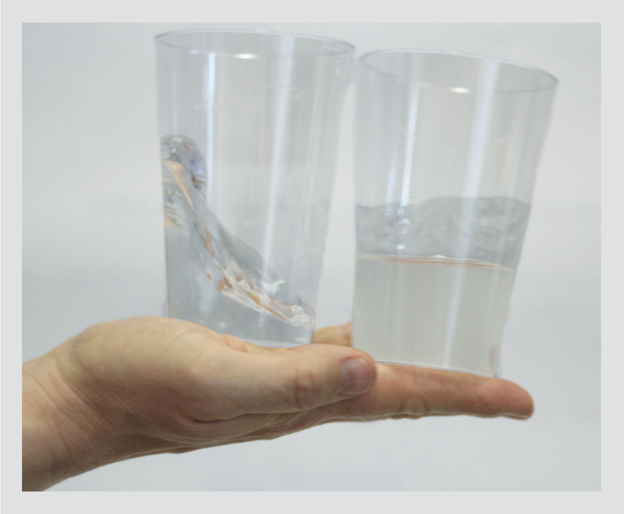

Figure 3: Shaking two partially filled cups of liquid by hand. The left most cup contains water, while the right contains honey thick water. Note that the motion of the surface of the viscous liquid is heavily damped relative to that of the water.

es (forces) is relatively easy to estimate since the driving force is gravity acting on parts of the bolus at different heights (imagine you tip a half empty glass of water and hold it at an angle; the water will flow to return the surface to the horizontal due to the hydrostatic gravitational stress, as illustrated in Figure 3). Assuming that the tongue cup depth, *h*, is in the order of 1 cm (maximum), we can estimate the maximum hydrostatic stress as

$$\sigma = \rho g h \approx \frac{1000\ kg}{m^3}\,\frac{10\ N}{kg}\,0.01\ m = 100\ Pa \tag{2}$$

where units of stress (Pa) equal N/m². To estimate a relevant Reynolds number using Equation 1, we have to proceed indirectly since we have no explicit knowledge of a fluid velocity at this stage. We can estimate a maximum velocity that could be generated by the gravitational stress and then the Reynolds number given by such a velocity. If this Reynolds number is very large (i.e. $Re > 1$), our initial assumption of inertially controlled flow would seem correct. For a complete conversion of gravitational energy to kinetic energy, this maximum velocity would be equivalent to $\sqrt{(2gh)}$, i.e. approximately 0.4 m/s using the above estimate. For the case of water at room temperature, this velocity would correspond to a Reynolds number of $(\rho U h/\eta) \approx 1000 \cdot 0.4 \cdot 0.01 / 0.001 = 4000$. A very significant increase of viscosity (to at least 100 times the viscosity of water) is therefore required before viscous friction inside the bolus will affect control of the bolus during this stage. Current thickened fluids used in clinical practice can indeed deliver viscosity increases of such 1 magnitude [11, 12].

If we consider a smaller fluid bolus, *h* will be smaller, leading to a smaller acceleration, smaller *Re* and a stronger influence of viscosity. This may at least partially explain why subjects with difficulties in controlling bolus containment also benefit from smaller bolus volumes. If, on the other hand, the viscosity is high enough to produce viscous stresses reducing the gravitational acceleration of the liquid, its effect can be quite easily estimated. The approximate stress of 100 Pa then becomes equivalent to the stress generated by the motion of the fluid (100 Pa = fluid stress = viscosity × shear rate). The fluid velocity at the part furthest above the tongue is directly proportional to the shear rate, so we can conclude that the observed fluid velocity is inversely proportional to viscosity. Putting this into a clinical context we would say that increasing the fluid viscosity will slow down the bolus in the mouth and make manipulation easier, reducing involuntary, premature bolus spill into the pharynx. Slower movements imply that bolus control is less reliant on patients having a fast reaction time to adjust to sensorially perceived differences in the bolus[3]. This is analogous to steering a car – the faster you drive, the faster you have to make small adjustments to the steering wheel to avoid crashing, the further off course you get. This gives a quite straightforward justification for the use of thickened (higher viscosity) liquids for bolus control in the oral cavity. It further raises an interesting question regarding the optimum height of the bolus on the tongue surface that will reduce the likelihood of spill due to height disturbance [13].

