Differential changes in human pharyngo-esophageal
motor excitability induced by swallowing, pharyngeal stimulation and anesthesia

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Short title: Pharyngo-esophageal excitability and sensorimotor input

Abbreviations: EMG, electromyography; NTS, nucleus of the tractus solitarius; T, Tesla; TMS, transcranial magnetic stimulation; UES, upper esophageal sphincter

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Abstract

We investigated the effects of water swallowing, pharyngeal stimulation and oro-pharyngeal anesthesia on corticobulbar and craniobulbar projections to human swallowing musculature. Changes in pathway excitability were measured via electromyography from swallowed intra-luminal pharyngeal and esophageal electrodes to motor cerebral and trigeminal nerve magnetic stimulation. Following both water swallowing and pharyngeal stimulation, pharyngo-esophageal corticobulbar excitability increased (swallowing: pharynx = +59 ± 12%, p<0.001; esophagus = +45 ± 20%, p<0.05, pharyngeal stimulation: pharynx = +76 ± 19%, p<0.001; esophagus = +45 ± 23%, p=0.05), being early with swallowing but late with stimulation. By comparison, craniobulbar excitability increased early after swallowing but remained unaffected by pharyngeal stimulation. Following anesthesia, both corticobulbar (pharynx = -24 ± 10%, p<0.05; esophagus = -28 ± 7%, p<0.01) and craniobulbar excitability showed a late decreased. Thus, swallowing induces transient early facilitation of corticobulbar and craniobulbar projections, while electrical stimulation promotes delayed facilitation mainly in cortex. With removal of input, both corticobulbar and craniobulbar projections show delayed inhibition, implying a reduction in motoneuron and/or cortical activity.
Introduction

Swallowing is a complex sensorimotor activity which depends upon a hierarchical interaction between the cerebral cortex, the brainstem swallowing center and cranial nerves V, IX, X and XII (11). The process of swallowing has both volitional and reflexive components reflecting central pathways within swallowing centers in the cortex and brainstem respectively, but is highly dependent on sensory feedback both for its initiation, and modulation during the patterned sequence of neuromuscular events (12).

Over the last decade, transcranial magnetic stimulation (TMS) has become a well-established non-invasive technique for interrogating human cortical physiology (5). TMS appears to have much of its effect due to intra-cortical influences upon the excitability of interneurones within the motor cortex resulting in indirect activation of cortico-spinal tracts through synaptic inputs (5). TMS has recently been used to map the normal pattern of motor cortex projections to a number of swallowing muscles in healthy adult humans by evoking and mapping EMG responses in oral, pharyngeal and esophageal musculature (9). This demonstrated that the swallowing muscles are somatotopically but asymmetrically represented on the motor and premotor cortex of both cerebral hemispheres. This asymmetry is independent of handedness and greatest in the pharynx and esophagus. More recently, TMS has been used to measure pharyngeal responses in patients with brain injury, on admission and at 1 and 3 months after dysphagic hemispheric stroke (8). The study found that return of swallowing was associated with increased pharyngeal representation in the unaffected hemisphere, suggesting, firstly that compensatory adaptation the intact hemisphere drives much of this recovery and secondly that these responses have physiological relevance to swallowing recovery in stroke.
The cranial nerves involved in swallowing, convey much of this sensory input and display extensive brainstem convergence, with trigeminal (and vagal) afferent fibres terminating within the trigeminal spinal nuclei and nucleus tractus solitarius (NTS) of the dorsal region of the brainstem swallowing centre (11, 15-16). These afferent fibres are not only capable of influencing brainstem motoneuron and interneuron excitability, but also that of higher circuitry in the cerebral cortex (12, 18, 19). Indeed, previously TMS studies have shown that excitation of (afferent) pathways in cranial nerves V and X, for example from the face or neck, produces a “reflex” response in the human pharynx and esophagus which is likely to be generated via neurons within the brainstem, and possibly through the central pattern generator itself (6, 7). Stimulation of these craniobulbar responses, when combined with cortical input, produce short-term (100-200ms) facilitation of the cortically evoked pharyngeal and esophageal responses, suggesting that both pathways involve similar populations of bulbar neurons.

