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ORIGINAL ARTICLE

Tongue Pressure Patterns During Water Swallowing

Daniel Kennedy · Jules Kieser · Chris Bolter · Michael Swain · Bhavia Singh · J. Neil Waddell

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Abstract Bolus propulsion during the normal oral phase of swallowing is thought to be characterised by the sequential elevation of the front, middle, and posterior regions of the dorsum of the tongue. However, the coordinated orchestration of lingual movement is still poorly understood. This study examined how pressures generated by the tongue against the hard palate differed between three points along the midline of the tongue. Specifically, we tested three hypotheses: (1) that there are defined individual patterns of pressure change within the mouth during liquid swallowing; (2) that there are significant negative pressures generated at defined moments during normal swallowing; and, (3) that liquid swallowing is governed by the interplay of pressures generated in an anteroposterior direction in the mouth. Using a metal appliance described previously, we measured absolute pressures during water swallows in six healthy volunteers (4 male, 2 female) with an age range of 25–35 years. Participants performed three 10-ml water swallows from a small cup on five separate days, thus providing data for a total of 15 separate water swallows. There was a distinct pattern to the each of the pressure signals, and this pattern was preserved in the mean obtained when the data were pooled. Furthermore, raw signals from the same subjects presented consistent patterns at each of the five testing sessions. In all subjects, pressure at the anterior and hind palate tended to be negative relative to the preswallow value; at mid–palate, however, pressure changes were less consistent between individuals. When the pressure differences between the sites were calculated, we found that during the swallow a net negative pressure difference developed between anterior and mid-palate and a net positive pressure difference developed between mid-palate and hind palate. Large, rapid fluctuations in pressure occurred at all sites and these varied several-fold between subjects. When the brief sharp reduction in pressure that occurred early in each swallow was used to determine the sequence of events, we found that activity occurred first at the anterior of the palate followed by the mid-palate and then the hind palate. There was a considerably longer and more variable delay between the start of activity at the front of the palate than at the rear of the palate. To obtain an index of the "effort" involved in generating the pressures at each site regardless of direction (positive or negative), we obtained the product of the root mean square (RMS) pressure change during each swallow (kPa) and its duration (s). Overall, the most effort appears to have occurred at the front of the palate and the least at mid-palate. Our results also showed that some participants exerted a small amount of midline pressure when swallowing, while others used a relatively large amount of tongue pressure. We conclude that while tongue behaviour during swallowing follows a classical sequence of rapid shape changes intended to contain and then propel the bolus from the oral cavity to the pharynx, there is a large range of individual variability in how this process is accomplished.

D. Kennedy · B. Singh
Department of Oral Sciences, Faculty of Dentistry, University of Otago, Dunedin, New Zealand

J. Kieser (✉)
Sir John Walsh Research Institute, Faculty of Dentistry, University of Otago, Dunedin, New Zealand
e-mail: jules.kieser@stonebow.otago.ac.nz

C. Bolter · J. N. Waddell
Department of Physiology, School of Medical Sciences, University of Otago, Dunedin, New Zealand

M. Swain
Department of Oral Rehabilitation, Faculty of Dentistry, University of Otago, Dunedin, New Zealand

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Introduction

The human tongue is a highly adaptable and intricately configured muscular organ whose actions are crucial to normal swallowing. Its activity during deglutition is a complex, integrated, biomechanical process that includes a series of rapid shape changes intended to contain and then propel the bolus from the oral cavity to the pharynx [1]. Impaired tongue function has a profound effect on swallowing. While numerous studies have focused on oropharyngeal kinematics (in other words, the motion of the bolus relative to other structures such as the tongue or hyoid bone), little consideration has been given to the forces that produce bolus motion [2]. A key question is whether it is possible to record pressure distributions within the mouth that can be used to reconstruct the temporal behaviour of the tongue during normal swallowing.

One of the first studies to investigate tongue pressure during swallowing was that of Kydd and Toda [3], who used transducers placed into an acrylic removable dental appliance. Not only did they find that mean forces required for swallowing saliva were higher than those for water, but that there was considerable intersubject variation in these forces. More recently, the Iowa Oral Performance Instrument, consisting of a hand-held measurement device connected to a single intraoral bulb, has been used by a number of researchers [4–10]. Although useful for simple assessment of tongue pressure, the usefulness of this device is limited by the size of the bulbs, lack of precise fit, and protruding recording wires that do not allow the jaws to close.

In an effort to focus attention on the simultaneous gathering of data from different sites within the mouth, Ono and coworkers [11, 12] have documented the pattern of contact between the tongue and hard palate during water swallowing. Using an acrylic appliance fitted with seven pressure sensors, they were able to show that the order, magnitude, and duration of tongue pressure against each part of the palate were highly coordinated. However, their recording device was not able to capture negative pressures that may occur at those sites.