2.2 BOLUS PROPULSION (THE TONGUE AS PROVIDER OF FORCE)

Returning to our visual imagery, we have a bolus sitting on the cupped tongue (posterior tongue raised), ready to be transported into the pharynx. Note that in order to maintain the simplicity of the model, we will assume that the tongue surface is moist and that the bolus will move easily along the tongue surface when transport is initiated. Complications due to more complex conditions on the tongue surface (e.g. dry regions, thickened saliva) might have consequences on these boundary conditions of flow, but will not be part of our considerations here. With the bolus held in position, the posterior tongue drops, allowing the bolus to flow into the pharynx. The speed at which the bolus is squeezed back and propelled into the pharynx depends on: (a) the stress (force) that is exerted by the tongue on the bolus (i.e. on tongue strength) and (b) on the viscosity of the bolus resisting the deformation that is inevitable during the propulsion step. Application of the driving force by the tongue happens practically simultaneously with the posterior tongue dropping, causing the bolus to naturally flow from this region towards the pharynx with no directly opposing force. Incompetent velopharyngeal closure provides an opportunity for a pressure

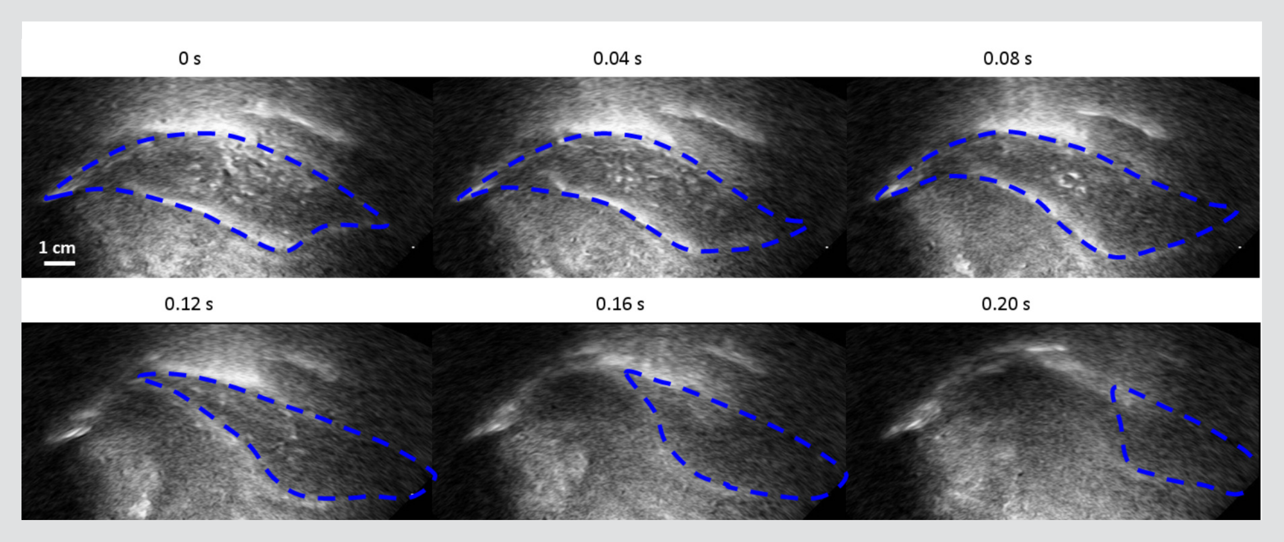

Figure 4: Successive frames illustrate ultrasound images of bolus motion in the mouth during the initial (oral) phase of a healthy volunteer swallowing a sip of lightly carbonated water. For orientation, the lips are to the left hand side, the pharynx to the right, the tongue below and the soft palate above. Time progression is from left to right by row, Note the thinning of the tail of the bolus due to the squeezing action of the tongue and palate. Since the Reynolds number is directly proportional to the thickness of the fluid layer, one obtains lower Reynolds numbers at the tail of the bolus than in the central region.

leak, which can impair downward movement of the bolus into the pharynx.

