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ORIGINAL ARTICLE

The Effects of Electrical Stimulation Pulse Duration on Lingual Palatal Pressure Measures During Swallowing in Healthy Older Adults

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Abstract

Limited research in swallowing physiology has suggested that the most common existing transcutaneous electrical stimulation (TES) protocol (VitalStim) may not penetrate to layers of tissue to affect deep swallowing muscles. TES amplitude is the primary parameter that determines the depth of electrical current penetration (DECP). Preliminary work suggests that replacing a long-pulse duration with a short-pulse duration can increase maximum amplitude tolerance (MAT) within subjects' comfort level. Increasing MAT may indicate a higher DECP. The current study evaluates this premise in reference to the effects of varying pulse duration on lingual-palatal pressure during swallowing. Thirty healthy older adults (60–70 years of age) participated in this study. Each subject swallowed three trials of 10 mL pudding under three TES conditions: no stimulation, short-pulse duration, and long-pulse duration. TES was delivered using two pairs of surface electrodes on the submental muscles. MAT and perceived discomfort levels were identified separately for short and long-pulse TES conditions. Lingual-palatal peak pressure, pressure integral, and pressure duration were measured under each condition. Two-way repeated measures ANOVAs were conducted to identify within subject effects of TES condition and tongue bulb location. Lingual-palatal pressure and pressure integral were significantly reduced in the short-pulse duration condition. MAT was significantly higher in the short-pulse duration versus the long-pulse duration condition. Furthermore, MAT was significantly correlated with lingual-palatal pressure. Changing pulse duration had no significant impact on tongue pressure duration. Results suggest that a short-pulse duration may penetrate deeper into muscles involved in swallowing. The specific impact is reflected in a reduced upward pressure of the tongue on the palate during swallowing. This 'restrictive' effect of TES on tongue pressure may have the potential to be used during a resistive exercise paradigm for tongue elevation during swallowing.

Keywords Transcutaneous electrical stimulation · Aging · Deglutition · Deglutition disorders

Introduction

The tongue is an important structure that contributes to oral and pharyngeal phases of swallowing [1]. During the initial oral phase of swallowing, the tongue helps to form and maintain the bolus in the oral cavity. During the oral transition stage, the anterior and middle tongue facilitates the initiation of swallowing. In addition, the posterior tongue contacts with the velum and creates a positive pressure that pushes the bolus back into the oropharynx [2–4]. Adequate tongue strength is necessary for safe swallowing [5, 6]. Reduced tongue strength is associated with longer meal times, reduced food consumption, and the presence of dysphagia [7–9]. These facts emphasize the necessity of applying effective strategies to improve tongue strength during dysphagia rehabilitation.

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Tongue strengthening has been one of the treatment goals in dysphagia rehabilitation for many years. The traditional approaches have mainly focused on isometric tongue exercises using different type of devices such as tongue depressor and Iowa Oral Performance Instrument [10]. Different studies have been performed regarding the effect of applying these devices on tongue strength and functional swallowing with controversial findings [11–14]. These findings may indicate that a one-size-fits-all approach to tongue strengthening might not be suitable for patients with different etiologies. For example, in head and neck cancer patients, mouth sores subsequent to chemoradiotherapy might prevent intense tongue strengthening exercises [15]. Furthermore, one recent study in patients with acquired brain injury indicated that, despite improvements in lingual strength, no clinical improvement was observed in swallowing function [16]. These results may also indicate that the existing tongue strengthening approaches focus only on tongue strengthening exercises outside of the context of swallowing. As a result, new treatment strategies might be required to integrate the effect of improved lingual strength into the complex synergistic swallowing function. Transcutaneous electrical stimulation (TES) may have the potential to induce the desired impact on tongue muscles within the context of swallowing.

Introduced in 2002, VitalStim—hereafter referred to as the existing TES protocol- is a frequently-used treatment modality in swallowing therapy [17]. One potential goal of TES-based swallowing therapy is to augment weak swallowing muscle contractions during swallowing. Multiple studies have evaluated the clinical impact of TES in patients with dysphagia. Since these studies vary greatly in quality and methodology, the findings are equivocal—some reporting positive outcomes and other no benefit from TES inclusion [18]. Other studies have focused on the physiologic impact of TES rather than treatment outcomes. For example, existing evidence from kinematic swallowing studies has suggested hyoid and/or laryngeal descent upon stimulation of the anterior neck muscles (whether both submental and infrahyoid muscles or infrahyoid muscles alone) at rest [19–21]. This descending effect of TES has been proposed as a resistive exercise paradigm for hyolaryngeal elevation during swallowing. The same paradigm can potentially be applied to tongue muscles upon stimulation of the submental area. The genioglossus and the hyoglossus have important roles during the oral and pharyngeal phases of swallowing. These muscles function as antagonists of tongue elevation during swallowing [22]. Thus, if a surface electrical current can facilitate increased contractions in the genioglossus and the hyoglossus, one result might be a descending drive against tongue elevation during swallowing that may decrease tongue pressure during swallowing.