To improve our understanding of pressure dynamics during swallowing, we recently introduced a rigid, custom-fitted platform for the simultaneous recording of absolute pressure within the oral cavity during function [13]. This device was able to deliver continuous readings of both positive and negative pressures from eight sites within the oral cavity. Our results highlighted two aspects that were not fully explored in those studies. First, we showed that large and prolonged negative pressures may be generated during swallowing. Second, we found that swallowing patterns appeared to vary substantially between individuals.

The objective of the present work was to expand our study of the patterns of intraoral contact pressure changes during deglutition. Specifically, we focus on the differences between individuals in the patterns (magnitude and timing) of changes in pressure along the midline of the tongue during water swallowing. Then we attempt to interpret these individual pressure patterns in terms of the functionality of the swallowing apparatus. In line with previous laboratory results, it has been shown that during liquid swallowing there are stable, spatially coordinated relationships between the mandible and three points along the midsagittal groove of the tongue: anterior (blade), middle (body), and posterior (dorsum) [14]. In this study we chose to determine the relationships of pressure exerted at these three lingual zones along the midline of the oral cavity rather than measure tongue/jaw spatiotemporal movement patterns.

We tested three hypotheses: (1) that there are defined individual (in respect to person) patterns of pressure change within the mouth during liquid swallowing, (2) that there are significant negative pressures generated at defined moments during normal swallowing, and (3) that liquid swallowing is governed by the interplay of pressures generated in an anteroposterior direction in the mouth. In other words, can these changes in pressure account for the movement of the fluid bolus?

Methods

This study protocol was approved by the University of Otago Ethics Committee.

Subjects

Our participants were six healthy volunteers (4 male, 2 female, age = 25–35 years), recruited from the postgraduate students at the School of Dentistry, University of Otago. All subjects had full permanent dentitions (with the exception of third molars) and Angle Class I occlusions with acceptable overbite and overjet relationships. All were in excellent medical condition with no history of orthodontic treatment, oromotor/swallowing defects, or neurologic conditions.

Chromecobalt Baseplate

Our appliance was designed to provide a rigid platform for the simultaneous measurement of pressure at specific buccal and palatal locations in the mouth [13]. Three miniature pressure transducers (Type 105 S, Precision Measurement

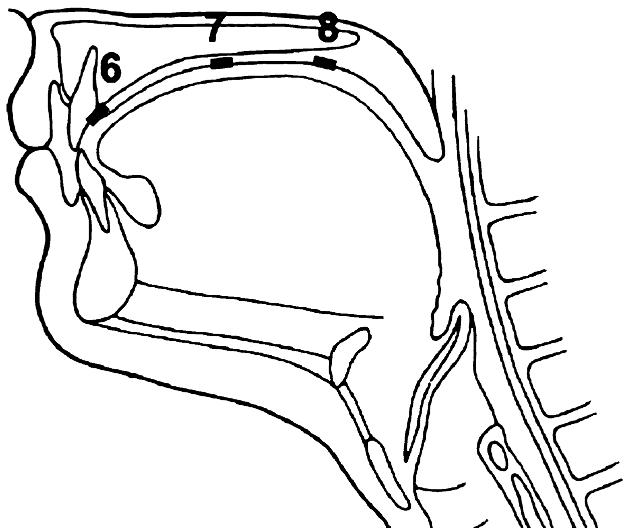

Fig. 1 Diagram showing the positioning of the three miniature pressure transducers in the midline: one on the palatal surface of the right upper central incisor tooth (6) and the other two in the midline of the palate, one at the level of the distal of the first premolar (7) and the second slightly anterior to the junction of the hard and soft palates (8). For ease of reference we have used the same numbers as those used in our previous article [3] to indicate the sensors

Company, Ann Arbor, MI, USA), with stainless-steel diaphragms, were used for absolute pressure measurement (0–420 kPa maximum peak negative and positive values; frequency response = 10 kHz). One transducer was located on the palatal surface of the right upper central incisor tooth (anterior palate) and the other two were placed in the midline of the palate, one at the level of the distal of the first premolar (mid-palate) and the second slightly anterior to the junction of the hard and soft palate (hind palate, Fig. 1). For ease of reference, we have referred to these sites using the same numbers that were used in our previous article: site 6 was anterior palate, site 7 was mid-palate, and site 8 was hind palate [13].

Data Recording

Data were obtained under aseptic conditions in a quiet testing laboratory. Subjects were seated comfortably in an upright position in a dental chair and encouraged to relax. After an initial 30-min period for accommodation, we recorded intraoral pressures while participants performed three 10-ml water swallows from a small cup. Each subject performed this procedure on five separate days, which provided data for a total of 15 separate water swallows. As described previously, raw data from the three transducers were filtered (100 Hz low pass) and recorded using an ADI ML 785 Power Lab via a Bridge Amplifier with LabChart software (ADInstruments, Castle Hill, NSW, Australia) at a rate of 100 samples per second. Data were saved to a computer. Each transducer was calibrated at the start of every session [13]. We used routines within the Chart programme to obtain the derived measurements that are described in the Results section. All raw and derived data were extracted digitally for further analysis (Excel spreadsheets) and graphical presentation.

