

Efficacy of EMG/Bioimpedance-Triggered Functional Electrical Stimulation on Swallowing Performance

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Abstract— In order to support swallowing, the efficacy of functional electrical stimulation for different stimulation settings of the submental musculature has been investigated. The stimulation was administrated at rest and synchronously to voluntary initiated swallows. The onset of a swallow was detected in real-time by a combined electromyography/bioimpedance measurement at the neck in order to trigger the stimulation. The amplitude and speed of larynx elevation caused by the FES has been assessed by the observed change in bioimpedance whereas a reduction of bioimpedance corresponds to an increase in larynx elevation. Study results from 40 healthy subjects revealed that 73% of the subjects achieved a larger and faster larynx elevation during swallowing with triggered FES and therefore a better protection of their airways. However, we also observed a decrease in larynx elevation compared to normal swallowing in 11 out of the 40 subjects what might not benefit from such a treatment. The largest improvement of larynx elevation and speed during swallowing could be achieved with three stimulation channels formed by four electrodes in the submental region.

I. INTRODUCTION

Electrical stimulation has been widely applied in the therapy of patients with dysphagia. One general aim is to train the submental and suprahyoidal and infrahyoidal muscles by applying electrical stimulation for longer periods of time by means of surface electrodes (see e.g. [1,2]). Most existing systems do not take into account present volitional swallowing activity of the patients. As reported in [3], the stimulation in the vicinity of larynx can even have a negative effect on the protection of the airways during a real swallow as muscle can be activated that lower the larynx (e.g. the *M. sternohyoideus*). Only stimulation of the submental muscles proved to be safe with a positive effect on swallowing mechanics most of the time [3]. Another therapy approach is to apply sensory stimulation to the posterior pharyngeal wall by using a stimulation catheter that is inserted via the nasal passage [4]. Also in the case, stimulation is applied in a non-controlled manner.

In our previous work [5] we demonstrated that a functional electrical stimulation of the submental muscles synchronously to the voluntary induced swallows is feasible and can help in increasing the amount and velocity of larynx elevation. The onset of stimulation was detected in real-time by an initial drop in bioimpedance (BI) in conjunction with EMG activity measured at the neck. The bioimpedance measurement (absolute value of bioimpedance measured at 50 kHz) was furthermore used to assess the resulting larynx elevation (negative proportional relation) during swallowing [6]. As alternative to our automatic triggering, a hand switch triggered stimulation can be used to synchronize FES with swallows [7].

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In this contribution, we evaluate the effect of different submental stimulation strategies (electrode configurations) and two different stimulation intensities on the bioimpedance and therefore on the larynx elevation.

II. METHODS

The examination was performed on 40 healthy subjects (18 females, 22 males, mean age of 29 years) without any swallowing impairment. The study was approved by the Charité Berlin Ethics Committee in the vote EA1/019/10.

The subjects were stimulated at rest (non-swallowing) and during swallowing water using an adapted current-controlled stimulator (RehaStim1, HASOMED GmbH) with a maximum current amplitude of 30 mA. For the onset detection of the water swallows we used a self-developed EMG/BI measurement system [6].

Four self-adhesive surface electrodes (MultiStick-Gel, 25mm, Axelgaard, Denmark) were attached for FES at the submental region. We placed two electrodes (2xS1) on the mouth base and two other electrodes in the yaw angle (S2 and S3). Based on these four electrodes three stimulations channels have been set up (cf. Fig. 1): Channel 1 (S1-S1), Channel 2 (S1-S2) and Channel 3 (S1-S3). Three stimulation settings were applied:

- A) stimulation via channel 1 only,
- B) stimulation via channels 2 and 3 (sequentially with 1.5 ms interval between the two channels),
- C) stimulation on all three channels 1, 2 and 3 (sequentially with 1.5 ms interval between the three channels).

The stimulation intensity was set to 30 Hz for all settings. The pulse width of the biphasic stimulation pulses was fixed at 200 μ s, whereas the current amplitude I served as adjustable stimulation intensity.