Current TES protocols have not demonstrated the capability to penetrate through multiple tissue layers to reach swallowing muscles that are deeper within the mechanism. Available data on the effect of TES on tongue function during swallowing are limited. Berretin-Felix et al. [23] reported that high TES amplitude selectively reduced anterior lingua-palatal peak pressure during swallowing. No significant impact was noted for middle and posterior lingual-palatal pressures. Similarly, Barikroo et al. [24] reported no immediate effect of TES on lingual-palatal pressure timing during swallowing. The results of these studies suggest that the existing TES protocol potentially stimulates only superficial muscles and may not penetrate sufficiently deep to stimulate the genioglossus and hyoglossus muscles [25, 26]. Increasing TES amplitude is one potential mechanism to facilitate deeper penetration of electrical stimulation [27–35]. However, increasing TES amplitude is limited by a subject's maximum amplitude tolerance (MAT) and discomfort level [25, 36]. One potential way to increase MAT within subjects' comfort levels is to replace the long-pulse duration in the existing TES protocol (700 µs) with a short-pulse duration (300 µs) [37]. Yet, the effect of increased MAT subsequent to the application of short-pulse duration on lingual-palatal pressure measures during swallowing is unclear.

Thus, the aim of this study was to compare the effect of varying pulse duration on mean lingual-palatal peak pressure, pressure integral (i.e., area under the curve), and pressure duration across three tongue bulb locations during swallowing in healthy older adults. We hypothesized that stimulation with a short-pulse duration would induce resistance in the lingual antagonist muscles resulting in lower lingual-palatal peak pressure and pressure integral and longer pressure duration across all three lingual-palatal measurement points compared with a long-pulse duration.

Materials and Methods

Participants

Thirty self-reported healthy community-dwelling older adults between 60 and 70 years of age (15 males and 15 females) with a mean age of 64.27 years (SD = 2.70 years) were enrolled in this study over a four-month period. The participants were recruited to the study using convenience sampling. All participants reported eating a regular diet (Functional Oral Intake Scale = 7) [38], and denied having a current or previous history of dysphagia or any disease known to be associated with dysphagia. The local Institutional Review Board (IRB) approved this study, and all subjects signed an informed consent form.

Lingual-Palatal Pressure Measures

Swallowing pressure data were collected using the Digital Swallowing Workstation (DSW) with integrated Swallowing Signals Laboratory (Model 7100; Pentax Medical, Montvale, NJ, USA). All physiological measures for this study were digitally recorded and analyzed offline. Lingual-palatal swallowing pressures were collected using a three-bulb tongue pressure array affixed to the midline of the hard palate with Stomahesive (Product# 25542; ConvaTec, Princeton, NJ, USA). The tongue bulb placement reflected the physiologic participation of anterior, middle, and posterior tongue during actual swallowing [39]. Prior to affixing the tongue bulb array, the roof of the mouth was wiped with gauze to dry the tissue and promote optimal bulb-to-palate contact and adhesion. Subsequently, the tongue bulb array was positioned approximately one mm posterior to the upper dentition, with the anterior bulb placed along the alveolar ridge and the middle and posterior bulbs positioned on the hard palate at 8 mm intervals.

Transcutaneous Electrical Stimulation

TES was delivered using the VitalStim Experia Electrotherapy System (VitalStim; DJO Global, Vista, CA, USA). This particular device has the ability to modify electrical stimulation parameters (i.e., pulse duration and frequency) to produce different TES protocols. Before electrode placement, the skin on the neck was cleaned with the skin wipes included in the VitalStim electrode package to eliminate any substance that might affect electrode contact with the skin. TES was delivered through four stimulating electrodes. Both electrode channels were aligned obliquely above the hyoid bone on the submental region of the neck (Fig. 1). The proximal electrode was attached at the midpoint between the chin and the lesser cornu of the hyoid bone. Since palpation of the lesser cornu is difficult, the approximate location of the lesser cornu was identified with reference to the hyoid body (superior aspect of the hyoid body and approximately 2 cm away from midline).The lateral electrode was attached at the midpoint between the chin and mandibular angle.