Results

Initially, we examined raw data traces to determine the primary features of the response. In particular, we wished to identify features that occurred consistently across all subjects. From this overview, it was apparent that at all three recording sites there was an early, usually initial, brief sharp drop in pressure during swallowing (Figs. 2, 3, 4). Subsequently, we used this component of the signal to align the data temporally to examine and describe the signal at a specific site for each subject.

In addition to examining the pressure signal recorded at the three sites, we derived and examined the pressure differences between sites 6 and 7 and between 7 and 8. A positive value for these differences indicated that the pressure at the anterior site was positive relative to the pressure at the posterior site.

General Description of the Pressure Signal

To provide a summary description of the pressure changes that occurred during swallowing in a particular subject, we needed to demonstrate that there was sufficient between-trial consistency in the signals such that their major features would be retained when data were pooled. We were concerned with the reliability of the amplitude, polarity, and timing of the pressure signals. Figure 2 depicts the three original and two derived pressure signals obtained during a session with one subject. There was a distinct pattern to each of the pressure signals, and this pattern was preserved in the mean value of the pooled data. Furthermore, raw signals from this subject presented a consistent pattern at all five testing sessions (Fig. 3).

Similar consistency was evident for each subject, with the mean of the pooled data preserving the key features of the pressure signals (Fig. 4). In all subjects, pressure at the anterior and hind palate (sites 6 and 8) during the swallow tended to be negative relative to the preswallow value. In comparison, at mid-palate (site 7), pressure changes during swallowing were less consistent between individuals. They were generally smaller than the changes at 6 and 8, with some tending negative (subjects A, C, and D) and others tending positive (subjects B, E, and F).

When the pressure differences between the sites were calculated, we found that during the swallow a net negative