From a fluid mechanics perspective, we first need to consider how the motion of the bolus in the mouth is controlled. The 'real' feedback control system is likely to be both complex and multiparametric, however, we can consider the two extreme possibilities in order to gain some insight^4. These two extremes are controlled stress (i.e. constant force) or controlled rate (i.e. constant speed). These two extremes would lead to very different relations between bolus propulsion time and viscosity. We postulate that for the motion of the tongue during deglutition, a controlled stress model provides a more realistic approximation. Using this assumption, we can then estimate a maximum Reynolds number *Re* associated with propulsion of the bolus. The appropriate characteristic dimension in this case is the gap between the tongue and palate. This introduces an additional complication since this gap is laterally non-uniform, varying from the anterior to posterior regions of the oral cavity and changes with time as the flow progresses and the tongue approaches the palate. To obtain an estimate of the maximum Reynolds number, we may consider that the largest gap during this phase is in the order of 3 cm (according to currently unpublished ultrasound data by Nestlé Research). If we assume that the initial motion of the bolus is controlled by a constant stress (force) imposed by the tongue, we need to estimate a typical time for application of this stress and the area over which it is applied to the bolus. We can then obtain an estimated maximum velocity (similar to the argument in the previous section) from which we can establish a maximum Reynolds number for this phase. The velocity *U* attained by a bolus with volume *V* and density ρ accelerated by a stress σ, which is acting on a contact area *A* between the tongue and bolus to produce an acceleration *a* over a time *t*, can be estimated as

$$U = at = \frac{F}{m}t = \frac{\sigma A}{\rho V}t \tag{3}$$

The Reynolds number is then given by

$$Re = \frac{\rho U h}{\eta} = \frac{\rho \sigma A t h}{\eta \rho V} = \frac{Ah}{V}\frac{\sigma}{\eta}t \approx 0.3\,\frac{\sigma}{\eta}t \tag{4}$$

If we maintain our previous assumption of a bolus volume of 20 ml, suppose a contact area of 2 cm^2 during the application of the constant stress and assume a maximum gap of 3 cm. If the stresses applied by the tongue are in the order of 1 kPa (1000 Pa) or more [14], the Reynolds number reaches large values within milliseconds for thin liquids like water ($\eta \approx 0.001$ Pas).This would suggest that the initial stages of bolus propulsion will be rather independent of bolus viscosity, at least anteriorly because of the large initial gap between the tongue and palate.

As the tongue propels the liquid into the pharynx, the fluid that remains between the tongue and the palate is progressively squeezed from the bolus tail towards the bolus head (Figure 4). This reduces the tongue/palate gap towards the bolus tail and leads to a concomitant increase in the shear rate experienced (i.e. the relative velocity difference between bolus motion and tongue/palate occurs over smaller distances). Hence, even for very thin materials, at some stage there will be a transition to a slow "creeping flow" (*Re* << 1) for which the fluid viscosity is the most significant factor in controlling the flow rate. The point at which this transition occurs will itself depend on the viscosity of the fluid. We should therefore expect that, at least for healthy individuals, the speed of the

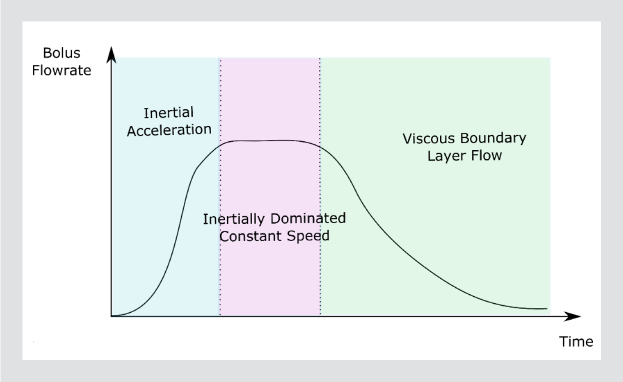

Figure 5: Transition from initial acceleration of fluid bolus to inertially dominated flow to viscosity dominated flow.

bolus head (relevant for bolus arrival in the pharynx and hence triggering of the airway protection reflex) should depend only weakly on bolus viscosity, but the time taken to propel the entire bolus into and through the pharynx would be expected to strongly correlate with viscosity. The reader may wish to consult Nicosia and Robbins [13] for a related quantitative analysis of the bolus ejection.