Three TES conditions were presented: no stimulation, TES with 300 µs (short) pulse duration, and TES with 700 µs (long) pulse duration. Pulse frequency was set at 80 HZ. To minimize any impact of TES on the no TES condition, this latter condition was completed first in the sequence. As such, the no TES condition served as a baseline comparison to the active TES conditions. The other TES conditions were randomized based on a computer-generated random assignment list to minimize any order effect on lingual-palatal pressure during swallowing. Three-minute rest periods of no stimulation were provided between each condition to minimize the possible effect of fatigue on tongue pressure. During this period, participants were first asked to rate any discomfort that they perceived after reaching MAT on a Visual Analogue Scale (VAS). The VAS provided a continuous scale (100 mm) for magnitude estimation and comparisons of discomfort levels ranging from "No Discomfort" to "Worst Discomfort Ever." [40] Subsequently, a memory game (Lumos Labs, Inc., San Francisco, CA) was given to distract participant's attention and minimize any learning effect on other TES conditions. Three bolus trials were tested for each TES condition. In both TES conditions with short and long-pulse durations, TES was started and MAT was established. MAT was defined as the highest level of electrical current that a participant could tolerate for each TES protocol. Following MAT identification, the first bolus was presented immediately. TES was continuous throughout the three swallow trials for each condition. TES ceased following swallowing completion of the third bolus swallow in each TES condition. If the entire bolus was not swallowed with a single attempt, that attempt was discarded and another bolus swallow was completed.

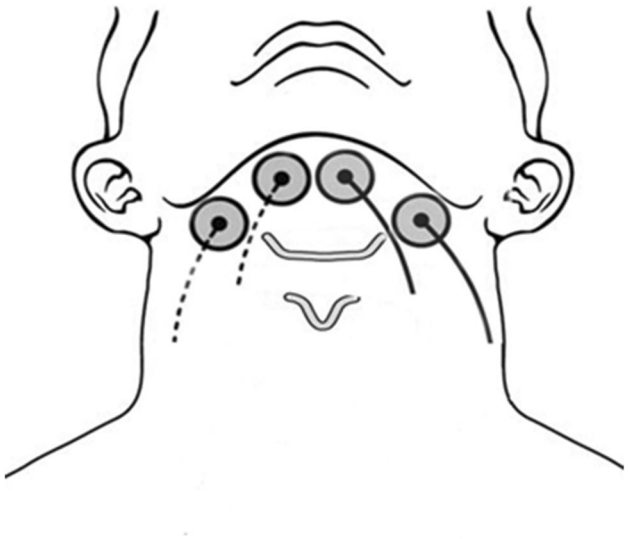

Fig. 1 TES electrode placement

Swallow Materials

For each TES protocol, participants swallowed three × 10 mL bolus trials with pudding consistency. The pudding material was prepared by mixing thin liquid material (water) with a commercial food thickener (Milani Thick-It) following a standard formula. Based on this formula, two tablespoons of food thickener were dissolved into 100 mL of water. Then, the thickened liquid was left to stand for 1 min to achieve pudding consistency. Using slip-tip syringes, 10 mL of pudding was placed in the participant's mouth. The participant was instructed to control the bolus in the mouth and then

swallow the entire bolus with a single swallow attempt on command.

Data Measurement

Outcomes included changes in lingual-palatal peak pressures, pressure integrals, and pressure durations as a function of change in TES condition. Specific measures included the following.

Lingual-Palatal Peak Pressure during Swallowing

Three lingual-palatal pressure waveforms were analyzed for each swallow: anterior, middle, and posterior tongue. To measure lingual-palatal peak pressure, the highest value during the positive peak pressure for each wave was identified visually and confirmed by the software program incorporated into the Swallowing Signals Laboratory.

Lingual-Palatal Pressure Integral During Swallowing

Pressure integral refers to the area under the pressure wave. To measure lingual-palatal pressure integral, the entire pressure wave was selected (i.e., from onset to offset time points) and pressure integral was calculated by the software program incorporated into the Swallowing Signals Laboratory.

Lingual-Palatal Pressure Duration during Swallowing

To measure lingual-palatal pressure duration, the onset and the offset times of the positive pressure for each wave was identified visually and recorded by the software program incorporated into the Swallowing Signals Laboratory. Pressure duration was calculated by subtracting the onset from the offset time points.