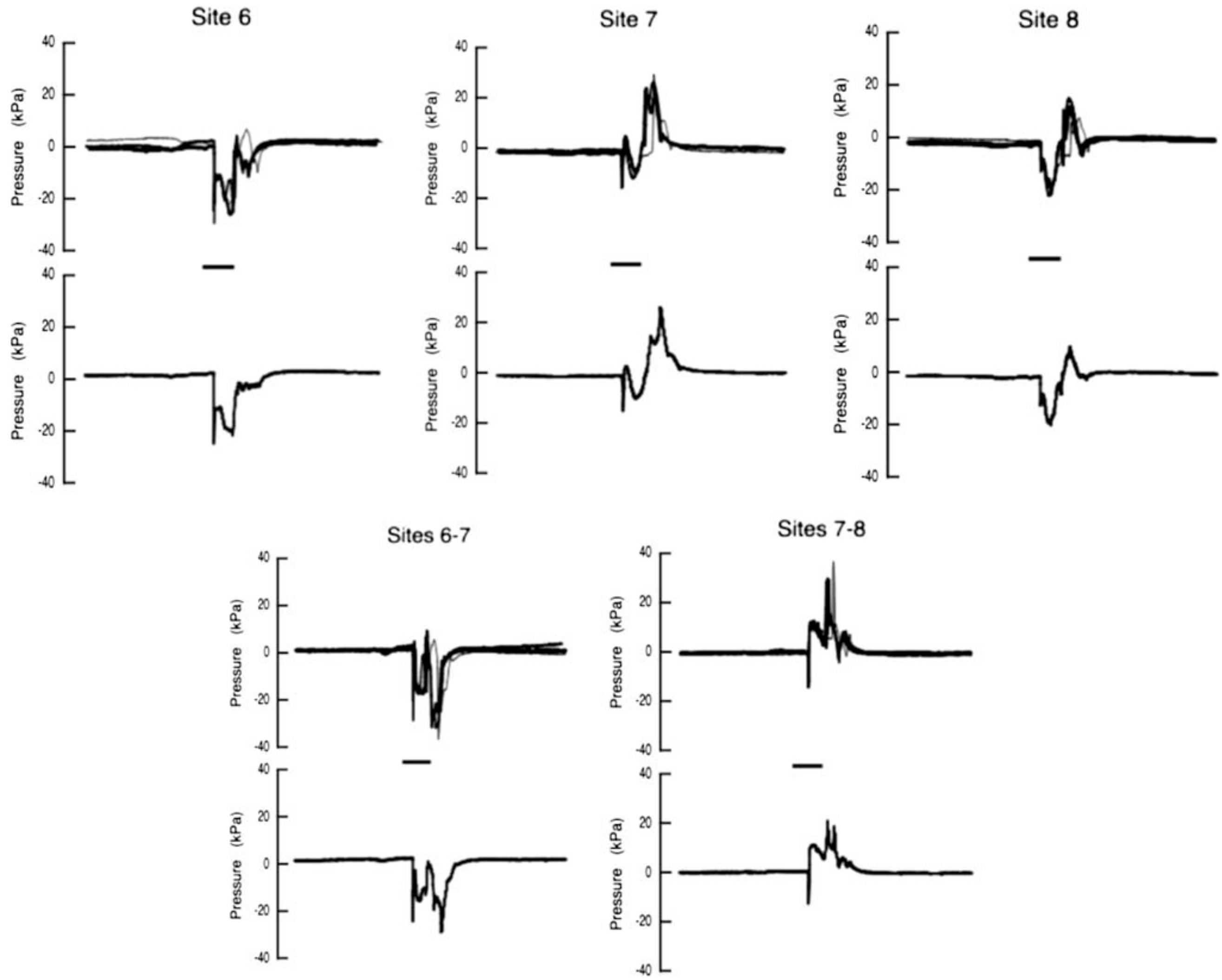

Fig. 2 Key features of the pressure fluctuations associated with a water swallow were preserved in the mean of pooled data. Records were obtained during a single session on one subject. The responses to the three consecutive swallows are shown in the upper part of each panel, and the mean of these responses is displayed in the lower part. Horizontal bars in each panel represent 1 s. The individual responses were aligned to the short sharp drop in pressure that occurred at the start of the complex of pressure fluctuations

pressure difference developed between anterior and mid-palate (sites 6 and 7) and a net positive pressure difference developed between mid-palate and hind palate (sites 7 and 8).

Values for Pressure and its First Derivative

Several features of the pressure signals were quantified. Figure 5 shows the time course of pressure and its first derivative for a swallow performed by a representative subject. Behaviour of the first derivative highlights the occurrence of sharp changes in pressure that occurred during the swallow, including the initial fall in pressure that we chose for the timing reference. For data from the recording sites (6, 7, and 8) and for the pressure difference between them (6–7, 7–8), we obtained the values for the peak negative and peak positive pressures and for the maximum positive and negative values for the first derivates of the pressure fluctuations. What is clear from the information in Figs. 6 and 7 is that large fluctuations in pressure occurred at all sites, and that some of these were rapid, achieving values in excess of $\pm$1,000 kPa s^{-1}. These fluctuations varied several-fold between subjects (compare subject B with subject D).

Timing

The brief, sharp reduction in pressure that occurred early in the swallow was used to determine the sequence in which the events occurred at the anterior, mid-, and hind palate (sites 6, 7, and 8). Figure 8 shows that activity occurred

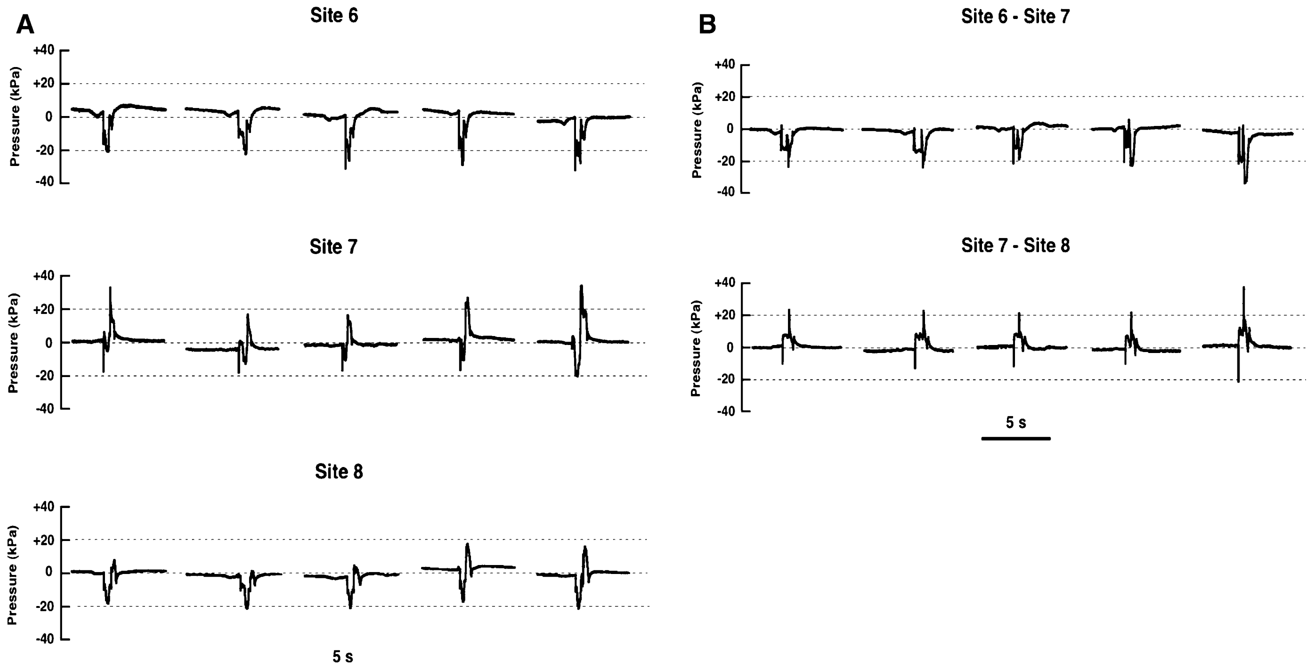

Fig. 3 Consistency, over five separate sessions, of pressure signals recorded from a single individual during a 10-ml water swallow. **a** Pressure at the three recording sites (anterior palate = 6, mid-palate = 7, and hind-palate = 8). **b** Calculated difference in pressure between sites 6 and 7 and sites 7 and 8. Each column shows the responses recorded during the second swallow on a separate experimental day