To summarize this section, fluid mechanics predicts that, for a constant tongue stress, the total time taken to eject the entire bolus into the pharynx should increase with viscosity. For constant-viscosity (Newtonian) fluids, this time should be approximately proportional to viscosity. It is worth noting that the latter stages of fluid propulsion into the pharynx have no clearly predictable endpoint (the fluid will be continually squeezed out at an exponentially decreasing rate as long as the tongue applies a constant squeezing stress). Dong Chen [15] has described this scenario. As noted earlier, we are used to watching frame-by-frame Videofluoroscopy images (or perhaps high resolution manometry) of bolus movement to understand what controls the movements. From the moment when the bolus is propelled from the mouth, there are three phases of bolus motion. Phase one is the initial acceleration period. This is very short in most cases of interest, although it depends on the force exerted by the tongue. The second phase is the constant speed inertial region, and the final phase is the boundary layer expulsion. This is schematically illustrated in Figure 5. The viscosity of the fluid is an important parameter that determines where the transition point from inertially dominated to viscous flow occurs. Increasing the viscosity moves this transition earlier (towards the left of Figure 5), with the consequence that, at a fixed point in time, a larger proportion of the bolus will remain as a residue if the entire tongue motion is of constant duration. This may explain the need or desire (even for non-dysphagic individuals) to use a clearing swallow after swallowing very thick liquids like honey. Although the initial swallow clears the majority of the bolus, it cannot clear the entire bolus, leaving a larger viscous layer than a thin liquid. Hence there is a desire for a clearing swallow.

2.3 BOLUS PASSAGE THROUGH THE PHARYNX

If we turn to our visual image of the swallowing system as a stylized series of pumps, valves and pipes, we can consider the tongue acting as a positive displacement pump (with no retrograde leakage) to deliver the bolus out of the mouth pipe into the pharynx pipe. For this process to be efficient, we need to close a number of valves so that the force generated by the tongue, does not inadvertently push parts of the bolus through these valves (velopharynx and larynx).

Further downstream in the pharynx, the role of the epiglottis can be considered to be that of a deflector plate, much like a rock in a stream. Figure 6 illustrates that this deflection effect relies on the flow being dominated by inertia. The boundary layer of relatively slow viscous flow seems to detach from the rear surface of the cylinder for the high Reynolds number case (i.e., low viscosity and/or high bolus speed, such as in the case of water), reducing the likelihood of bolus penetration into the larynx. In the case of the low Reynolds number (i.e. high viscosity and/or low bolus speed, as in the case of a Newtonian thickened liquid) the region of slow flow near the surface is preserved. Clearly we could expect that low bolus propulsion velocities should lead to creeping flows (flows at very low Reynolds number, i.e., dominated by viscosity) in the vicinity of the epiglottis, with the potential for penetration of fluid underneath the epiglottis[5]. For some individuals with transient penetration, the bolus may be ejected from the region underneath the epiglottis during hyolaryngeal excursion.

As we have seen from our earlier estimate of Reynolds numbers, the initial flow of the bolus head through the pharynx is expected to be fast and dominated by inertia. Physiologically, this would seem to make sense because the required synchronization of the swallowing sequence then becomes relatively independent of bolus rheology, which would suggest a certain robustness of the swallowing mechanism including airway protection. The literature, although sparse, suggests that the transit time through the pharynx remains in the order of one second, more or less regardless of bolus viscosity [16–18]. In-vivo measurements of average and maximum bolus velocities in the pharynx above the epiglottis during swallowing of healthy volunteers using ultrasound or videofluoroscopy [19–22] show that increased viscosities can lead to lower velocities as well as to flatter velocity profiles (i.e. less difference between minimum and maximum velocities in the bolus). These observations may not only be explained by the effect of viscosity alone, but also by effects of shear-rate dependent viscosity of the test liquids used and will not be discussed further in this article. Several attempts have been made to de-