Statistical Analysis

Sample Size Calculation

A statistical power analysis was performed for sample size estimation using G*Power 3.1.5 [41] based on data from our preliminary study. Measures of effect size were calculated directly using partial eta squared. The required sample size was obtained from lingual-palatal pressure duration measure that had the smallest effect size equal to 0.47. Based on this analysis, we found that a minimum sample of 30 healthy older subjects would provide sufficient statistical power ($1-\beta=0.80$) to detect changes in lingual-palatal pressure measures during swallowing across varying TES conditions.

Reliability

Inter-rater Agreement

A second rater was trained on DSW operation prior to making independent measurements. After the initial ratings, this second rater scored a randomly selected subset of swallows representing 10% of the original number of swallows to obtain a measure of reliability.

Intra-rater Agreement

Once all subjects had been measured and a two-week wash out period had passed, the investigator re-scored this same randomly selected 10% subset of the total number of swallows to obtain a measure of reliability.

Descriptive and Inferential Statistics

Descriptive statistics and graphic analyses were used to characterize the distribution of the data, assess assumptions, and search for outliers. To identify any possible trial order effects on lingual-palatal peak pressure, pressure integral, and pressure duration, separate repeated measure analyses of variance (ANOVAs) were conducted across the randomly presented TES trials and the trials within each TES condition. Furthermore, three separate two-way repeated measure ANOVAs were conducted to identify within subject effects of TES condition (no stimulation, short-pulse duration, and long-pulse duration) and tongue bulb location (anterior, middle, and posterior tongue bulbs) on lingual-palatal pressure, pressure integral, and pressure duration during swallowing. The post hoc Bonferroni test was selected to explore pairwise significant differences within TES conditions. Two separate paired sample t-tests were performed to compare MAT and perceived discomfort level across short versus long-pulse duration conditions. Additionally, three bivariate correlational analyses were performed using Pearson's correlation coefficient to examine the overall relationship between MAT with the lingual- palatal peak pressure, pressure integral, and pressure duration regardless of pulse duration and tongue bulb location. The significance level was set at $p<0.05$. IBM SPSS Statistics 22.0 (IBM Corporation, Somers, NY) was used for all statistical analyses.

Table 1 Mean (SD), range, and 95% confidence interval (CI) of lingual-palatal peak pressures (mm Hg) and pressure durations produced during swallowing across varying tongue bulb locations and TES conditions

Measure	Tongue bulb location	No stim			Long-pulse duration			Short-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]
Peak pressure	Anterior	115.540 (76.250)	20.430–373.146	[86.536,144.543]	99.582 (83.847)	5.748–392.076	[68.273,130.891]	84.005 (77.747)	8.502–369.850	[54.974,113.037]
	Middle	96.016 (57.751)	11.541–220.292	[74.451,117.581]	84.751 (48.017)	5.240–209.074	[66.821,102.681]	77.523 (49.893)	0.000–157.458	[58.893,96.154]
	Posterior	172.973 (64.509)	63.701–310.834	[148.885,197.061]	164.780 (77.527)	69.538–414.451	[135.831,193.730]	152.770 (74.318)	50.342–359.57	[125.020,180.521]
Pressure integral	Anterior	105.573 (139.060)	0.000–701.463	[53.646,157.500]	97.818 (115.479)	1.126–463.622	[54.697,140.940]	91.524 (113.574)	2.030–464.326	[49.115,133.933]
	Middle	40.670 (30.0373)	0.000–104.569	[29.453,51.886]	37.0971 (31.397)	1.561–146.442	[25.373,48.821]	35.418 (30.992)	0.000–124.179	[23.845,46.991]
	Posterior	69.503 (34.944)	9.067–163.113	[56.454,82.551]	73.775 (54.798)	4.572–232.527	[53.313,94.237]	66.602 (51.390)	5.174–233.421	[47.413,85.791]
Pressure duration	Anterior	0.951 (0.525)	0.335–2.361	[0.751,1.150]	0.950 (0.513)	0.157–2.030	[0.760,1.142]	0.867 (0.468)	0.123–1.658	[0.692,1.042]
	Middle	0.741 (0.408)	0.060–2.176	[0.589,0.893]	0.704 (0.292)	0.019–1.332	[0.595,0.813]	0.653 (0.362)	0.000–1.546	[0.517,0.788]
	Posterior	0.809 (0.356)	0.127–1.861	[0.676,0.943]	0.913 (0.525)	0.048–2.320	[0.717,1.109]	0.801 (0.297)	0.123–1.392	[0.690,0.913]

Results

The data were first examined for normal distribution. All variables met parametric assumptions. Descriptive results for the lingual-palatal pressures are presented in Table 1. Inferential results are as follows.