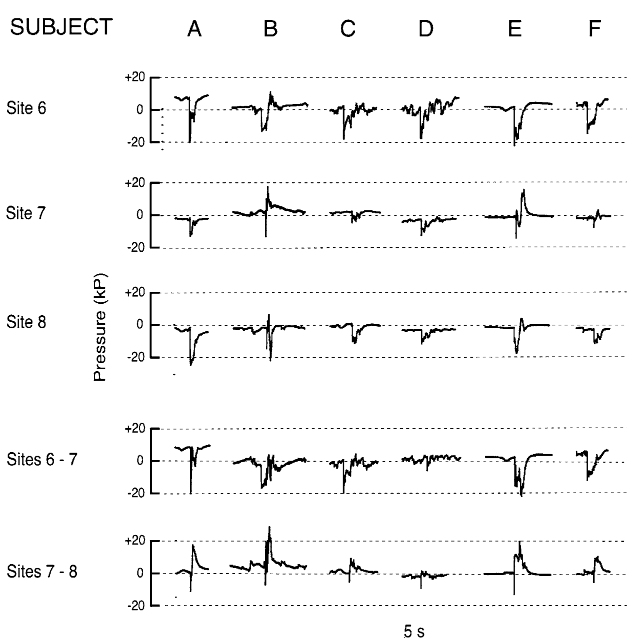

Fig. 4 Profile of pressure fluctuations during swallowing for each subject (columns A–F) during a 10-ml water swallow. The responses presented were derived as the mean of the responses obtained in the second trial on each of the five experimental days

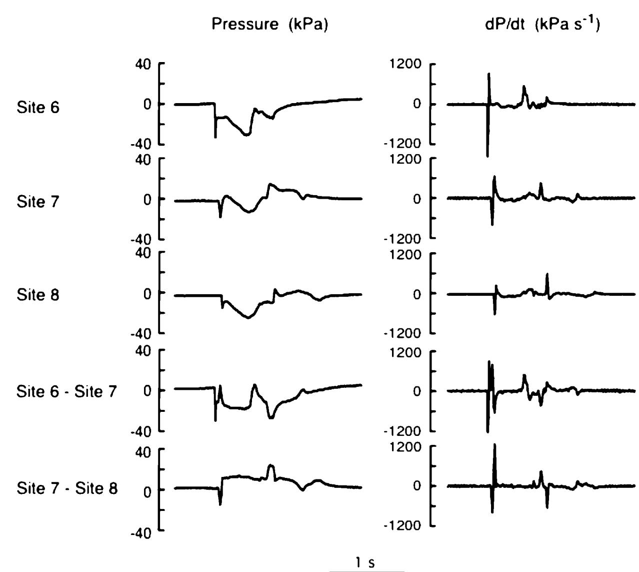

Fig. 5 An example from one subject of the pressure and pressure differences recorded at the three sites during a 10-ml water swallow and the first derivative of these signals. Data are from a single swallow performed by the subject whose data also appear in Figs. 2 and 3

first at the anterior of the palate (site 6), followed by the mid-palate (site 7), and the hind palate (site 8) in that order. In general, there was a considerably longer and more variable delay between the start of activity at the front of the palate (sites 6 and 7) than at the rear of the palate (between sites 7 and 8).

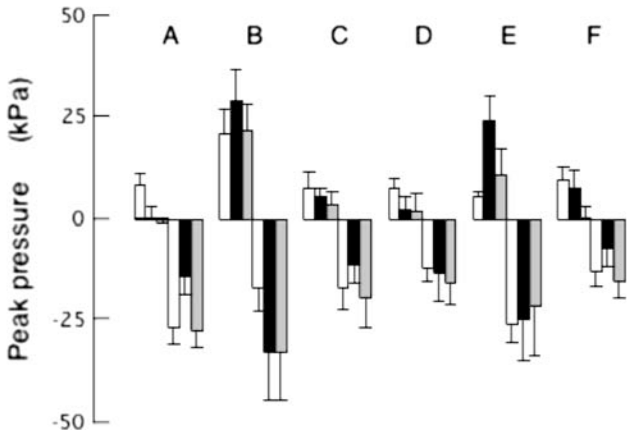

Fig. 6 Values of peak pressures achieved during swallowing. For each subject the first three bars show peak positive values and the second three bars show peak negative values. Open, filled, and gray bars represent data from sites 6, 7, and 8, respectively, and values are the mean ± SD of all swallows ($N = 15$) performed by each subject

