Application of Ultrasound Doppler Technique for In-Vitro Flow Visualization of Human Swallowing

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Swallowing disorders, known as "Dysphagia" is a growing global problem and it is estimated that dysphagia affects roughly 8% of the world population. The number of aged people with Dysphagia has increased in the world with the advent of an aging society. Dysphagia can be the consequence of several pathologies, such as throat and neck cancer, stroke, dementia, or other neurodegenerative conditions and Dysphagia patients are not capable of controlling laryngeal closure, and therefore often aspirate liquid foods. The aspiration problem is especially caused by low viscosity foods as they are easily deformed during swallowing. The bolus is formed in the mouth under the pressure produced by the tongue surface, moving toward the hard palate, which results in the formation of a bolus and a downward flow. The bolus is subjected to large shear rates as it flows down into the pharynx via a peristaltic motion. It is important to be able to study the flow properties of liquid foods during human swallowing in order to develop innovative foods for dysphagia patients. At the moment the only tools available in clinical examination of dysphagia are manometry, which is invasive, and video-fluorography, which exposes the patients to radiation. In this work an in-vitro device which mimics human swallowing was developed and equipped with a novel ultrasonic velocity profiling (UVP) sensor to study the flow properties of liquid in the same way as during in-vivo experiments but non-invasively and without using any contrast media.

Keywords: Dysphagia, human swallowing, Gothenburg Throat Model, Ultrasonic Velocity Profiling, rheology, non-Newtonian

1. INTRODUCTION

Dysphagia is referred to the condition when individuals fail to adequately transfer food and liquids from mouth to the stomach. Dysphagia is often noticed in patient's suffering from neuro disorders such as; Parkinson's disease, Alzheimer diseases, brain damage and head injuries etc. [1] Symptoms of dysphagia is more common in aging population due to diminished co-ordination between the muscles involved to undergo the swallowing process in a normal way [2]. According to estimates dysphagia effects 8% of the world population and the condition is projected to increase due to increase in elderly population [3].

People suffering from dysphagia cannot handle the fast flow of fluids through their oropharynx due to eddies and vortices formation. Such individuals are restricted to textured modified diet. Texture modification is commonly performed by either using gum or starch thickened fluids. Both gum and starch-based thickeners differ in the way they increase consistency. Starch based thickener swells upon hydration while a gum-based thickener arrests water forming network in the solution upon hydration [4]. In either case the fluid becomes highly shear thinning, that is the viscosity becomes shear thinning. Clinically, dysphagia is diagnosed by either video-fluoroscopy or manometry. Video-fluoroscopy is based on adding contrast media typically barium or iodine based to enhance visualization while in manometry a catheter with pressure sensors is inserted into patients' airways. Both the methods are invasive and often lead to inconsistent results [5]. Based on a patient's response to a given consistency of a liquid from clinical diagnosis, a certain consistency is recommended often following American National Dysphagia Diet (NDD, 2002) standards. The scale characterized fluids from thin (1-50mPa.s) to pudding (>1750 mPas) consistency at 25C and shear rate $50s^{-1}$. A patient recommended for honey-consistency liquid might still aspirate due to unexpectedly high shear rates in swallowing process thereby reducing the consistency to a different range on the scale. Accurate shear rate prediction in swallowing is extremely difficult due to complex pharyngeal geometry and nature of swallowing process. Transit time of bolus flow in pharynx is typically <1 second and swallowing can be considered as batch process with a time interval of 1-10 seconds between individual swallows. Performing such experiments using in-vivo experiments leads to both ethical issues and patient's discomfort. Numerical simulations used to determine the shear rate distribution in pharynx assumes highly idealized conditions such as; homogeneity, Newtonian consistency and isotropy which is not analogous to the actual biological process. Hence an in-vitro simulator in which the bolus can be deformed in the same manner as in actual bio-processes is greatly needed. This paper presents the measurements using ultrasound velocimetry in maltodextrin with three different viscosities. This work is the first step to verify the UVP technique by using high speed camera images. Continuous and bolus flow was tested using the UVP technique.

2. METHODS AND APPARATUS

2.1 The Gothenburg Throat Model

In this work an in-vitro device which mimics human swallowing was developed, the so-called "Gothenburg Throat Model". A detailed description of the in-vitro swallowing simulator has been submitted for publication elsewhere, [6-7], and an overview is given below. The model consists of a fluid storage tank and a syringe with circular cross section for bolus delivery that can inject a

specified volume of liquid, up to 20 ml. The pharynx in the model is elliptical with a length ~6.3 cm and a width of 2.8-3 cm at the largest measure and a circular entrance area of 314 mm² (20 mm diameter). The model was 3D printed from Accura ® Clear vue™ due to its suitability for usage in medical models, transparency for fluid flow visualization and liquid resistance. The Gothenburg Throat Model is shown in Figure 1. The model has similar geometry to the human pharynx, simulation of closing of the vocal chords and the upper esophageal sphincter, opening and closing of the epiglottis and the opening to the nasopharynx. The Gothenburg Throat is equipped with sensors for monitoring of bolus velocity profile during swallowing, temperature control and pressure measurement at different locations of interest e.g. at the entrance of pharynx, mid-pharynx, nasopharynx and UES. The pharynx channel is transparent for visual observations and high-speed camera measurements.