Reliability Analysis

Participants completed 270 swallows. Ten percent of these swallows (27 swallows) were randomly selected and analyzed for concordance by the primary and secondary raters. Consistency of tongue pressure measurements by the primary rater was demonstrated by ICC measures ranging from 0.926 to 0.998, depending on the variable of interest [(lingual-palatal peak pressure: ICC = 0.998, 95% CI 0.998 to 0.999); (lingual-palatal pressure integral: ICC = 0.975, 95% CI 0.961 to 0.984); (lingual-palatal pressure duration: ICC = 0.926, 95% CI 0.886 to 0.952)]. Consistency of tongue pressure measures between the two raters was determined by ICC ranging from 0.911 to 0.998, depending on the variable of interest [(lingual-palatal peak pressure: ICC = 0.998, 95% CI 0.997 to 0.999); (lingual-palatal pressure integral: ICC = 0.973, 95% CI 0.959 to 0.980); (lingual-palatal pressure duration: ICC = 0.911, 95% CI 0.861 to 0.943)].

Order Effect

No significant order effect was identified across the randomly presented TES trials [F (2, 58) = 2.806, $p < 0.07$] or the trials within each TES condition [F (2, 58) = 1.301, $p < 0.280$].

Peak Pressure

No significant interaction effect was identified between pulse duration and tongue bulb location [F (4, 116) = 0.633, $p < 0.640$]. However, a significant main effect of pulse duration was identified [F (2, 58) = 6.273, $p < 0.008$, $\eta p2 = 0.785$]. Lingual-palatal peak pressure was significantly lower in the short-pulse duration condition versus no stimulation ($p < 0.002$) and long-pulse duration ($p < 0.048$) conditions (Fig. 2). Furthermore, a significant main effect of tongue bulb location was identified [F (1.5, 45.0) = 16.561, $p < 0.0001$, $\eta p2 = 0.997$]. Posterior lingual-palatal peak pressure was significantly greater than anterior ($p < 0.003$) and middle ($p < 0.0001$) lingual-palatal peak pressures (Fig. 3).

Pressure Integral

The interaction effect between pulse duration and tongue bulb location was not significant [F (4, 116) = 0.633, $p < 0.670$]. Likewise, no significant main effect of tongue bulb location was identified [F (2, 58) = 1.167, $p < 0.319$, $\eta p2 = 0.0210$]. However, a significant main effect of pulse duration was identified [F (2, 58) = 5.734, $p < 0.02$, $\eta p2 = 0.785$]. Lingual-palatal pressure integral was significantly lower in short-pulse duration when compared with no stimulation ($p < 0.008$) and long-pulse duration ($p < 0.001$) (Fig. 4).

Pressure Duration

The interaction effect between pulse duration and tongue bulb location was found to be not significant [F (4, 116) = 1.33, $p < 0.272$]. Likewise, no significant main

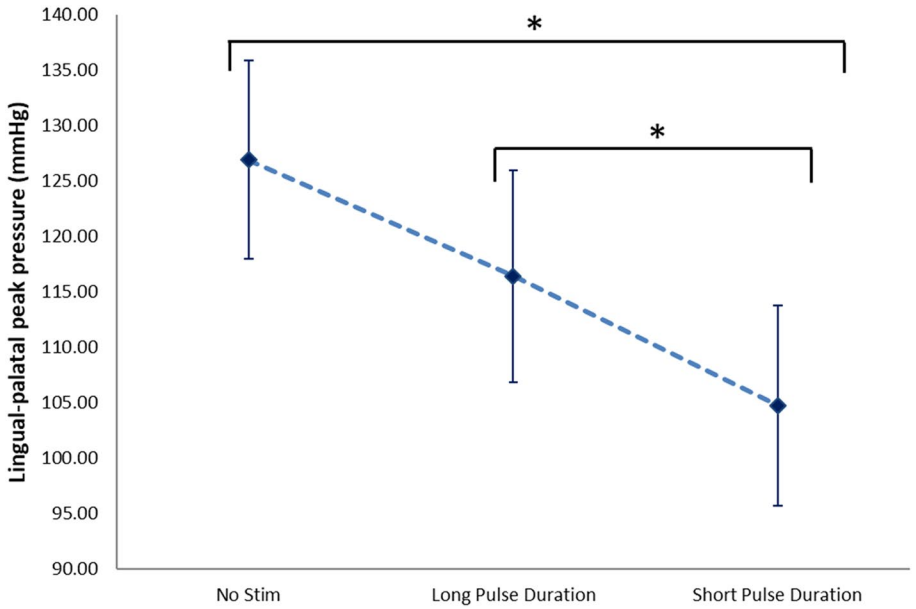

Fig. 2 Mean lingual-palatal peak pressures (mmHg) across different TES conditions