Alterations in sensory input by peripheral stimulation also produce more persistent changes in motor cortical excitability (4, 10): 10 minutes of pharyngeal stimulation increases pharyngeal cortical excitability for at least 30 minutes after the input, without changes in bulbar excitability. The application of pharyngeal stimulation to dysphagic stroke patients produces similar corticobulbar changes, which crucially are associated with short-term improvements in swallowing performance, seen as a reduction in aspiration at videofluoroscopy. Whether such central changes can be driven by more natural stimuli such as that produced by volitional water swallowing remains uncertain. Moreover, little is known about the effects of oro-pharyngeal anesthesia on the central swallowing pathways. There is evidence that a reduction in oro-pharyngeal sensation by local anesthesia can disrupt the normal pattern of volitionally initiated swallowing measured by manometry (13), with the speculation that there could be centrally mediated factors.
Despite these suggestions, the comparative effects of increased sensory input (e.g. the motor task of swallowing vs. direct pharyngeal stimulation) or decreased sensory input (anesthesia) on the excitability of human pharyngeal and esophageal projections from cortex to motoneuron have not been examined. This is of particular importance, as an appreciation of how interventions such as behavioral training, passive stimulation, and denervation can alter central neural swallowing physiology is likely to be of importance in guiding the future rehabilitation of swallowing problems after brain injury (4).

The aims of our study were therefore to compare and contrast the effects of volitional (water) swallowing, pharyngeal (electrical) stimulation and oro-pharyngeal (topical) anesthesia on corticobulbar and craniobulbar pharyngo-esophageal sensorimotor pathways in healthy human subjects.

Methods

Participants: were healthy adult (n=8) volunteers (6 male, age range 24-36 yrs, mean age 31 yrs). None reported any swallowing problems and all gave informed written consent before study, previously approved by the Salford and Trafford Health Authority Ethics Committee.

Electrophysiological Techniques

Cortical stimulation: was performed using a magnetic stimulator (Magstim 200, MAGSTIM Company Limited, Whitland, Dyfield SA34 0HR, Wales) connected to a 70 mm outer diameter figure-of-8 coil, placed over the regions of interest on the scalp (9). Using this configuration, the maximal magnetic field generated by the stimulator is 2.2 Tesla (T).
Cranial nerve stimulation: was performed using the magnetic stimulator connected to a smaller, 50 mm diameter, figure of eight coil, placing the centre of the coil over the supraorbital branch of the trigeminal nerve on the face, as previously described (6). Using this configuration, the maximum magnetic field generated by the stimulator is 2.0 T.

EMG responses: were detected from the pharynx and upper esophagus using 2 pairs of bipolar platinum ring electrodes, 7 cm apart, built into a 3 mm diameter, intra-luminal catheter (Gaeltec, Dunvegan, Isle of Skye IV55 8GU, Scotland). Two single solid-state strain gauge transducers (Gaeltec) also incorporated into the catheter, one between each electrode pair enabled manometric positioning of the catheter within the lumen. Each electrode pair was connected to a pre-amplifier (CED 1902, Cambridge Electronic Design, Cambridge CB4 4FE, England) with filter settings of 5Hz-2kHz. Response signals were then collected through a laboratory interface (CED 1401 plus) at a sampling rate of 4-8 kHz.

Electrical stimulation of the pharynx: was performed using the pharyngeal electrodes connected to an electrical stimulator (Model DS7; Digitimer, Welwyn-Garden City, Herts, UK) via a trigger generator (Neurolog System, Digitimer), which delivered stimuli (0.2 ms pulses, 280 V) at a frequency of 5 Hz, as previously determined (4), using a set intensity of 75% maximum tolerated sensation (see below) and 10 minutes duration.