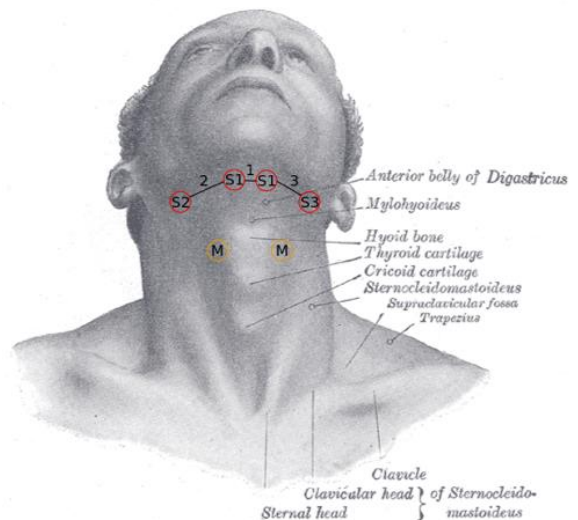


Figure 1. Position of electrodes for forming three stimulation channels. M – measurement electrodes, S1-S3 – stimulation electrodes, 1 – 3 channels

Stimulation with each setting was repeated three times for each subject in a fixed order (at rest and during swallowing). Additionally, swallows without stimulation have been recorded. Initially, before the first measurement (first application of the three stimulation settings), we determined the maximally tolerated stimulation intensity for each setting in every subject and denoted this values as I_{init} . The obtained values were used for the first application of the stimulation settings. One readjustment of these values took place after the first measurement round was completed and before applying all stimulation settings another two times. The updated intensities were denoted as I_{update} .

In order to assess the effect of stimulation at rest (non-swallows) and to compare swallows without and with stimulation, the amplitude A_{BI} of the bioimpedance drop (positive values for a drop in BI) and the corresponding speed S_{BI} (A_{BI} divided by the time to reach the maximum drop) have been determined for stimulation at rest and during all swallows. A larger amplitude A_{BI} corresponds to a larger larynx elevation, while the elevation velocity is directly described by the speed of the BI change [6].

A Wilcoxon test has been applied to look for statistically significant differences in the stimulation settings.

III. RESULTS

The mean I_{init} -intensity was 8 mA (male = 8 mA, female = 7 mA). The mean I_{update} -intensity was 10 mA (male = 10 mA, female = 9 mA). Details are reported in Table I.

The evaluation included 598 non-swallows. For the non-swallows we could prove significant differences ($p < .001$) between the I_{init} -intensity ($n = 279$) and the I_{update} -intensity ($n = 319$). For the amplitude A_{BI} , the highest value was detected for the I_{update} -intensity. However, the speed shows the highest value with the I_{init} -intensity (see Table II). We observed an increase of 25% in the maximally tolerated stimulation intensity by updating this value.

TABLE I. AVERAGE MAXIMALLY TOLERATED STIMULATION INTENSITIES FOR THE DIFFERENT STIMULATION SETTINGS: A) CHANNEL 1, B) CHANNEL 2 & 3 AND C) CHANNEL 1, 2 & 3.

Setting	Initial intensity I_{init} (mA)			Updated intensity I_{update} (mA)		
	A	B	C	A	B	C
Total	8	7	7	11	9	10
Male	8	7	8	12	10	10
Female	7	6	7	10	9	9

Overall, we included 2132 swallows (729 swallows without stimulation, 1403 swallows with stimulation) in our analysis. For 29/40 (520 swallows without stimulation, 1028 swallows with stimulation) subjects we detected a significant increase ($p < .001$) in the amplitude A_{BI} and speed S_{BI} of the BI drop (i.e. laryngeal elevation) when comparing FES-assisted swallowing and normal swallowing. The highest values were detected for I_{update} . Table III shows the obtained results for this subgroup of subjects. The corresponding 29/40 subjects were 12 females and 17 males.

All the remaining 11/40 subjects showed a significant decrease of the amplitude ($p = .003^{**}$) under swallowing with stimulation compared to unassisted swallowing. The speed of laryngeal elevation shows no significant variance (see Table

IV). The 11/40 subjects who showed a decrease of swallowing performance were 6 females and 5 males.