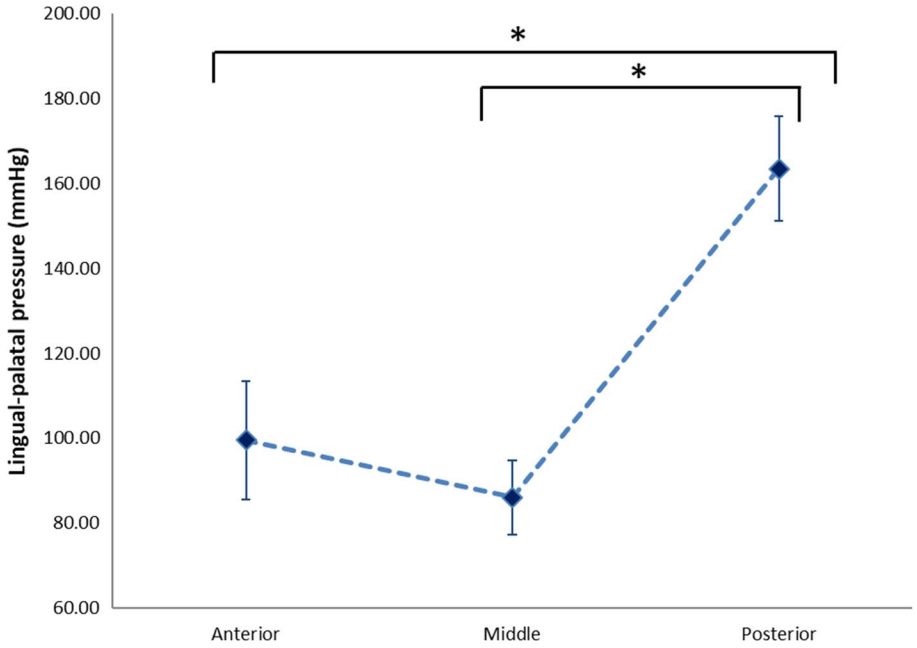

Fig. 3 Mean lingual-palatal peak pressures (mmHg) across different tongue bulb locations

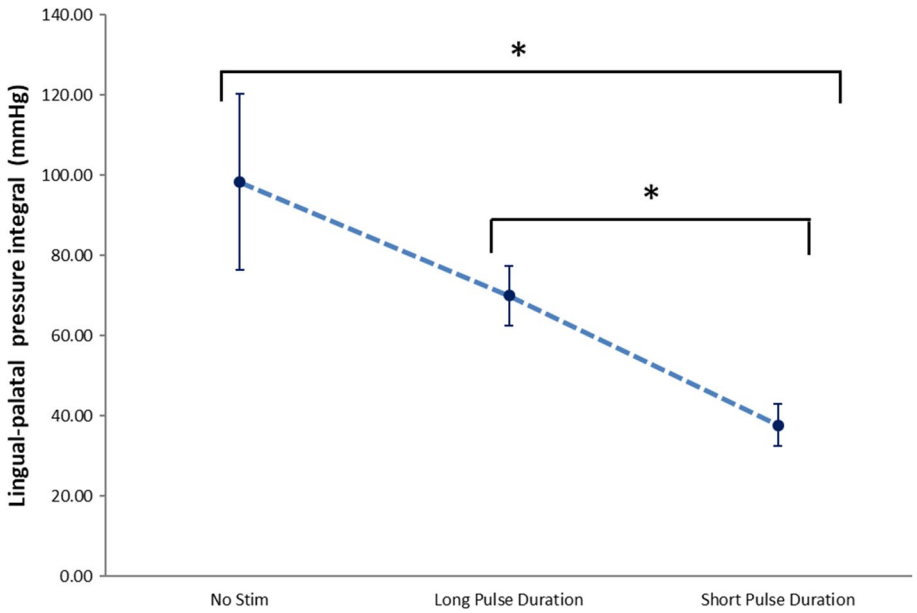

Fig. 4 Mean lingual-palatal pressure integrals (mmHg) across different TES conditions

effects were identified for pulse duration [F (2, 58) = 1.33, $p < 0.269$] or tongue bulb location [F (1.3, 37.1) = 2.897, $p < 0.088$].