Volitional water swallowing: Sterile water was infused from a 1000 ml capacity fluid reservoir attached to a plastic infusion line, the ending of which was placed into the oral cavity in the mid-line, 4 cm from the incisors. The base of the fluid reservoir was positioned 10 cm above the mastoid processes. The infusion line was connected to a peristaltic pump (H.R. Flow Inducer, Watson-Marlowe Ltd., Falmouth, Cornwall, UK), allowing continuous
water infusion at a rate of 60 ml per minute, thus maintaining a constant bolus volume per swallow of 5 ml when subjects swallowed at a fixed frequency of 0.2 Hz.

**Topical anesthesia of the pharynx:** Twenty standard dose aerosol puffs (equivalent to 200mg) of Lidocaine (Xylocaine Spray, AstraZeneca AB, Kings Langley, Hertfordshire, UK) were sprayed into the oro-pharynx of each subject, the applicator being placed 4 cm aboral to the incisors in the midline. At the end of the application, the subject was asked to swallow rapidly 3 times to ensure adequate dispersion of the local anesthetic.

**Pharyngeal sensory thresholds:** In order to quantify the level of electrical pharyngeal stimulation to be applied and to assess the effects of topical anesthesia, electrical pulses (0.2 ms pulses, 280 V) were delivered to the pharynx at 5 Hz using the pharyngeal electrodes of the swallowed intraluminal catheter, and the mean of three (just perceived) sensory thresholds (ST\textsubscript{min}) and maximum tolerated sensory thresholds (ST\textsubscript{max}) were measured. The 75% maximum tolerated intensity was calculated as: \( ST_{\text{min}} + 0.75(ST_{\text{max}} - ST_{\text{min}}) \).

**Experimental Protocols**

For each study, the volunteer sat comfortably in a chair and the pharyngo-esophageal EMG catheter inserted transnasally or transorally depending on subject preference. The catheter was then adjusted manometrically so the pharyngeal electrodes were 3 cm above and the esophageal electrodes 4 cm below the upper esophageal sphincter (UES).

The cranial vertex was then marked on the scalp, and the optimal sites for magnetic stimulation determined for both the pharynx and esophagus by discharging the 70 mm figure-of-eight coil over multiple scalp positions using supra-threshold stimulus intensities.
The sites evoking the largest EMG responses for the pharynx and esophagus were then identified and marked on the scalp. A series of cortical stimulations over these positions was then performed, commencing at a sub-threshold intensity and increasing by 5% stimulator output steps until a threshold intensity was found which evoked pharyngeal and esophageal EMG responses of greater than 20 µV on at least 5 of 10 consecutive trials. Repeated stimulations were then carried out at intensities of: 95, 100, 105 and 110% threshold, in a randomised order. Ten stimuli were delivered at each intensity, with an interval of 5 seconds between each stimulation.

The right trigeminal nerve was then stimulated at supra-threshold intensities by discharging a 50 mm figure of eight coil over the face. Again, the site evoking the largest reflex EMG responses for the pharynx and esophagus was identified and marked. Following a series of cranial nerve stimulations commencing at sub-threshold intensity, stimulator output steps were increased by 5% and a threshold intensity evoking pharyngeal and esophageal reflex EMG responses of greater than 10 µV on at least 5 of 10 consecutive trials was identified. Twenty stimulations at 120% threshold were then carried out at 5-second intervals.

The following protocols were performed on separate days in randomised order. Inter-study intervals were at least 24 hours. In pilot measurements (n=6) of corticobulbar (pharyngeal) excitability to only having the catheter inserted (without any intervention), responses were unchanged after 30 or 60 minutes (Δ = 4±6% and 7±3%, p=0.54, respectively), compared to baseline responses recorded immediately after intubation. Subjects swallowed on average once per minute during these measurements. Thus, these
control studies demonstrated that there was no effect of the catheter alone on excitability measured by TMS.

