ORIGINAL ARTICLE

Submental transcutaneous electrical stimulation can impact the timing of laryngeal vestibule closure

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Abstract

Background: Laryngeal vestibule closure (LVC) is one of the critical airway protection mechanisms during swallowing. LVC timing impairments during swallowing are among the common causes of airway invasion in patients with dysphagia.

Objectives: To understand whether using submental transcutaneous electrical stimulation (TES) with varying pulse durations can impact the LVC reaction time (LVCrt) and LVC duration (LVCd) measures in healthy adults.

Methods: Twenty-six healthy adults underwent three TES conditions while receiving three trials of 10 ml pureed: no TES, TES with short pulse duration (300 μs) and TES with long pulse durations (700 μs). Two pairs of electrodes were placed diagonally on the submental area. For each active TES condition, the stimulation was increased up to the participant's self-identified maximum tolerance. Each swallow trial was recorded using videofluoroscopic swallowing study. All data were extracted and analysed offline using VideoPad Video Editor program.

Results: Submental TES reduced LVCrt during swallowing [$F_{(2, 46)} = 7.234$, $p < .007$, $\eta p2 = .239$] but had no significant impact on LVCd [$F_{(2, 50)} = .1.118$, $p < .335$, $\eta p2 = .043$]. Furthermore, pulse duration had no distinguished impact on any LVC timing measures.

Conclusion: Transcutaneous electrical stimulation may benefit patients with dysphagia who suffer from delayed LVC during swallowing. Future studies should seek whether the same physiologic effect can be observed in patients with dysphagia.

KEYWORDS
airway protection, duration, laryngeal vestibule closure, reaction time, swallowing, transcutaneous electrical stimulation

1 | BACKGROUND

Understanding the mechanics and kinematics of how safe swallows occur has a critical role in mitigating the ramifications of dysphagia. Laryngeal vestibule closure (LVC) is the primary airway defensive mechanism in pharyngeal swallowing, during which the epiglottis tilts over the larynx and arytenoids and approximating the epiglottis petiole to close off the airway in a timely manner.[1,2] Two important LVC timing measures that are often impacted in patients with dysphagia are LVC duration (LVCd) and reaction time (LVCrt).[3] LVCrt reflects how quickly the laryngeal vestibule reacts to the presence of a bolus to shut off the airway after the swallow has been triggered,

while LVCd refers to how long the airway closure lasts during swallowing.[1] The LVC timing impairments often lead to penetration and aspiration of the bolus materials, increasing the risk of aspiration pneumonia and death.[4,5] These findings underscore the necessity of implementing effective treatment strategies to improve the LVC timing measures during swallowing.

Different treatment approaches have been tested to improve the LVC timing measures during swallowing ranging from compensatory to rehabilitative modalities. For example, some studies have demonstrated that using the chin down manoeuvre allows for the LVC to occur earlier in the swallowing sequence, assisting slowed LVCs the opportunity to close the space in a much quicker manner.[6,7] Along with this, the Mendelsohn manoeuvre is another common compensatory or rehabilitative strategy for individuals suffering from pharyngeal dysphagia. This manoeuvre prolongs the LVCd, extending the PES relaxation and creating a safer swallow.[8–10] However, despite the positive effects of these manoeuvres,[11] they are often hard to train and may require extended exposure of patients to x-ray to ensure the training is acquired.[12,13] Moreover, even with the increased exposure from x-ray, some evidence indicates that not all manoeuvres may transfer to post-training swallows.[14] This signifies the limited function of manoeuvres in the long-term improvement of swallowing safety. As a result, novel treatment strategies might be required to impact the LVC timing measures to improve swallowing safety. Transcutaneous electrical stimulation (TES) may have the potential to provide beneficial impacts on LVC timing measures.