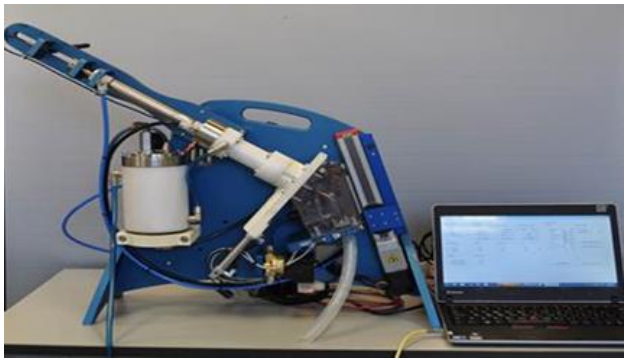


Figure 1: Photo of the Gothenburg Throat Model.

2.2 Flow visualization and Bolus flow measurements using high-speed camera

A high-speed camera (Sony, DSC-RX100M5) was installed at 50 cm from the flow model and was used to capture the bolus flow and images were captured at 500 frames per second. The bolus was color dyed blue for better contrast and it was ensured that the color addition did not influence bolus rheology. A linear ruler was attached to the model to determine the true velocity of the bolus flow from the high-speed camera photos. The determined velocities were used to validate the UVP measurements and to optimize the time delay settings for the valves in the model and the syringe to accurately mimic the human swallowing process.

2.3 Flow visualization and Bolus flow measurements using ultrasonics

The Incipientus system is a commercial and fully integrated platform for high resolution Doppler measurements as well as in-line rheometry. It features 2 transmit/receive (TX/RX) channels that can work in stand-alone or pitch-catch configuration. The transmitters, based on an Arbitrary Waveform Generator (AWG), can produce bursts, typically at 30-80 Vpp with a frequency of 5 MHz. The inputs are amplified with Time Gain Control (TGC) units featuring a gain up to 55 dB, converted to digital at 16-bit 100 MS/s, and processed in an FPGA. The FPGA include coherent demodulators, filters and an FFT processor for spectral analysis [8-9]. The base frequency of the non-invasive ultrasound transducer was 5 MHz, and 5 cycles per pulse were used for velocity profile measurements. The Gothenburg Throat was equipped with a novel Flow-Viz sensor (Incipientus AB, Sweden) to study the flow properties of liquid in the same way as during in-vivo experiments but non-invasively and without using any contrast media. The non-invasive UVP sensor set-up is shown in Figure 2. The ultrasonic beam passes through the polycarbonate material of the model into the actual fluid flow (Fig. 1) which means that it will be refracted at each interface. The Doppler angle inside the model cavity was determined using a combination of the angled Flow-Viz and a reference 90° ultrasound beam. The RF data time delay differences were used to determine the Doppler angle of 59.5° and ellipse short axis radius 8.4mm. An average of 8192 and 128 pulses were used to determine the velocity profiles in continues and bolus flow respectively. The sound velocity in maltodextrin was determined to be in the range 1486-1492 m/s.

Figure 2: Photo of the customized UVP sensor measuring the flow of ketchup inside the pharynx.

2.4 Materials

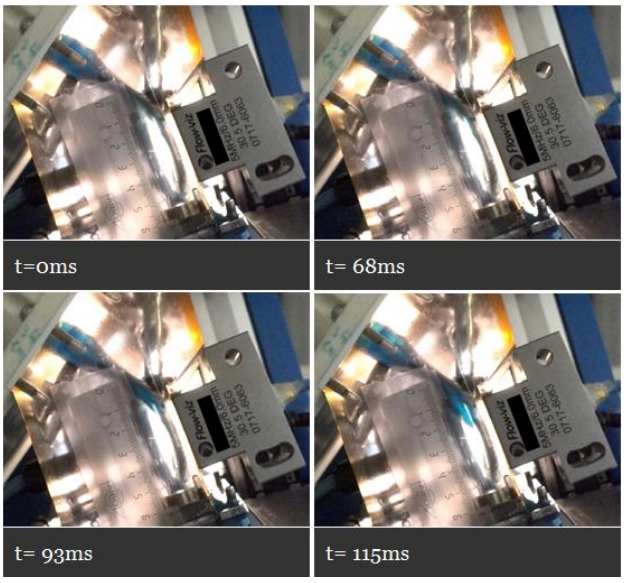
In this work, three aqueous solutions of maltodextrin with viscosities of 0.78 Pa.s, 1 Pa.s and 1.7 Pa.s were used to validate the flow in the pharynx of the Gothenburg Throat Model. The maltodextrin was dyed blue using a commercial food dye for the high-speed camera measurements to improve the contrast.