**Protocol 1: Effects of volitional swallowing on corticobulbar and craniobulbar motor pathways**

Following the baseline procedure outlined above, the pharyngo-esophageal catheter was left in situ and the water infusion line inserted into the subject’s mouth, 4 cm aboral to the incisors. During water infusion, each subject swallowed a 5 ml bolus of sterile water every 5 seconds for 10 minutes using an analogue clock as a visual cue. As an additional measure, the experimenter also recorded the number of swallows during this interval. The infusion line was then removed and cortical and cranial nerve stimulations were performed immediately and at 15-minute intervals for 1-hour, using the identical intensities and experimental sequence to that used for the baseline measures.

**Protocol 2: Effects of pharyngeal stimulation on corticobulbar and craniobulbar motor pathways**

As with protocol 1, following baseline measures with the catheter in situ, electrical stimulation of the pharynx was applied for 10 minutes at a frequency of 5Hz, using a predefined current of 75% of the maximum tolerated intensity. The experimenter also recorded the number of swallows during pharyngeal stimulation. Following 10 minutes of stimulation, cortical and cranial nerve stimulations were performed immediately and at 15-minute intervals for 1-hour, using the identical intensities and experimental sequence to those used for the baseline measures.
Protocol 3: Effects of oro-pharyngeal anesthesia on corticobulbar and craniobulbar motor pathways

As with protocol 2, following baseline measures, and with the catheter in situ, the pharyngeal sensory threshold (defined above) was measured. Two hundred milligrams of lidocaine was then sprayed into the oro-pharynx. The number of spontaneous swallows was then recorded over the next 10 minutes. Cortical and cranial nerve stimulations, using the identical intensities and experimental sequence to those used for the baseline measures followed by re-checking of pharyngeal sensory thresholds was then performed immediately and at 15-minute intervals for 1-hour.

Data Analysis

For each protocol, the individual mean values of the cortically evoked early and craniobulbar evoked late EMG responses were compared using two-way ANOVA (Friedman test) across all intensities, for each interval in both the pharynx and esophagus: (i) to determine the effect of time against pre-stimulation levels and (ii) to determine the conditional effects of volitional swallowing, pharyngeal stimulation and oro-pharyngeal anesthesia.

The response amplitude was defined as the peak-to-peak difference in the EMG potential and the response latency was defined as the time taken between stimulus onset and the onset of the first deflection of the relevant EMG potential.

Results

The mean intensity used for cortical stimulation across studies was 1.7 ± 0.1 T. In all subjects, cortical stimulation evoked reproducible early biphasic or triphasic pharyngo-esophageal responses (Fig 1), with pre-intervention mean amplitudes of 57±9 and 47±8
μV for pharynx and esophagus, respectively. The mean intensity used for trigeminal nerve stimulation was 1.1 ± 0.2 T. In all subjects, trigeminal nerve stimulation evoked early (~25 ms) and late (~60 ms) EMG pharyngo-esophageal responses, which were usually polyphasic. Because these early reflex responses were small and inconsistent, only the late responses (pre-intervention mean amplitudes being 32±4 and 28±6 μV, for pharynx and esophagus, respectively) are reported below. The number of swallows made during water swallowing, pharyngeal stimulation and anesthesia were 120 ± 5, 23 ± 3 and 9 ± 1 respectively.

**Effects of volitional swallowing on corticobulbar and craniobulbar motor pathways**

Volitional swallowing of water bolus was well tolerated by all subjects. The effects of volitional swallowing on the cortical and craniobulbar pathways are shown in Figures 1 and 2, and Table 1.

**Corticobulbar:** Both pharyngeal and esophageal cortically evoked response amplitudes were facilitated immediately after volitional swallowing (pharynx Δ = +59 ± 12%, p<0.001; esophagus Δ = +45 ± 20%, p<0.05) before returning to baseline. There was also a small reduction in response latencies at 15 min, p<0.01 (Table 1).

**Craniobulbar:** As with the cortical responses, swallowing facilitated both pharyngeal and esophageal cranial nerve evoked response amplitudes. Again, the main effect occurred immediately after volitional swallowing (pharynx Δ = +70 ± 20%, p<0.01; esophagus = Δ +49 ± 9%, p<0.01). Response latencies were also decreased at 15 min, p<0.05 (Table 1).
Effects of pharyngeal stimulation on corticobulbar and craniobulbar motor pathways

Pharyngeal stimulation was well tolerated, being described by subjects as a “sharp buzzing” or “acid” sensation felt in the throat. Mean stimulation intensity for pharyngeal stimulation was 13.7 ± 0.5 mA. The effects of pharyngeal stimulation on the cortical and craniobulbar pathways are shown (Figures 1 and 3, Table 1).