Transcutaneous electrical stimulation was primarily purported to strengthen the weaker muscles and re-educate safe swallowing.[15,16] However, despite significant clinical studies that have been conducted regarding the efficacy of TES on dysphagia treatment, the findings are still inconclusive.[17] Thus, recent efforts have revolved around a better understanding of the modulating effects of TES parameters on different aspects of swallowing physiology. Pulse duration is one of the TES parameters that determine the time period of a single pulse. Recent studies have shown that using a shorter pulse duration leads to a higher maximum amplitude tolerance, affecting the amount and potentially the strength of given stimulation.[18,19] This enhanced stimulation might penetrate the deeper swallowing muscles optimising the TES-based dysphagia rehabilitation.[20] For example, recent studies indicated that using submental TES with a short pulse duration put the hyoid in a more forward position before swallowing onset and reduced the range of anterior hyoid excursion during swallowing, which can facilitate swallowing.[21–23] However, a research gap existed regarding the effect of this protocol on temporal measures of LVC. Furthermore, limited evidence exists regarding the modulating effect of TES on LVC. Recently, a pilot study on healthy adults suggested that submental TES could induce faster LVCrt but no significant impact was found on LVCd during swallowing.[24] Thus, a larger study was needed to fully investigate the effect of pulse duration on LVC timing measures.

This study aimed to investigate the effects of submental TES with varying pulse duration on LVC timing in healthy adults. We hypothesised that using a TES with a short pulse duration can improve LVC timing, leading to a faster LVCrt and shorter LVCd when compared with long pulse duration. This hypothesis is driven by recent studies supporting the effect of short pulse duration compared with long pulse duration in improving the depth of electrical current penetration on anterior neck muscles.

2 | METHODS

2.1 | Participants

Twenty-five healthy female adults from ages 20 to 86 participated in this study with a mean age of 36.36 years (SD = 21.64 years). These participants were made aware of this study through convenience sampling using flyers and word of mouth. All participants indicated no difficulty with swallowing or therapy regarding their swallowing behaviours and reported maintaining healthy diets based on the Functional Oral Intake Scale (FOIS = 7).[25] All participants signed an informed consent form for their participation and this study was approved through the local institutional Review Board (IRB# 19-114).

2.2 | Transcutaneous Electrical Stimulation (TES)

Participants experienced the different TES protocols through the VitalStim Plus Electrotherapy System (VitalStim; DJO Global). The system allows the investigators to administer different protocols by varying aspects, such as the frequency or pulse duration of the stimulation. Four electrodes were placed on the submental skin after cleaning the skin with alcohol wipes provided by VitalStim. Both electrodes were placed above the hyoid bone, one end at the midpoint between the chin and superior aspect of the hyoid while the other end inferior to the mandibular angle.[21]

In this experiment, the participants were introduced to three different TES conditions, no TES, short pulse duration TES at 300 μs and long pulse duration TES at 700 μs. The pulse frequency was set consistently at 80 Hz. No TES was provided to all participants at the beginning to ensure that there was no lasting impact from previous TES trials on normal swallowing function, thus acting as the baseline for the study. The short pulse and long pulse TES conditions were randomised among the participants using an online program (https://www.randomizer.org) to eliminate any possible bias or reduce order effect on swallowing function across TES conditions. A 10-minute rest period was taken between conditions to ensure fatigue of the muscles was reduced as much as possible and to reduce any carryover effects from previous conditions. Three swallow trials in each condition were conducted, starting at maximum amplitude tolerance identification in each of the live TES conditions. To identify maximum amplitude tolerance, the TES amplitude was increased consecutively by 1 mA increments every 5 s. Participants were instructed to signal the investigator when they could no longer tolerate higher amplitude
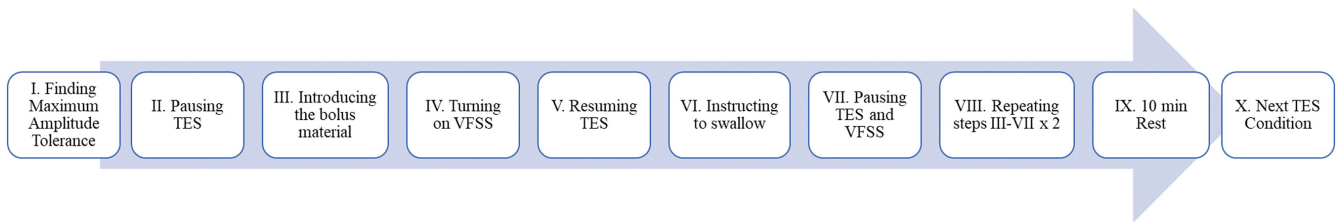
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FIGURE 1 Study design showing the order of tasks during each live transcutaneous electrical stimulation condition

levels. After identifying maximum amplitude tolerance, TES was temporarily paused, and the first swallow material was given to them. Subsequently, videofluoroscopy was turned on, TES resumed, and participants were asked to swallow. TES and videofluoroscopy were paused at the end of each swallow trial (See the study design in Figure 1).