Pulse Duration, MAT, and Discomfort level

MAT differed significantly across pulse durations [t (29) = − 8. 844, $p < 0.0001$]. Specifically, short-pulse duration induced higher MAT compared with the long-pulse duration condition (Fig. 5). However, perceived discomfort level was not significantly different across pulse durations [t (29) = − 227, $p < 0.822$].

MAT and Lingual-Palatal Pressure Measures

MAT was inversely related with lingual-palatal peak pressure ($r = -0.24$; $p < 0.001$). However, MAT demonstrated non-significant relationships with lingual-palatal pressure integral (r = − 0.107; $p < 0.152$) and pressure duration ($r = -0.130$; $p < 0.082$).

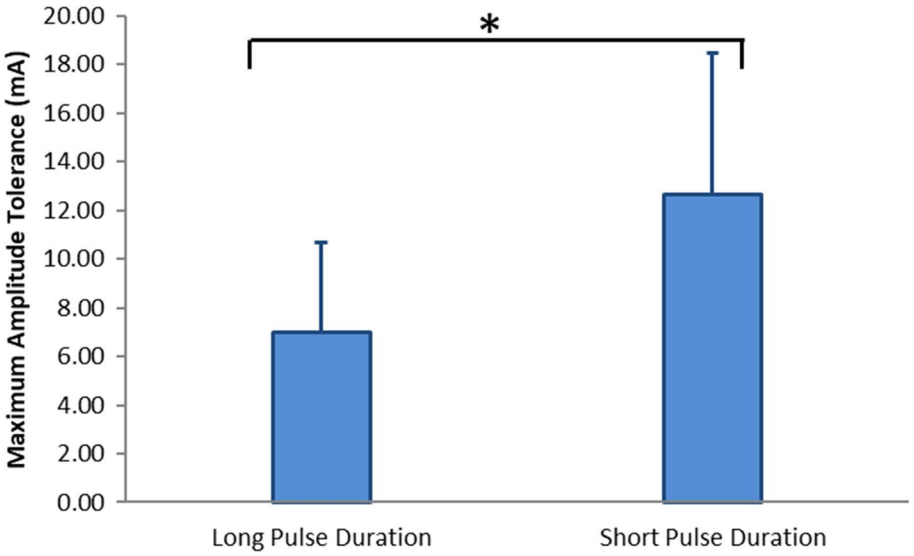

Fig. 5 Mean MAT (mA) across different pulse duration conditions

Discussion

The aim of this study was to compare the effect of varying pulse durations on lingual-palatal peak pressure, pressure integral, and pressure duration across three tongue bulb locations during swallowing in healthy older adults. Collectively, the results of this study supported the primary hypothesis indicating the effect of short-pulse duration on inducing resistance in the lingual antagonist muscles.

Short-pulse duration induced a lower lingual-palatal peak pressure and pressure integral compared with long-pulse duration or no TES. Furthermore, MAT was inversely related with lingual-palatal peak pressure. Consistent with prior work, short-pulse duration also had higher MAT [37]. Higher MAT may increase depth of electrical current penetration (DECP) [42, 43]. As a result, increasing DECP through the submental area may stimulate deep lingual muscles such as lingual elevator antagonists (i.e., the genioglossus and hyoglossus) and depress the tongue during swallowing. This potential mechanism may explain lower lingual-palatal peak pressure and pressure integral during swallowing observed in the present study. However, correlations between MAT and lingual-palatal peak pressure were low and accounted for little variance. Thus, an alternative explanation to consider is that of TES-induced fatigue in the tongue depressor muscles (i.e., genioglossus and the hyoglossus) associated with stimulation via long-pulse duration.