Corticobulbar: Pharyngeal stimulation facilitated pharyngeal and esophageal cortically evoked response amplitudes. Compared to volitional swallowing, changes were greater both in magnitude and duration. Pharyngeal response amplitudes were more affected than the esophageal responses, the maximal effect being seen at 60 min (pharynx Δ +76 ± 19%, p<0.001; esophagus Δ = +45 ± 23%, p=0.05). Response latencies were unaffected.

Craniobulbar: In contrast to cortical responses, pharyngeal and esophageal cranial nerve responses were unaffected by pharyngeal stimulation.

Effects of oro-pharyngeal anesthesia on corticobulbar and craniobulbar motor pathways

Oro-pharyngeal anesthesia was tolerated without difficulty. Sensory threshold increased from 4.7 ± 1.0 mA pre-anesthesia to a maximum of 9.1 ± 1.2 mA immediately afterwards, before returning to baseline by 60 min (Figure 4). The effects of oro-pharyngeal anesthesia on the cortical and craniobulbar pathways are shown (Figures 1 and 5, and Table 1).

Corticobulbar: Oro-pharyngeal anesthesia inhibited both pharyngeal and esophageal cortically evoked responses. The main effect occurred 45 min post-anesthesia (pharynx Δ = -24 ± 10%, p<0.05; esophagus Δ = -28 ± 7%, p<0.01). In addition, both pharyngeal and esophageal response latencies were increased at 45 minutes, p<0.05 (Table 1).
Craniobulbar: Oro-pharyngeal anesthesia inhibited only the pharyngeal evoked responses (pharynx $\Delta = -37 \pm 11\%$, p<0.05). Response latencies were also increased in the pharynx at 30 minutes, p<0.05 (Table 1).

Discussion

In previous studies we have demonstrated that short-term sensory stimulation of the pharynx can induce sustained changes in the corticobulbar pathway to pharynx and esophagus (4, 10), which we argued were indicative of “cross-system” effects in the cortical swallowing network. Our data now show that both the level and duration of motor excitability with the pharynx and esophagus can be altered within both corticobulbar and craniobulbar projections depending on the nature of the (sensorimotor) input.

With respect to volitional swallowing, we observed a transient early increase in corticobulbar excitability for pharynx and esophagus in the period immediately after swallowing, mirrored by the reflexes to cranial nerve stimulation. One implication from these findings is that volitional swallowing could be altering brainstem circuitry, which in turn facilitates the changes in cortical excitability. Excitation of the brainstem would seem entirely reasonable, given that swallowing engages the entire deglutitive apparatus, so that input from multiple swallowing fibres will be arriving at the nucleus of the tractus solitarius (NTS), before converging on brainstem swallowing interneurons and motoneurons (11, 12). Such continuous input to brainstem circuitry would probably provide more persistent (excitability) changes in the network that might be expected to last minutes rather than milliseconds, as normally seen after a single swallow. Whether volitional swallowing could have direct effects on cortical swallowing excitability, remains less clear, since any brainstem changes would mask the former. Previous work assessing the effects of task
training on cortical excitability has demonstrated that motor system organisation can be modified by long periods of muscle use (3): an effect termed use-dependent plasticity. An example of this is seen after extensive (hours) use of the hand muscles in violin playing, where the motor cortical representation of the target hand muscle becomes enlarged, without changes in spinal (motoneuron) excitability (3). Thus, it is possible that a similar phenomenon might be occurring to repetitive swallowing, although in the absence of direct intra-cortical recordings this suggestion must remain speculative.