2.3 | Videofluoroscopic Swallowing Study (VFSS)

Each subject was seated upright in a lateralised viewing plane in a mobile videofluoroscopic unit. Images of swallowing sequences were obtained by a licenced physician from MBS Envision, a Patheous Health Company, using continuous video and recoded digitally on a USB drive for offline analysis. Each sequence was limited to being no longer than 6 s in length and total radiation time was restricted to less than 90s total across all conditions for each participant. Calibration was achieved by taping a 24.26 mm coin on the lateral neck region and was kept throughout the trials.

2.4 | Swallow materials

This study required participants to swallow 10 ml of thickened liquid barium on three occasions. First, the thickened liquid barium was created by combining Barium sulphate oesophageal Cream (60% w/w) (E-Z-PASTE®, E-Z-EM, Canada Inc.) and a pudding cup (Jell-O) (50/50). After combining these ingredients, the level of thickness was measured to be equivalent to Level 4 of the International Dysphagia Standardisation Initiative Scale (i.e., Pureed).[26] Next, each bolus material was inserted into the participants' mouths using a 10 ml Kendall Monoject Oral Medication Syringe, and they were asked to hold the bolus until the investigator instructed them to swallow.

2.5 | LVC timing measures

All LVC timing measures were captured using VideoPad Video Editor© (NCH Software). An independent MBSImP certified graduate student researcher underwent extensive lab training to perform LVC timing measurements. The ratter was blind to the TES conditions. The LVC timing measurement technique was adapted from Vose and Humbert.[2] In order to calculate the LVC reaction time, two frames were extracted in each swallow, including the first frame of

TABLE 1 Inter-ratter and intra-ratter reliability for laryngeal vestibule closure measures

Measures	Intra-ratter ICC[a]	Inter-ratter ICC
Laryngeal vestibule closure	.99	.845
Laryngeal vestibule reopening	.99	.845

[a]Intra class coefficient.

hyoid burst followed by the first frame of laryngeal vestibule closure, which was reflected as arytenoids approximation to the epiglottis petiole. The time difference between these two frames indicated the LVC reaction time. Furthermore, LVC duration was measured by subtracting the time difference between the first frame of laryngeal vestibule closure from the first frame of laryngeal vestibule reopening, which was reflected as the appearance of air between the arytenoids and the epiglottis petiole. The time measurements were recorded in milliseconds.

2.6 | Statistical analysis

Training of a second ratter was utilised regarding the analysis prior to measuring the individual measurements. 10% of the original number of swallows were randomly selected to measure to ensure reliability measure was consistent. The primary ratter re-scored this same randomly selected 10% subset of the total number of swallows to establish a measure of reliability once all individuals had been assessed and a two-week period had passed. Statistics and analyses were completed to find data distribution, assess assumptions in the study and delve for outliers that could possibly impact the data and results. One-way repeated ANCOVAs were performed to analyse the effects of the three conditions presented to the participants (No TES, short pulse duration and long pulse duration) on LVC timing measures during swallowing while controlling for age. In addition, the post-hoc Bonferroni's test was conducted to identify significant pairwise differences within the three TES conditions. Furthermore, a single paired t-test was conducted to compare maximum amplitude tolerance between two live TES conditions. The significance level was set at $p < .05$. All statistical analyses were performed using IBM SPSS Statistics 28.0 (IBM Corporation).

TABLE 2 Means and standard deviations for laryngeal vestibule closure reaction time (LVCrt) and duration (LVCd) during swallowing across different TES conditions

Measure	No TES			Short pulse duration			Long pulse duration		
	Mean (SD)	Range	95% CI [lower, upper limit]	Mean (SD)	Range	95% CI [lower, upper limit]	Mean (SD)	Range	95% CI [lower, upper limit]
LVCrt	.222 (.108)	.067–.528	[.173, .271]	.145 (.057)	.073–.328	[.119, .170]	.153 (.074)	.074–.509	[.116, .191]
LVCd	.551 (.103)	.363–.759	[.515, .586]	.525 (.092)	.315–.671	[.487, .562]	.546 (.082)	.385–.759	[.515, .578]

3 | RESULTS

3.1 | Reliability analysis

Twenty-two swallows out of 216 total completed swallows by participants were randomly selected for reliability analyses. In general, both intra-ratter and inter-ratter analyses showed strong intraclass correlation coefficients for laryngeal vestibule closure and reopening measures (See Table 1).