TABLE II. EFFECT OF STIMULATION INTENSITY ON BI DROP (LARYNX ELEVATION) AT REST (FOR NON-SWALLOWES). REPORTED ARE MEAN VALUES WITH STANDARD DEVIATIONS.

Parameters of BI drop	I_{init} -Intensity	I_{update} -Intensity
Amplitude (Ohm)	0.186 (0.14)	0.278 (0.19)
Speed (Ohm/s)	1.967 (10.06)	1.675 (0.27)

TABLE III. COMPARISON OF SWALLOWES WITH AND WITHOUT STIMULATION FOR DIFFERENT STIMULATION INTENSITIES. REPORTED ARE MEAN VALUES WITH STANDARD DEVIATIONS OF THE BI DROP AMPLITUDE (LARYNX ELEVATION) AND SPEED (LARYNX VELOCITY) FOR 29 OUT OF THE 40 PATIENTS WHO SHOWED AN INCREASE IN LARYNX ELEVATION COMPARED TO UNASSISTED SWALLOWING.

Parameters of BI drop	Swallow without stimulation	Swallow with stimulation (I_{init})	Swallow with stimulation (I_{update})
Amplitude (Ohm)	0.637 (0.28)	0.787 (0.34)	0.845 (0.36)
Speed (Ohm/s)	2.735 (1.38)	3.175 (1.34)	3.676 (1.75)

TABLE IV. COMPARISON OF SWALLOWES WITH AND WITHOUT STIMULATION FOR DIFFERENT STIMULATION INTENSITIES. REPORTED ARE MEAN VALUES WITH STANDARD DEVIATIONS OF THE BI DROP AMPLITUDE (LARYNX ELEVATION) AND SPEED (LARYNX VELOCITY) FOR 11 OUT OF THE 40 PATIENTS WHO SHOWED AN DECREASE IN LARYNX ELEVATION COMPARED TO UNASSISTED SWALLOWING.

Parameters of BI drop	Swallows without stimulation	Swallows with stimulation (I_{init})	Swallows with stimulation (I_{update})
Amplitude (Ohm)	0.664 (0.30)	0.588 (0.26)	0.571 (0.28)
Speed (Ohm/s)	2.486 (0.99)	0.691 (1.44)	2.526 (1.49)

For the two sub groups of subjects (29/40 and 11/40) reported above we investigated again the effect of stimulation at rest in order to evaluate if a prediction of the responses during FES-assisted swallowing based on the stimulation results at rest is possible. The obtained data are displayed in the Tables V and VI. For the 29/40 sub group the differences between the I_{init} and I_{update} were significant for A_{BI} ($p < .001$) and S_{BI} ($p < .001$). The highest value for A_{BI} and S_{BI} were shown again with the I_{update} -intensity. For 11/40 sub group the differences between the I_{init} and I_{update} were significant for A_{BI} ($p = .007^{**}$) and S_{BI} ($p = .005^{**}$). As shown for the 29/40 subjects the highest values for 11/40 subjects were also with the I_{update} . Both sub groups showed an increase in larynx elevation at rest by applying electrical stimulation.

TABLE V. EFFECT OF STIMULATION INTENSITY ON BI DROP (LARYNX ELEVATION) AT REST (FOR NON-SWALLOWES) FOR THE 29/40 SUBJECTS WHO SHOWED AN INCREASE IN LARYNX ELEVATION BY FES DURING SWALLOWING COMPARED TO NORMAL SWALLOWING. REPORTED ARE MEAN VALUES WITH STANDARD DEVIATIONS.