In contrast to volitional swallowing, pharyngeal stimulation produced a sustained, albeit delayed, increase in corticobulbar excitability without altering craniobulbar excitability, a pattern seen in our previous studies. This effect occurred well beyond the period of input, being maximal at 60 minutes after stimulation. As with the findings from our previous experiments (4), it seems that pharyngeal stimulation can affect cortical excitability by activating direct and/or indirect ascending pathways to pharyngeal motor cortex. Nonetheless, an important question raised by our data is: why does pharyngeal stimulation NOT induce the same sustained excitation in craniobulbar circuitry as with volitional swallowing? To answer this question, it is relevant to consider the sensory innervation of the pharynx, and it’s processing within the brain. Input from the pharynx projects to NTS via the glossopharyngeal nerve and the superior laryngeal branch of the vagus. From this relay, input is conveyed to interneurons of the central pattern generator, and via a relay in the pons to cortical centres (12). During volitional swallowing, the entire sensorimotor sequence (involving trigeminal, glossopharyngeal and vagal cranial nerves) is activated whereas during pharyngeal stimulation, the input is from a small area of pharynx alone. Pharyngeal stimulation applied by our methodology may not, therefore, provide enough direct sensory input to produce long-term alterations in lower level circuitry, even though it seems adequate for cortical excitation.
A further possible explanation is that with volitional swallowing, there are likely to be strong descending cortical inputs to the brainstem associated with each task. Cortical input has been shown in animals to directly excite swallowing circuitry within the brainstem, and can initiate swallowing movements (2, 20). In contrast, the cortical drive to the brainstem swallowing centres with pharyngeal stimulation alone may actually be reduced, as subjects try to suppress the urge to swallow. Indeed, in our study, pharyngeal stimulation produced less than 1/5th of the number of swallows produced by the active volitional swallowing task. The result may be that pharyngeal stimulation produces much less cortically derived excitability on the brainstem, and that the latter may be important for inducing more sustained excitatory changes in brainstem swallowing circuitry, when measured by craniobulbar stimulation.

A final explanation relates to the nature of the reflex responses evoked to cranial nerve stimulation. In previous studies (6, 7) we argued that the early and late pharyngo-esophageal reflexes evoked to both vagal and trigeminal nerve stimulation were likely to be brainstem in origin. The reason for this contention was that: i. The morphology and latency of the responses were similar to the R1 and R2 reflexes seen in the blink reflex, which has been well characterised, and recognised to be brainstem mediated (1); ii. The properties of these reflexes, to differing inputs (e.g. pharyngeal stimulation) were dissimilar to responses evoked to cortical stimulation: in the case of the latter, the cortical response is facilitated when the reflex response is not. Nonetheless, it is conceivable that the late reflex response may be trans-cortical in nature, multisynaptic, and impinge on cortical networks outside of those utilised by the corticopharyngeal pathways evoked to TMS. If this were the case, then volitional swallowing, which likely activates all cortical swallowing networks would activate both pathways. However, pharyngeal stimulation, being more
direct, might only activate the cortico-pharyngeal pathway without altering excitability in other cortical swallowing networks and hence not affect the “reflex” response. Against this notion is the fact that following volitional swallowing (and with anesthesia) there were latency shifts in both pathways, which are more typically seen when motoneurons in the bulbar nuclei and or muscle are depolarised (7). At present, our data cannot fully resolve the issue of the nature of the reflex pathway, and consequently this remains open to further study.