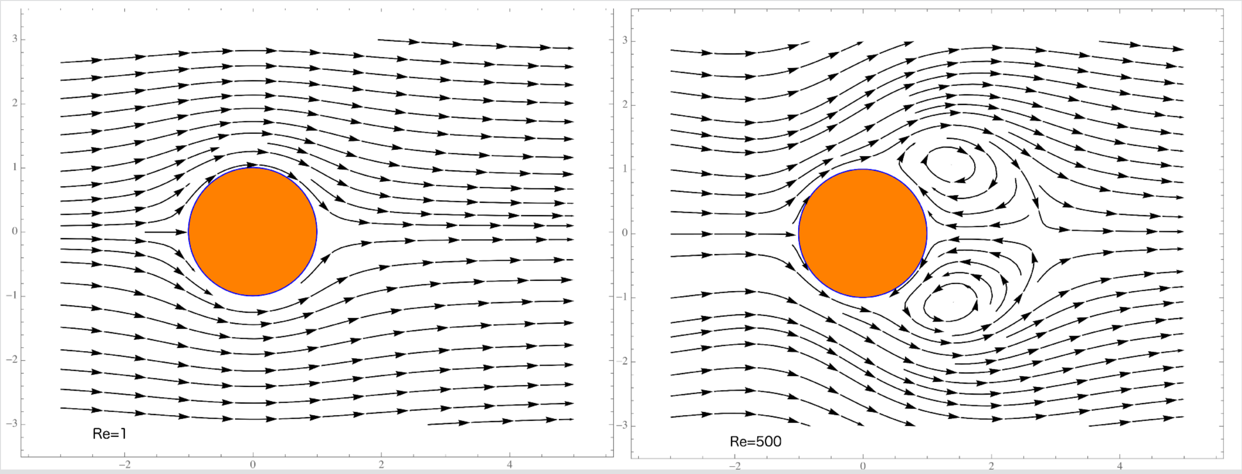

Figure 6: Velocity vectors illustrating flow boundary layer detachment from an immersed sphere: Flow at Re = 1 (Left panel) and flow past a cylinder at Re=500 (right panel). The flow direction is from left to right. Note the detachment of the flow at higher Re leading to streaming of the liquid past a pair of trailing vortices. In this case the vortex fluid is permanently trapped 5 behind the sphere and there is no exchange. An analogy can drawn with the flow around th epiglottis by considering just the top half of each panel. In this case the flow would be expected to detach near the lowest point and that the trapped vortex would be made of air (air is also a fluid). Images generated from the Wolfram demonstrations project (this provides and online applet that allows visualisation of flows at different Reynold numbers (http://demonstrations.wolfram.com/FlowAroundASphere-AtFiniteReynoldsNumberByGalerkin11 Method/).

scribe bolus flow behavior in the pharynx in a more quantitative fashion using computational fluid dynamics to capture the irregular anatomical shapes [23–28]. Much progress remains to be made in this area, particularly in considering the limiting situations (geometries, driving pressures) of such approximations and we believe a thorough investigation of dominant and secondary effects should always precede numerical simulations.

2.4 BOLUS RESIDUES IN THE PHARYNX

The flow conditions in the pharynx will not only affect the speed of bolus transport, but also the amount of fluid that remains attached to the pharyngeal surfaces. We assume a classical no-slip (zero velocity) condition at the pharyngeal walls, i.e. we postulate that no complex wetting/dewetting or slippage effects play a significant role. Whilst such a no-slip boundary condition may not appear intuitive, it has been shown to be valid for an extremely wide range of fluid/solid contact conditions (see for example [29]) and only breaks down under rather extreme flow conditions or for certain very peculiar fluids (not relevant in our case).

Even if the majority of pharyngeal bolus movement occurs at a high Reynolds number ($Re > 1$), there will then be a boundary layer close to the surface of the pharynx where low Reynolds number ($Re << 1$) flow prevails. Fluid mechanical theory suggests that this boundary layer (at any position along the pharynx) will have a thickness proportional to the square root of the reciprocal Reynolds number, $\sqrt{(1/Re)}$ (see for example [29, 30]). The fluid in this region travels at a much lower average velocity than the main portion of the bolus and some of it will be left behind when the main bolus tail has passed through the pharynx. This suggests that thicker fluids with higher viscosity might more strongly coat the walls of the pharynx and other surfaces they flow on, such as the pyriform sinuses. Since the Reynolds number depends on fluid velocity, one would also expect that poor tongue strength (i.e., low bolus ejection speed) will lead to a thicker boundary layer, and hence more fluid residue after the majority of the bolus has passed.

2.5 CLEARING OF THE BOLUS TAIL: PHARYNGEAL SQUEEZE

While the tongue generates the propulsion of the bolus through the pharynx, the pharyngeal constrictors play an important role to clear the posterior part (tail) of the bolus into the UES so that the pharyngeal region near the larynx is cleared of liquid in time to safely resume breathing. As already noted, there will always be a residual boundary layer attached to the walls of the pharynx after the bolus has passed, and most of this residual fluid should be removed before the airway is opened again for breathing. Given that there is a limited time between breaths, this sets a limit on the allowable time for the residual fluid to drip down from the pharynx wall. The time needed for this dripping is proportional to viscosity. A simple experiment to illustrate this effect is to compare the drip times of a spoonful of water with a spoonful of honey or syrup.