Parameters of BI drop	I_{init} -Intensity	I_{update} -Intensity
Amplitude (Ohm)	0.195 (0.15)	0.297 (0.19)
Speed (Ohm/s)	1.088 (0.94)	1.622 (1.10)

TABLE VI. EFFECT OF STIMULATION INTENSITY ON BI DROP (LARYNX ELEVATION) AT REST (FOR NON-SWALLOWES) FOR THE 11/40 SUBJECTS WHO DID NOT SHOW AN INCREASE IN LARYNX ELEVATION BY FES DURING SWALLOWING COMPARED TO NORMAL SWALLOWING. REPORTED ARE MEAN VALUES WITH STANDARD DEVIATIONS.

Parameters of BI drop	I_{init} -Intensity	I_{update} -Intensity
Amplitude (Ohm)	0.149 (0.12)	0.221 (0.17)
Speed (Ohm/s)	0.936 (1.09)	1.305 (1.24)

Bioimpedance, i.e. larynx elevation and speed, were influenced differently by the three stimulation settings.

For stimulation at rest (non-swallows), the amplitude A_{BI} shows the highest value for the stimulation setting A (channel 1) and the lowest value for the stimulation setting B (channel 2 & 3) ($p = .013^*$ (A vs B)). The parameter speed S_{BI} shows the highest value for stimulation setting C (channel 1, 2 & 3) and the lowest for setting B (channel 2 & 3) ($p = .015^*$ (C vs B)) (cf. Table VII).

TABLE VII. INFLUENCE OF THE STIMULATION SETTING ON THE PARAMETERS OF THE BI DROP DURING REST. REPORTED ARE MEAN VALUES WITH STANDARD DEVIATIONS FOR ALL 40 SUBJECTS AND BOTH STIMULATION INTENSITIES.

Parameters of BI drop	Setting A	Setting B	Setting C
Amplitude (Ohm)	0.254 (0.18)	0.213 (0.16)	0.242 (0.18)
Speed (Ohm/s)	1.829 (10.03)	1.590 (3.06)	2.025 (7.08)

During swallowing with FES support, we found significant differences in the stimulation settings for A_{BI} ($p < .001$ (A vs C), $p = .035^*$ (B vs C)), and for S_{BI} ($p = .043^*$ (B vs C)). The highest values for amplitude and speed were detected for setting C (cf. Table VIII).

TABLE VIII. INFLUENCE OF THE STIMULATION SETTING ON THE PARAMETERS OF THE BI DROP DURING SWALLOWING WITH FES SUPPORT. REPORTED ARE MEAN VALUES WITH STANDARD DEVIATIONS FOR ALL 40 SUBJECTS AND BOTH STIMULATION INTENSITIES.

Parameters of BI drop	Setting A	Setting B	Setting C
Amplitude (Ohm)	0.746 (0.36)	0.718 (0.34)	0.774 (0.36)
Speed (Ohm/s)	2.430 (6.50)	2.914 (3.77)	3.391 (2.02)

IV. CONCLUSION

The study results show that an EMG/BI-triggered FES is feasible in a larger population of healthy subjects. Subjects got used to FES at the submental region, and maximally tolerated stimulation intensities could be increased by 25% after some stimulations. The effect of FES on the amplitude of the BI drop (the larynx elevation) could be modulated by the stimulation intensity. For EMG/BI-triggered FES in dysphagia therapy, a four electrode setup can be recommended as that gives the largest support in larynx elevation (in terms of amplitude and speed). Based on the four electrodes three stimulation channels are formed.

73% of the subjects could significantly improve amplitude and speed of larynx elevation by EMG/BI-triggered FES compared to normal water swallowing without FES. In patients this will potentially lead to improve of protection of the airways. However, we also found a decrease in larynx elevation in 27% of the healthy subjects. Such an undesired outcome will be automatically detected by the EMG/BI measurement system during swallowing. Patients who show a decrease in larynx elevation are probably no candidates for such a triggered FES approach. A simple prediction of the effect of FES during swallowing on the results obtained by stimulation at rest was not possible. During stimulation at rest we always observed an increase by larynx elevation by applying electrical stimulation to the submental muscles. We are currently investigating possible reasons why some subjects have negative responses during FES-assisted swallowing while showing positive responses at rest.

After we have found the best stimulation setting, we plan a larger study with patients suffering from dysphagia to confirm these results with patients.

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