Following oro-pharyngeal anesthesia, both cortical and craniobulbar excitability was reduced, the effect maximising at 45 minutes, when sensory thresholds were returning to normal. Given our observations, it could be argued that the change in excitability was secondary to changes in the muscle or motoneuron. Locally applied anesthesia such as lidocaine will preferentially block A-delta and C-fibres involved in sensory transmission, compared to A-beta fibres, which are more involved in motor function (14). The fact that sensory thresholds were normalising implies that the anesthetic effects on A-delta and C-fibre function were starting to recover. Our data cannot determine whether there were both motoneuron and/or direct cortical effects. Certainly, the small increase in latency might imply that some of the inhibition was occurring in lower-level circuitry. However, in a previous study looking at the effects of anesthesia (nerve block) on hand muscles, cortical representation of the affected muscle was reduced, without concomitant reductions in peripheral or root reflexes, implying that much of the effect was cortical (17). Therefore, as with our other models of stimulus-induced pharyngo-esophageal motor cortex excitability, where the effects of stimulation take time (> 30 minutes) to build up, removal of input may also take time to alter cortical properties. Of course in the latter case, it is complicated by the restoration of sensation, but again possibly with a delay. Interestingly, only pharyngeal (and not esophageal) craniobulbar responses were affected by the anesthesia. Whether
this is a consequence of the fact that the anesthesia was directed to the oro-pharynx and not the esophagus remains unclear. Certainly less anesthesia would have reached the upper esophagus, and perhaps a specific threshold of reduced input needs to be attained to drive any excitability changes. Nonetheless, despite the craniobulbar esophageal responses being unaffected, the cortically evoked esophageal responses where affected: this latter observation provides some evidence for the effect of anesthesia being in part at least at the level of the cortex. However, given the current limitations of the techniques used, these interpretations, on both corticobulbar and craniobulbar excitability, remain open to further study and speculation.

From a therapeutic perspective, our data provide some evidence to support the notion that if driving cortical changes are important in recovery of swallowing after stroke, then both volitional swallowing and pharyngeal stimulation appear to have the necessary “stimulus-driven” excitatory properties to promote such effects (4). However, from our observations in healthy subjects at least, it appears that the larger and longer lasting effect is provided by pharyngeal stimulation. This has advantages in dysphagic stroke patients, where performing volitional swallowing would be challenging, while pharyngeal stimulation is relatively passive, and involves little patient compliance. Thus, based on these finding, we would favour stimulation techniques over volitional exercises as the most beneficial approach to rehabilitate the dysphagic swallow after cerebral injury. Perhaps, future studies, assessing the relative merits of each technique in patients with neurogenic dysphagia will help to answer this question more definitively.
Acknowledgements

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References


Table 1: Table of cortical and brainstem evoked response latencies for (A) pharynx and (B) esophagus after volitional (water) swallowing, pharyngeal stimulation and oro-pharyngeal anesthesia post-lidocaine. Data are mean ± SEM (*p<0.05 compared to baseline).

### A. Pharyngeal cortical and craniobulbar response latencies

<table>
<thead>
<tr>
<th>Condition</th>
<th>Volitional swallowing</th>
<th>Pharyngeal stimulation</th>
<th>Oro-pharyngeal anesthesia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cortex (ms)</td>
<td>Craniobulbar (ms)</td>
<td>Cortex (ms)</td>
</tr>
<tr>
<td>Pre</td>
<td>8.6 ± 0.4</td>
<td>58.4 ± 1.5</td>
<td>7.8 ± 0.3</td>
</tr>
<tr>
<td>Immediate</td>
<td>7.8 ± 0.3</td>
<td>54.7 ± 2.1</td>
<td>6.9 ± 0.4</td>
</tr>
<tr>
<td>15min</td>
<td>7.7 ± 0.4*</td>
<td>52.6 ± 1.4*</td>
<td>6.5 ± 0.5</td>
</tr>
<tr>
<td>30min</td>
<td>8.1 ± 0.3</td>
<td>53.3 ± 1.3</td>
<td>6.4 ± 0.3</td>
</tr>
<tr>
<td>45min</td>
<td>7.9 ± 0.3</td>
<td>54.9 ± 1.7</td>
<td>6.8 ± 0.4</td>
</tr>
<tr>
<td>60min</td>
<td>8.0 ± 0.2</td>
<td>56.4 ± 1.6</td>
<td>6.7 ± 0.3</td>
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</table>