The tongue depressor muscles are composed of both small and large motor neurons. Based on the Henneman's size principle, under volitional muscle contraction, motor units are recruited from smallest to largest [44]. In practice, this means that slow-twitch, low-force, fatigue-resistant muscle fibers are activated before fast-twitch, high-force, less fatigue-resistant muscle fibers. However, TES- especially TES with long-pulse duration- recruits motor neurons in reverse order from smallest (fast fatiguing muscles fibers) to largest (fatigue-resistant muscle fibers) [45]. As a result, continuous TES with long-pulse duration can induce fatigue [46]. Fatiguing the tongue depressor muscles may reduce the descending effect of TES against tongue elevation, resulting in higher lingual-palatal peak pressure and pressure integral during swallowing following long-pulse duration compared with short-pulse duration. Observations in the current study are discrepant with those reported by Berretin-Felix et al. [23] regarding the impact of long-pulse duration on anterior and posterior lingual-palatal peak pressures. Methodological differences may explain the disparity in the results. For example, Berretin-Felix et al. [23] used one pair of electrodes in the submental region and one pair of electrodes in the infrahyoid region while we used two pairs of electrodes in the submental region. Another potential reason for inconsistent results between these studies might be related to using different bolus size and consistencies in Berretin-Felix et al.'s study [23] versus using single bolus size and consistency in the current study. Prior studies have demonstrated change in lingual-palatal pressure associated with swallowing different materials. [47–49].

No significant differences were found in pressure duration across the three TES conditions. Furthermore, increasing MAT had no significant impact on lingual-palatal pressure duration during swallowing. This outcome is consistent with Barikroo et al.'s study [24] indicating a lack of TES impact on lingual-palatal pressure timing during swallowing. This finding suggests that adjustments in lingual-palatal pressure timing may be controlled by different mechanisms than pressure amplitude. Appropriate swallow timing is an essential part of safe and efficient swallowing [50]. A lack of TES effect on pressure timing in older adults may reflect

an involuntary adjustment to sustain the integrity of swallowing under different TES conditions. Conversely, recent literature reports that continuous versus intermittent TES paradigms may have differential effects on swallow timing. Specifically, Humbert et al. [51] speculated that if TES is delivered continuously (i.e., during swallowing and between each swallowing trial), healthy adults might learn to keep timing variables stable (i.e., motor learning) in the presence of changing motor variables (i.e., lingual-palatal peak pressure changes). In contrast, intermittent stimulation of TES (i.e., only during swallowing, not between swallow intervals) may negatively influence the motor adaptation of swallowing timing, and increase the effect of TES perturbation on swallowing timing measures. Since the same continuous TES paradigm was used in our study, subjects may have learned to adjust the lingual-palatal pressure timing to maintain the integrity of swallowing.

The present study had no control over the possible effect of palatal morphology (i.e., palatal length, depth, width, and curvature) on lingual-palatal pressure measures during swallowing. Prior studies have shown a relationship between palatal morphology characteristics and lingual-palatal pressure during swallowing. For example, Hashimoto et al. [52] reported positive relations of palatal width and palatal curvature with lingual-palatal pressure peaks during swallowing in healthy young adults. Cheng et al. [53] reported that palatal depth and dental arch length are positively related with the magnitude of tongue movement during swallowing in healthy young adults. Although both of these studies focused on healthy young adults, the possible confounding effect of palatal morphology on lingual-palatal pressure in our study cannot be ruled out. Furthermore, the present study did not measure the participants' tongue strength at the baseline. This can be a confounding factor that should to be controlled in prospective studies. In addition, the sample in this study was limited to healthy older adults. While the sample size provided adequate power for this analysis, the scope of the sample was narrow. Future studies should consider additional subject variables including various age ranges and healthy versus different impaired populations. Further, it is acknowledged that different bolus materials result in different physiologic swallowing patterns. Thus, future work should evaluate the impact of different bolus materials on the patterns recorded in the present study.

This study is the second step in a continuum of research that may potentially lead to applications of a novel TES protocol for maintaining or restoring the strength of oropharyngeal muscles. Specifically, results of this study support the application of short-pulse duration on inducing a lowering drive against tongue elevation during swallowing. Combining this descending drive with a resistive exercise paradigm may have the potential to strengthen the tongue elevation during swallowing. While both the Park et al's study [54] and the current study demonstrate a potential TES-resistance impact on the swallowing mechanism, additional studies with patient populations should be completed to further understand the potential clinical applications and limitations. Future studies should consider the impact of varying TES pulse durations on other aspects of swallowing physiology. A focus on deep swallowing musculature may lead to development and evaluation of novel TES protocols in swallowing rehabilitation.

Conclusion

Results of the present study suggest that applying a short-pulse duration in a TES protocol may be an effective approach to stimulate deep muscles of swallowing. Future elaboration on these results has the potential to develop and evaluate a novel approach for strengthening weakened tongue muscles to improve swallow function. Additional physiologic studies are required to identify the immediate and long-term effect of novel TES protocol on tongue function and swallowing integrity in both healthy older adults and patients with dysphagia.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

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