For low viscosity fluids like water, the available time may be adequate such that there is no need to actively squeeze the residual fluid out with a clearing swallow. With higher viscosities, this will be no longer

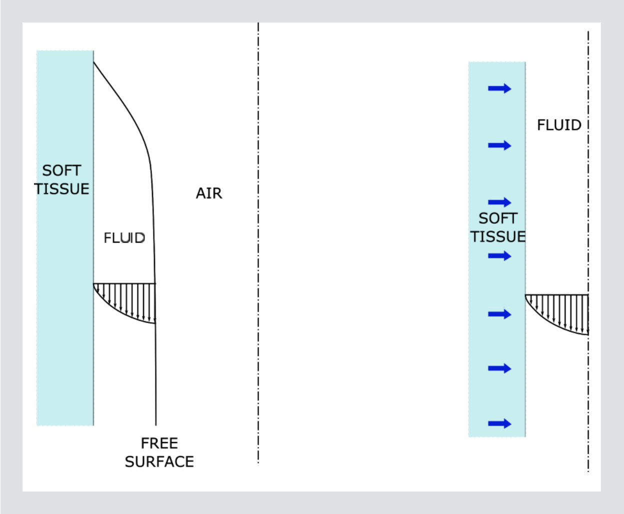

Figure 7: Schematic representation of dripping flow (left) and active squeezing flow (right). The parabolic arrows represent the velocity profile at a typical point in the flow. Note that the dot-dash line represents a line of symmetry (i.e. the flow is mirrored around this line).

the case. The squeezing flow involved in clearing swallows can be assumed to be dominated by the viscosity of the fluid because of the thin gap over which it occurs (see Figure 7). In this case, the difficulty of squeezing out the residual fluid from the pharynx should strongly correlate to the viscosity of the residual material. With a more viscous material, the remaining film will be thicker, making it easier for sensory receptors to detect it and initiate a clearing swallow. Residue that has not been cleared in time to resume breathing will be collected and held in the pyriform sinuses. These are like chutes that are wide at the top and narrow at the base, situated on either side of the larynx and have their lower boundary immediately above the upper esophageal sphincter. The pyriform sinuses have a limited fill capacity. Sensation from the pharynx is provided via the densely interwoven fibres of the pharyngeal plexus [31]. This innervation enables us to detect the presence of material/residue in the valleculae, the pyriform sinuses and in the laryngeal vestibule. When material overflows the catch basins of the pharynx and enters the laryngeal vestibule, receptors of the internal branch of the superior laryngeal nerve trigger a reflexive swallow [32]. The literature shows that young people and the elderly have different thresholds with respect to the fill capacity of the pharynx before a reflexive swallow is triggered. In healthy young adults, during slow continuous injection of water directly to the pyriform sinuses, a volume of 1.12 ml triggers a reflexive swallow and closure of the vocal folds. In older adults, a higher threshold of 1.85 ml is reported to be reached before these reflexive responses are elicited [33]. Consequently, fluid hold-up or pharyngeal residue can be related to the associated risk of aspiration, although for small boluses the volume of the pyriform sinuses will probably provide a safety margin to trap this remaining fluid before there is a significantly elevated penetration or aspiration risk. This suggests that we should include the total volume of the pyriform sinuses in our considerations. The risk of aspiration would be strongly increased once the volume of fluid hold-up exceeded the sinus volume.