### B. Esophageal cortical and brainstem response latencies

<table>
<thead>
<tr>
<th>Condition</th>
<th>Volitional swallowing</th>
<th>Pharyngeal stimulation</th>
<th>Oro-pharyngeal anesthesia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cortex (ms)</td>
<td>Craniobulbar (ms)</td>
<td>Cortex (ms)</td>
</tr>
<tr>
<td>Pre</td>
<td>10.1 ± 0.4</td>
<td>61.4 ± 2.4</td>
<td>9.5 ± 0.3</td>
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<tr>
<td>Immediate</td>
<td>8.9 ± 0.4</td>
<td>57.9 ± 2.6</td>
<td>9.1 ± 0.4</td>
</tr>
<tr>
<td>15min</td>
<td>8.7 ± 0.3*</td>
<td>56.6 ± 2.0*</td>
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<tr>
<td>30min</td>
<td>9.1 ± 0.4</td>
<td>57.1 ± 3.1</td>
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<td>45min</td>
<td>9.4 ± 0.4</td>
<td>58.2 ± 2.7</td>
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<tr>
<td>60min</td>
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<td>58.0 ± 2.5</td>
<td>9.7 ± 0.4</td>
</tr>
</tbody>
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Figure Legends

Figure 1: Raw data showing changes in cortical evoked pharyngeal responses after volitional swallowing, pharyngeal electrical stimulation and anesthesia

This figure shows representative data from one individual of 5 overlaid pharyngeal responses to cortical stimulation. After volitional swallowing, there is an early increase in response size, whereas after pharyngeal stimulation the increase is later (45-60 minutes). By comparison, after lidocaine-induced oro-pharyngeal anesthesia the responses become inhibited after 30 minutes.

Figure 2: Effect of volitional swallowing on corticobulbar and craniobulbar motor excitability

(A) Change in pharyngeal and esophageal cortical response (CEP) amplitudes after water swallowing. Maximal facilitation occurs mainly in the period immediately after swallowing before returning to baseline by 15 minutes. (B) Similar changes in pharyngeal and esophageal craniobulbar (BEP) reflex responses can be seen.

Figure 3: Effect of pharyngeal electrical stimulation on corticobulbar and craniobulbar motor excitability

(A) This figure shows that after stimulation, pharyngeal and esophageal cortical response amplitudes are increased at 45 minutes reaching significance at 60 minutes. (B) Craniobulbar reflexes remain unaffected

Figure 4: Lidocaine and pharyngeal sensory thresholds

This figure shows the change in sensory threshold for the pharynx, up to 1 hour after the application of oro-pharyngeal anesthesia. The maximal increase in sensory threshold occurs immediately after topical lidocaine with a return to baseline level by 30 minutes.
Figure 5: Effect of oro-pharyngeal anesthesia on corticobulbar and craniobulbar motor excitability

(A) Pharyngeal and esophageal cortical response amplitudes are maximally reduced 45 minutes post-lidocaine. (B) Craniobulbar reflexes for pharynx are similarly affected over a similar time interval.
Fig 1

- Water swallowing
- Pharyngeal stimulation
- Oro-pharyngeal anesthesia

Pre-intervention
Post immediate
Post 15 min
Post 30 min
Post 45 min
Post 60 min

Stimulus

50 µV
5 ms
Fig 2

A

B

Δ CEP amplitude (%)  

Δ BEP amplitude (%)  

time

-40 -20 0 20 40 60 80 100

immed 15 30 45 60

* p<0.05

** p<0.01

pharynx

esophagus
**Fig 3**

A

B

Δ CEP amplitude (%)

Δ BEP amplitude (%)

-40 -20 0 20 40 60 80 100

immed 15 30 45 60

-40 -20 0 20 40 60

immed 15 30 45 60

* p<0.05

** p<0.01

- pharynx

- esophagus

A

B
Fig 4

-40  -20  0  20  40  60  80  100  120

change in sensory threshold (%)

immed  15  30  45  60

time

* p<0.05
** p<0.01
Fig 5

A

B

-40
-20
0
20
40
60
80
100
immed 15 30 45 60

Δ CEP amplitude (%)

time

Δ BEP amplitude (%)

time

-40
-20
0
20
40

• pharynx

▲ esophagus

* p<0.05
** p<0.01