2.5 Experimental procedure for continuous- and bolus flow measurements

In the continuous flow experiments, the maltodextrin solutions were continuously pumped from a tank using a rotatory lobe pump (Sterilobe SLAS; Johnsons Pumps, Lanarkshire, UK) through the Gothenburg Throat Model in a closed circulation system using 1" flexible PVC hoses to ensure that the entire model was filled with the fluid. The valves on the trachea and nasal cavity were closed during all tests. The ultrasound transducer was attached to the model using a specially designed holder to ensure firm contact between the transducer face and the model. The position of the UVP sensor can be adjusted vertically as it is mounted on a high-precision linear axis equipped with a stepper motor. but it was installed at a fixed position in the center of the pharynx for all the measurements reported in this work. Continuous flow experiments were carried out at two different pump speed settings, corresponding to two different flow rates, 5 L/min and 10 L/min. In the bolus experiments a total volume of 15 ±1.2 ml was injected for each bolus. The temperature of the fluid was monitored during the experiments within 20.5˚–22.0˚C.

3. Results

Figure 3 shows high-speed camera images of maltodextrin bolus flow in the pharynx. As can be seen from the obtained photos the model can be used to deliver bolus with realistic velocity that will not break up during swallowing if the viscosity exceeds a certain value. The bolus velocity was determined to be in the range of 0.03 m/s to 0.08 m/s, using the camera and image processing software. This is in good agreement with velocities reported in clinical studies in the literature for bolus flow.



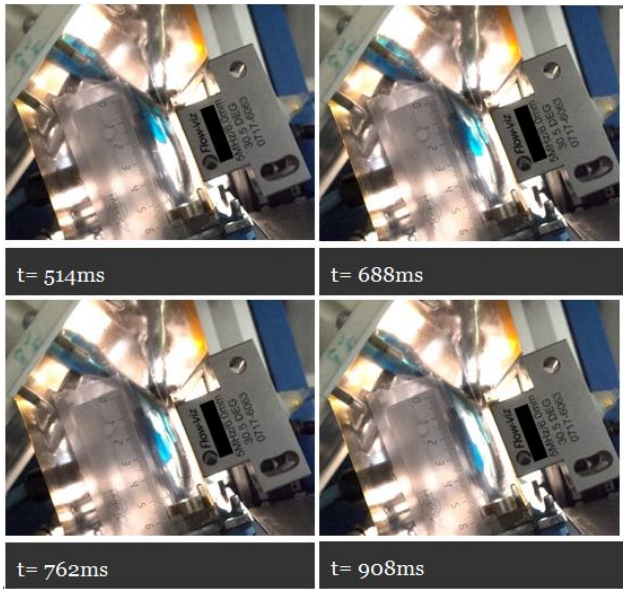


Figure 3: High-speed camera images of maltodextrin bolus flow in the pharynx, after 93ms up to 908ms.

Figure 4 shows and example of a velocity profile (Doppler spectra) of maltodextrin measured in continuous flow in the pharynx. A total of 8192 pulses were used to plot the Doppler spectra and to calculate the corresponding velocity profile. The acquired maximum velocities from the camera images was 0.044-0.049 m/s, which is in good agreement to the ones noticed in clinical studies and the maximum velocities measured by UVP, 0.042-0.048 m/s.

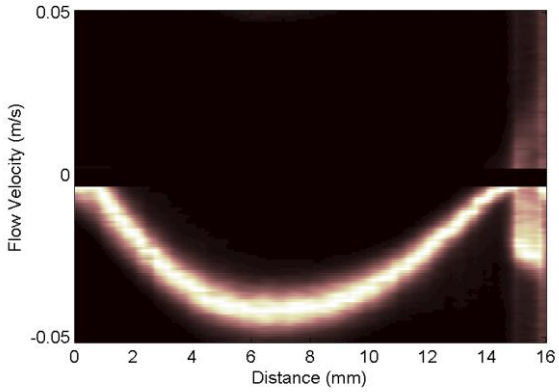


Figure 4: Velocity profile of maltodextrin measured in continuous flow in the pharynx.

Figures 5 shows examples of a velocity profiles (Doppler spectra) of maltodextrin bolus flow in the pharynx at three different viscosities ranging from 0.78 Pa.s, 1 Pa.s and 1.7 Pa.s. Due to the quick swallowing a total of 128 pulses were used to plot the Doppler spectra and to calculate the corresponding bolus velocity profile. Practically this means that high transmission and sampling frequencies must be used for UVP measurements in e.g. the pharynx model. The shapes of the measured bolus velocity profiles are not axis symmetric, which is expected due to the geometry of the pharynx. The shape of the measured profiles did not

change significantly with increasing viscosity. This is however expected since the maltodextrin solutions showed Newtonian flow behavior. However, the magnitude of velocities showed good agreement with camera technique.