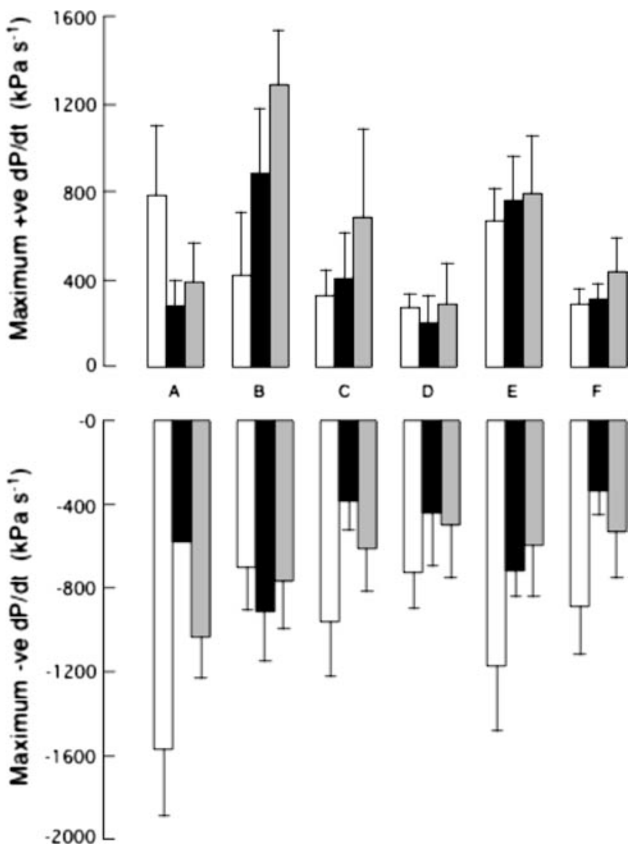

Fig. 7 Values of peak positive and peak negative *dP/dt* achieved during water swallowing. Open, filled, and gray bars represent data from sites 6, 7, and 8, respectively, and values are the mean ± SD of all swallows ($N = 15$) performed by each subject

Sustained Pressure

To provide an index of the potential for pressure fluctuations to generate a pressure gradient for fluid movement, we obtained the product of the net pressure change during the swallow and its duration. The magnitude and sign (positive or negative) of this product may reflect the net contribution of pressure fluctuations at each site to the generation of functional pressure gradients. The values for this product are presented in Fig. 9. All subjects showed a marked difference between the pressures sustained at site 7 versus sites 6 and 8, with differences ranging from about 5 kPa s (subject D) to 15 kPa s (subjects B and E).

To provide an index of the "effort" involved in generating the pressure fluctutations at each site, we obtained the product of the root mean square (RMS) of the pressure signal during each swallow (kPa) with its duration (s). This product will reflect the total effort of the mechanisms producing the pressure fluctuations. The values for this index are presented in Fig. 10. Overall, it appears that the greatest effort occurred at site 6 and the least effort at site 7.

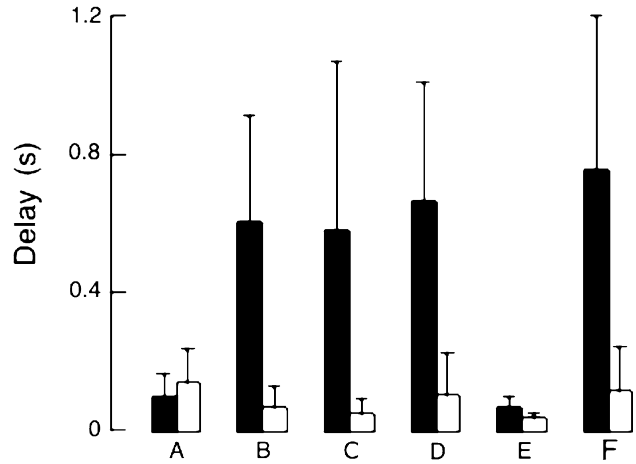

Fig. 8 Relative timing of the start of the pressure fluctuations at the three recording sites. Pressure fluctuations were initiated at site 6, followed by site 7, then site 8. The values for delay were calculated as the time differences between the sharp negative pressure waves recorded at the anterior and mid-palate sites (sites 6 and 7, solid bars) and between these negative waves at the mid- and hind-palate sites (sites 7 and 8, open bars). Values are the mean ± SD of all swallows ($N = 15$) performed by each subject

Discussion

It is thought that propulsion of the liquid bolus during swallowing is characterised by a sequential elevation of the anterior, middle, and posterior dorsal regions of the tongue [14–16], yet the coordinated activity of the tongue during typical and disordered swallowing remains poorly understood. The objective of the present work was to expand our study of the patterns of intraoral contact pressure changes during deglutition. We tested three hypotheses: (1) that there are defined individual patterns of pressure change within the mouth during normal water swallowing, (2) that