3.2 | Stimulation tolerance

A significant maximum stimulation tolerance difference was found between two TES pulse durations [t (25) = 7.553, $p < .001$]. Specifically, stimulation tolerance was greater in TES with short pulse duration (mean: 15.16 mA, SD: ±5.98 mA) than in TES with long pulse duration (mean: 8.52 mA, SD: ±4.41 mA).

3.3 | Laryngeal vestibule closure timing measures

A significant main effect was identified for LVCrt [F (2, 42) = 5.558, $p < .02$, ηp2 = .209] while controlling for age. The post-hoc analysis revealed that mean LVCrt was significantly decreased for both short and long pulse duration conditions compared with no TES condition (Table 2). Nevertheless, no significant difference was found between short and long pulse duration conditions. Likewise, no significant main effect was found for LVCd across different TES conditions controlling for age [F (2, 46) = .570, $p < .531$, ηp2 = .024] (Table 2).

4 | DISCUSSION

This study sought the effect of TES with different pulse durations on LVCrt and LVCd measures in a cohort of healthy adults. The findings of our study suggested that TES may induce a faster LVCrt but had no significant impact on LVCd. Furthermore, pulse duration had no differential effects on any LVC timing measures.

Transcutaneous electrical stimulation-induced faster LVCrt when compared with no TES condition. This finding may potentially reflect the physiologic effect of submental TES on laryngeal vestibule closure. Recent studies showed that submental TES facilitates hyoid excursion by placing it in a more forward position before the burst during swallowing.[21-23] Therefore, this TES perturbation may lead to a faster hyoid excursion onset, reducing the LVCrt. Alternative speculation might be that submental TES may increase the size of the laryngeal vestibule by placing the larynx in a more forward position before the swallow onset. Therefore, the reduced LVCrt is a compensatory response from CNS to modulate the TES perturbations in order to protect the airway during swallowing. This finding is also consistent with Watts & Dumican,[24] highlighting the effect of submental TES on reducing the LVCrt.

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This outcome has important clinical implications. Many patients with pharyngeal dysphagia suffer from impaired airway protection due to different physiological causes.[4,5] One of these causes may relate to delayed laryngeal vestibule closure. Submental TES may benefit these patients by improving the LVCrt. However, it seems varying pulse durations had comparable impacts on LVCrt. This might relate to the limited number of swallow trials in this study. Future studies may need to implement extended swallow trials to evaluate if varying pulse durations have any distinctive impact on LVCrt.

Submental TES had no impact on LVCd. This may reflect the fact that LVCd is a critical aspect of the swallow reflex and is very resistant to external perturbations such as TES in healthy adults. This finding replicates the findings of Watts, & Dumican[24] and Serel Arslan et al.[23] Future studies should further investigate if using other electrode placements can have a differential effect on LVCd. For example, previous studies have indicated that coupling effortful swallow with stimulating infrahyoid muscles can improve the hyolaryngeal excursion during swallowing in healthy adults[27] and patients with dysphagia.[28,29] It would be interesting to see if using this paradigm can also improve LVCd.

This study was limited to a small number of healthy young female participants. While these studies can give us valuable information about the physiologic effects of treatment modalities on swallowing function, the findings may not be entirely generalisable for the clinical population. Furthermore, we only tested three swallow trials for each condition. This may not be enough time for CNS to provide adaptation responses to a new perturbation. Future studies are encouraged to test the physiologic effect of TES with an additional number of swallowing trials (i.e., 15–20) to better monitor the adaptation of swallowing motor activity to external perturbation from TES.

5 | CONCLUSIONS

The findings of this study indicated that using submental TES may improve LVCrt in healthy adults but had no significant impact on LVCd. Furthermore, TES pulse duration had no distinctive effect on LVC timing measures. While further investigations are needed in the clinical population, this specific TES-induced effect may benefit patients with airway compromise due to delayed LVC during swallowing.

AUTHOR CONTRIBUTIONS

Ali Barikroo was involved in the conception, study planning, analysis, data interpretation and writing of the final manuscript. **Mitchell T. McLean** was involved in the data interpretation and writing of the final manuscript.

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CONFLICT OF INTEREST

DATA AVAILABILITY STATEMENT

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