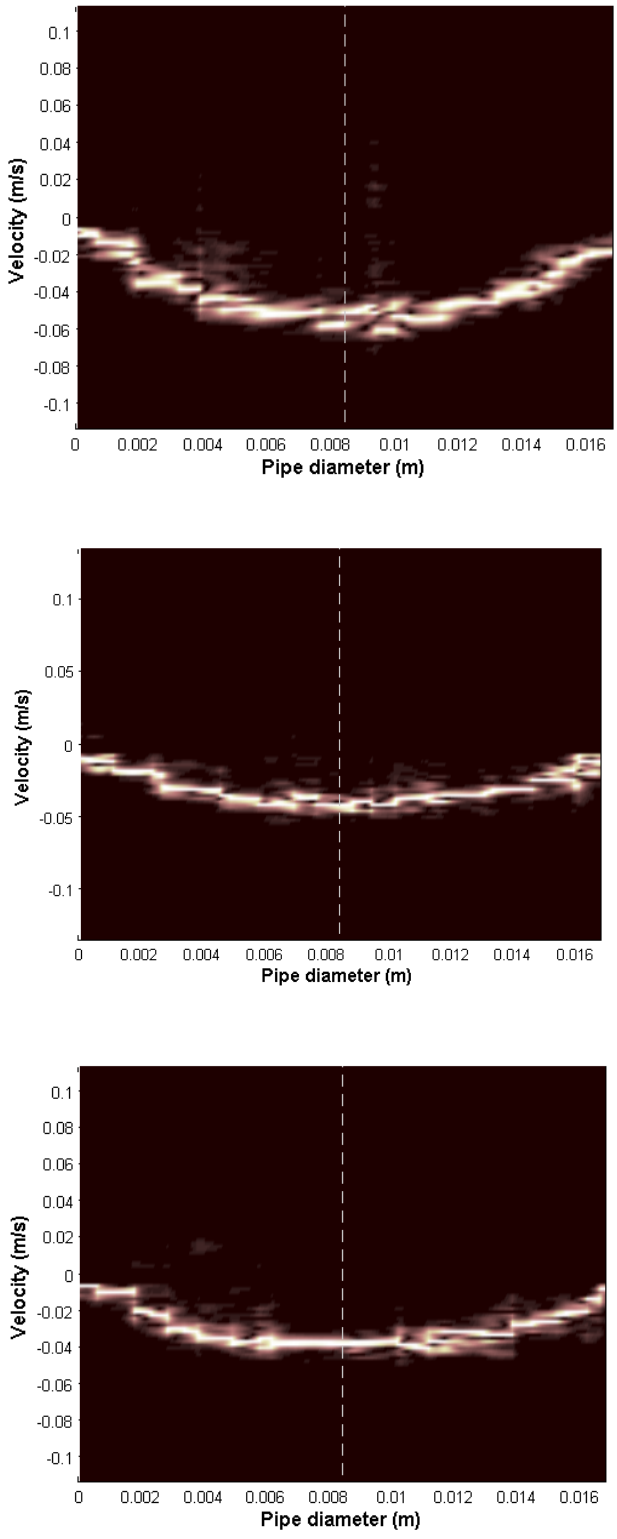


Figure 5: Velocity profiles of 0.78 Pa.s (top), 1.0 Pa.s (middle) and 1.7 Pa.s (bottom) maltodextrin bolus flow in the pharynx.

4. Summary

In this work an in-vitro device which mimics human swallowing was developed, the so-called "Gothenburg Throat Model". The model was equipped with high-speed camera, several pressure and temperature sensors and a novel ultrasonic velocity profiling (UVP) sensor to study the flow properties of liquid in the same way as during in-vivo experiments but non-invasively and without using any contrast media. The high-speed camera measurements showed that the model can be used to deliver bolus with realistic velocity, viscosity to accurately mimic human swallowing. Our UVP results obtained using maltodextrin with three different viscosities showed that velocity profile measurements can be made in the pharynx, both in continuous flow and bolus flow conditions with a good signal-to-noise ratio. The challenge is to measure accurate bolus profiles at different positions in the model due to the quick human swallowing process. The next objective will be to determine the shear rate distribution from the wall to the center from the velocity profiles measured with UVP. Differentiation of the obtained velocity profiles can provide the entire shear rate distribution from a single measurement. This type of data is currently not available in the literature. The developed model set-up can therefore become a valuable new tool for studying Dysphagia and to develop personalized easy-to-swallow food products for Dysphagia patients.

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