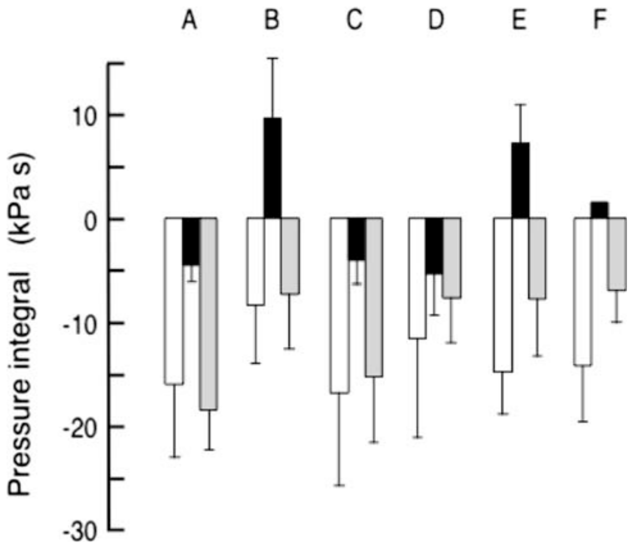

Fig. 9 Net direction and magnitude of the pressure development at each site during swallowing. These values show the integral of the absolute pressure at each site. At most sites the integral was negative, although in all subjects the integral was less negative, or even positive, at site 7. Open, filled, and gray bars represent data from sites 6, 7, and 8, respectively, and values are the mean ± SD of all swallows ($N = 15$) performed by each subject

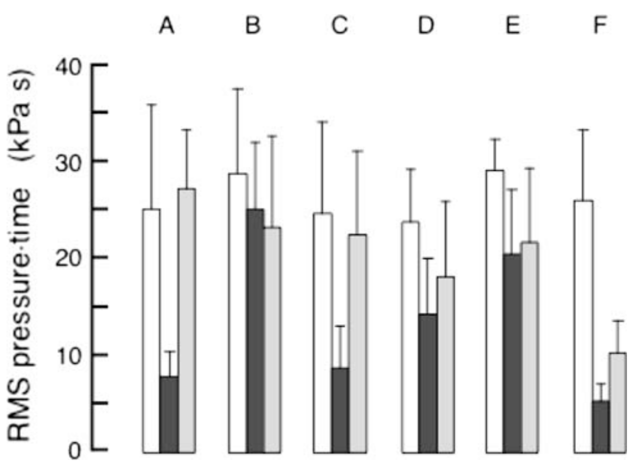

Fig. 10 Total sustained pressure development at each site during swallowing. These values show the integral of the rectified pressure signal (RMS value) at each site. Open, filled, and gray bars represent data from sites 6, 7, and 8, respectively, and values are the mean ± SD of all swallows ($N = 15$) performed by each subject

there are significant negative pressures generated at given moments during swallowing, and (3) that liquid swallowing is governed by an interplay of pressures generated in an anteroposterior direction in the mouth.

We found that the pressure profiles measured at the anterior, middle, and hind palate within an individual showed a high degree of reproducibility over a number of days (Fig. 2). However, there was much less uniformity in pressure profiles between individuals (Fig. 4). Shaker et al. [17] examined pressure flow dynamics from two supralingual sites in five volunteers using manometric gauges placed at the tongue tip and the dorsum of the tongue. They concluded that the oral phase of swallowing exhibited a wide range of intrasubject and intersubject pressure variation. Similarly, Youmans et al. [18] measured mean anterior tongue pressure in a large group of participants and found it to be highly variable between subjects. Our results, however, suggest that each individual had a reproducible pattern of pressure changes along the midline during normal swallowing. While some individuals had clearly defined profiles, others were "noisy," with frequent small fluctuations occurring within a dominant pressure profile (e.g., subjects B, C, and D in Fig. 4). The impression obtained from the graphs in Fig. 4 is that pressure profiles at the front of the palate (position 6) were more variable than at the mid- or hind palate, and that the pressure change at the mid-palate (position 7) was the smallest. This agreed well with the results from a recent X-ray microbeam study by Wilson and Green [19]. They observed greater similarity in the movement patterns of markers placed on the posterior of the tongue than of markers placed on the anterior. They attributed these differences to the operation of the tip and the blade of the tongue in securing the bolus against the palate.