2.6 FLOW INTO THE ESOPHAGUS

In a timely, well-functioning swallow the bolus will pass through the pharynx and the reflex-initiated pulley system of hyolaryngeal excursion will open the UES, typically for a period of time commensurate with apnea, allowing the bolus to pass into the esophagus. The propulsive force generated by the tongue sends the bolus deep into the pharynx, and the shortening and then constriction of the pharynx not only helps to engulf the head of the bolus, but also acts on the residual film of the boundary layer to clear the tail of the bolus into the esophagus (Figure 7, right hand panel). The constrictors work in a sequential manner with the superior, then middle and then inferior constrictors progressively squeezing the bolus into the esophagus. Note again, the importance of the valves in this system. The bolus starts with positive pressure from tongue propulsion above, and then meets a slight, but measurable negative pressure (relative to atmospheric pressure) in the esophagus. The bolus changes from being pushed fast into the pharynx, slowing once the propulsion has reached its full capacity, to the tip of the bolus being sucked or directed into the esophagus as a result of subatmospheric pressure within the thorax. Dejaeger et al. [34] note that tongue driving or propulsion force plays a major role in avoiding vallecular residue. When tongue propulsion force is intact and pharyngeal shortening and hyolaryngeal excursion is impaired, residue is more likely to be seen in the pyriform sinuses. When tongue driving force, pharyngeal shortening and hyolaryngeal excursion are all impaired, diffuse pharyngeal residue may occur. Once the primary peristaltic wave has been initiated inside the esophagus, the bolus should progress sequentially with squeezing actions just behind the bolus transporting it rhythmically through the esophagus. Within the esophagus, the mean velocity of the peristaltic wave is reported to be 2–4 cm/s, with the duration of each contraction ranging from 1 to 4 seconds. The pressure amplitude of the peristaltic wave ranges from 5–9 kPa to as high as 24–26 kPa [35]. Given these varying conditions, and changes in the geometry of the esophageal pipe, the Reynolds number is likely to vary strongly with time and position throughout the esophageal phase.

3 DISCUSSION

Reflecting back on the bolus journey that we have now discussed in some depth from a fluid mechanical view point, we can state that there are important variations in bolus velocity during any swallow – both in space (position) and in time (phase of the swallow) and that these variations have important consequences for the safety and efficiency of swallowing liquids such as beverages. Zooming in on some of the details of these variations, we have seen why and where thickened liquids are most likely to be effective to facilitate bolus control and safe swallowing and why optimal (rather than extreme) thickening is required for some types of swallowing disorders. Highly thickened Newtonian liquids (syrups or treacle) are difficult to swallow, even for healthy individuals, and a clearing swallow is required to remove pharyngeal residues in such cases, which is a particular challenge when the propulsive system is weak. The integrity of the sensory system to detect subtle residues is then also particularly crucial. A necessary compromise – especially when both bolus control and pharyngeal constriction are impaired – suggests that fluids with variable viscosity, i.e. shear-thinning behavior (high enough at low stresses, but low enough at higher stresses) should be an effective solution.

This type of behavior is offered by many commercially available thickening agents and thickened fluids. We plan to discuss in more depth how such shear thinning fluids affect swallowing in a future article, as well as other effects of more complex fluid and fluid/solid contacting situations (e.g. xerostomia, thickened or ropey saliva). We conclude by mentioning that the transport of solid and semi-solid food boluses requires a separate discussion. Although the physiological control and driving mechanisms remain the same, the flow and deformation behavior of these boluses can differ dramatically because of their complex (and often heterogeneous) flow characteristics and interactions with physiological surfaces. Similar cautions would apply to solid medications such as tablets or capsules.

CONFLICTS OF INTEREST

A.S. Burbidge and J. Engmann are employees of Nestec Ltd. J.A.Y. Cichero has received honorarium for participation in expert panels, speaking at conferences and reimbursement for travel expenses from Nestlé Health Science.

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FOOTNOTES

[1] In order to be strictly correct, we note that the motion of the fluid ‘packets’ themselves becomes more random and faster, but the coherence length (approximate size) of the packets reduces. The net effect of this is that, when viewed over a length scale that is large relative to the randomly moving packets, i.e. it is effectively averaged over a larger number of packets, the (average) motion appears to be uniform, despite the fact that the packets also mix together in a direction lateral to the observed flow.

[2] For intermediate values of *Re*, both viscous and inertial forces are important.

[3] In engineering parlance, there is a convective timescale associated with the flow, and a timescale associated with the applied force (i.e. the rate of change of boundary conditions).

[4] Our personal opinion is that the human oral control system is capable of controlled stress, or strain operation, and will adapt its mode dependent on circumstances.

[5] At first sight, the flow over an immersed cylinder and that over the epiglottis appear to be very different since the far field in one is a free surface and the other is a bulk fluid at uniform or zero velocity. In fact, however, the far field boundary condition in either case is vanishing shear stress (and, vanishing normal stress for free surface curvatures on the scale in which we are interested). Hence, the leading order mathematical description of singular perturbation problem that provokes the boundary layer formation at the cylinder (or epiglottis) surface is the same in each case.