Our results also show that some participants exerted a small amount of midline pressure when swallowing, while others used a relatively large amount of tongue pressure. This was particularly noticeable at the mid- and hind-palate (Fig. 4), where individuals 2 and 5 clearly had more forceful swallows than the other participants. These findings agree with those of Youmans et al. [18] who noted that since all their participants possessed normal swallowing ability, their results indicated a considerable variability in tongue physiology related to deglutition. Considerable variation of tongue movements during swallowing has also been reported in studies using ultrasound [20] and X-ray microbeam [15] recordings. Interestingly, Wilson and Green [20], using a similar method (microbeam), found the opposite to be the case, as did Chi-Fishman and Stone in their electropalatographical study [16]. To understand the effects of age on tongue function, Nicosia et al. [2] focused on lingual pressure generation during liquid swallowing. They showed that both young subjects reached maximum pressure with a first peak followed by a lower peak. In elderly individuals, maximum pressure was not reached on the first peak. This led to "pressure building," which they felt had important clinical implications because it was often associated with aspiration. Our results appear to question this finding; we clearly show that while some normal young subjects reach the maximum (albeit negative) pressure in the first peak, some do not. The reasons for this are not clear, but it does point to a need for future studies aimed at shedding light on interindividual variation in pressure generation during normal oral swallowing. The results will have a powerful bearing on the development of rehabilitative techniques for dysphagic patients.

In a recent article, Ono et al. [11] examined the patterns of tongue pressure on the hard palate during swallowing. To do this they recorded pressures simultaneously at seven different sites. They documented that tongue pressure was initially generated by the anteromedian part of the tongue, after which there was a well-coordinated series of contact events ending "…softly with the posteromedian part (of the tongue)" (p. 259). They also found that tongue pressure peaked rapidly, only to fade gradually before disappearing almost simultaneously from each site measured. Their approach to gathering these data was to use an acrylic plate fitted with sensors that recorded only positive pressure. However, as early as 1975, by using cantilever foil strain gauges fitted on the buccal aspects of the incisor teeth, Gould and Picton [21] had shown that negative pressures occur during swallowing. Using sensors that can respond to absolute pressure and which are mounted on a firm metal base, we are able to show both positive and negative pressure fluctuations that occur during normal swallowing. Interestingly, Figs. 2 and 3 clearly show that for that particular participant, anterior palatal pressures are almost entirely negative, in contrast to the mid- and hind palate where both negative and positive pressures are recorded for each swallow. This phenomenon is repeated in all the participants (Fig. 4).

Numerous studies have shown that the bolus is transported through the oral cavity by piston-like movements of the tongue during swallowing, and that these movements follow an orchestrated sequence from the anterior (blade), to the middle (body), and then on to the posterior (dorsum) of the tongue [14, 22, 23]. Despite accumulating electromyographic and videofluoroscopic evidence in support of this scenario, the physiologic role of tongue contact on the hard palate during swallowing has not been fully explored [12]. One of the critical questions that remain unanswered is whether the bolus is pushed or pulled toward the pharynx. In contrast to previous studies, our work clearly demonstrates that a combination of positive (push) and negative (pull) pressures are involved in water swallowing. This is illustrated in Fig. 5 which shows the pressure and its first derivative at each of the palatal locations for a given subject. The derivatives point to brief and rapid swings in pressure that occur during the swallow, including an initial fall in pressure (that we call the timing reference). What is clear from this Fig. 5 and from Fig. 6, which summarises the data for all subjects, is that large positive and negative fluctuations in pressure occurred at all sites and that some of these were rapid, achieving values in excess of ±1000 kP/s. Our recordings show that swallowing starts with a brief sharp *reduction* in pressure at the front of the palate (site 6), followed by drops in pressure at the mid-palate and then at the hind palate (site 7 and then site 8). In general, the delay between anterior and mid-palate (sites 6 and 7) is considerably longer and more variable than that between the mid- and hind palate (sites 7 and 8, Fig. 8). Taken together, this suggests that water swallowing is characterised by an initial pull followed by a positive lingual push toward the pharynx.

The results in Fig. 9 suggest that at sites 6 and 8 (anterior and hind palate) the pressure is substantially negative for the duration of the swallow, whereas at site 7 (mid-palatal) it is more balanced, with some individuals showing positive and some negative outcomes. The overall situation appears to be that the negative pressure predominates to assist transport of the liquid to the throat.

The results in Fig. 10 almost provide a counterpoint to the concept of some individuals exhibiting a more forceful swallow. If we consider sites 6 and 8, the observations in Fig. 10 show that there is a relatively small difference between individuals, with greater scatter at the mid-palate (site 7), probably reflecting the behaviour observed in Fig. 9. These observations also suggest that although the magnitudes (pressures recorded) differ for some individuals (e.g., subjects B and E), the summations of the duration of applied pressure during swallowing events are similar. Indeed, the sum of the outcomes at sites 6, 7, and 8 for all the individuals in Fig. 10 is remarkably consistent. This suggests that the work or energy expended to transport water, in this instance, through the oral cavity is almost constant.

In summary, our data suggest that while tongue behaviour during swallowing follows the classical sequence of rapid shape changes intended to contain and then propel the bolus from the oral cavity to the pharynx [1], there is a large range of individual variability in how this process is accomplished. It is thus questionable that there will ever be "norms" of sequential activity, a conclusion that would have a profound influence on clinical rehabilitative thinking.

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Daniel Kennedy BDS

Jules Kieser PhD

Chris Bolter PhD

Michael Swain PhD

Bhavia Singh MDS

J. Neil Waddell PGDipCDTech