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Tongue electrical impedance in amyotrophic lateral sclerosis modeled using the finite element method

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Abstract

Objective—Electrical impedance myography (EIM) of the tongue has demonstrated alterations in patients with amyotrophic lateral sclerosis (ALS) compared to normal subjects. Whether these differences are due to reduced tongue size or diseased-associated alterations in the electrical characteristics of intrinsic tongue muscles is uncertain.

Methods—We employed computer simulations using the finite element method, inputting data from healthy and ALS mouse muscle, to help answer that question, comparing our modeled results to human data.

Results—The models revealed that much of the electrical current flows superficially in the tongue and that tongue thickness only begins to have a major impact on the measured impedance when substantial atrophy is present. Modeled values paralleled the human tongue data.

Conclusions—These findings suggest that the observed changes in tongue impedance in ALS are mainly due to alterations in the electrical properties of the tongue and are not a mere consequence of tongue volume loss.

Significance—Further development of EIM for evaluation of bulbar dysfunction in ALS may provide useful information on drug efficacy and could serve as a biomarker in future clinical trials.

Keywords

Amyotrophic lateral sclerosis; tongue; electrical impedance; atrophy; modeling

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CONFLICT OF INTEREST

Dr. Rutkove has equity in, and serves a consultant and scientific advisor to, Skulpt, Inc. a company that designs impedance devices for clinical and research use; he is also a member of the company's Board of Directors. The company also has an option to license patented impedance technology of which Dr. Rutkove is named as an inventor. This study, however, did not employ any relevant company or patented technology.

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1. Introduction

The development of quantifiable indices of bulbar muscle deterioration due to amyotrophic lateral sclerosis (ALS) and other neuromuscular disorders remains a major research challenge. Because approximately 20–25% of ALS patients initially present with bulbar dysfunction (Gubbay et al., 1985; Caroscio et al., 1987), including dysarthria and dysphagia, diagnostic tools are needed as biomarkers for objectively detecting early tongue involvement and for documenting its progression over time. Needle electromyography of tongue remains one of the most frequently used approaches to help establish a diagnosis of bulbar involvement due to ALS (Jenkins et al., 2013; Tankisi et al., 2013). This approach, however, has significant limitations including that it is not easily quantifiable and that it requires full relaxation of the tongue. Motor unit number estimation, while potentially valuable in quantifying progression in appendicular muscles (Shefner et al., 2011), cannot be readily applied to the tongue given challenges in stimulating the hypoglossal nerve and recording from the tongue. Assessments of tongue function during speech and swallowing are also available for quantifying bulbar motor deterioration. These include instrumentation-based measures of lingual strength and kinematics (Langmore and Lehman, 1994; Yunusova et al., 2012; Green et al., 2013), measures of speech and swallowing decline (Robbins, 1987; Yorkston et al., 2007), and functional severity rating scales, such as the bulbar subscore on ALS functional rating scale revised (Cedarbaum et al., 1999). One potential disadvantage of these approaches, however, is that they can be affected by a variety of factors including effort, fatigue, and cognitive status.

One technique that potentially overcomes some of the limitations of existing approaches to quantifying bulbar muscle disease is electrical impedance myography (EIM). EIM has been shown to be sensitive to disease progression in appendicular muscles in ALS, in both human patients (Rutkove et al., 2012) and animal models (Wang et al., 2011b; Li et al., 2013b). More recently, a pilot study of tongue EIM was also completed (Shellikeri et al., 2015), in which an EIM electrode array was created by affixing four electrodes to a plastic tongue depressor wired directly to an impedance-measuring device. Significant differences could be detected between healthy individuals and those with ALS.

One unexplored possibility is that these EIM changes are driven by reductions in tongue volume that occur due to lingual muscle atrophy. Presumably, reductions in tissue volume could directly impact the measured resistance and reactance, the two major basic EIM parameters. Surface EIM data may also be influenced by disease-related alterations in the electrical material properties of the tongue. These properties, including the conductivity (the ability for charge to flow freely through the tissue), and permittivity (the ability for a polarized electrical field to develop within the tissue) are altered in ALS (Li et al. 2014), and thus could directly impact the obtained data. Thus, in this study, we performed a series of *in silico* analyses using the finite element method (FEM) to determine the interplay between disease-related tongue changes and EIM results, incorporating a combination of both animal tissue data and human tongue dimensions. We then compared those modeled values to a small set of human tongue data.

2. METHODS

2.1. Developing a FEM-based tongue model

There are several major tasks that need to be completed in order to develop a FEM-based model of the tongue following upon previous efforts made to create models of both human and animal muscle (Wang et al., 2011a; Jafarpoor et al., 2013). First, the electrical material properties (i.e., the conductivity and permittivity) of tongue tissues need to be obtained. These properties are critical to model development and have both a frequency and directional-dependence called anisotropy. Because the tongue is made up of several tissues, including epithelium and muscle, separate parameters for each tissue should be included in the model.

Second, an accurate geometric representation of the tongue using computer-assisted design techniques needs to be developed, including layers for the muscle and epithelium. This model should take into account not only the tongue's shape and size in its healthy state but also capture changes in the thickness with disease progression. The model also needs to include the electrode array itself placed on the surface of the tongue. Third, using commercial modeling software, the model is divided into a vast array of thousands of finite linear elements termed a "mesh," each of which helps approximate a boundary condition for that region of the model via numerical linear algebra, with the electrical material properties being input as parameters for these calculations. Having offered this overview, we now provide a more detailed description of the model development pursued here.

2.2. Electrical material properties

Ideally fresh cadaveric human tongue would be used for these analyses; however, this tissue was unavailable. Thus, for these analyses, we used data that was available—namely, mouse gastrocnemius muscle data from our previously reported studies in healthy and ALS animals (Li et al., 2014). While the gastrocnemius may seem far removed from the tongue, the basic pathological processes of motor neuron loss and subsequent cell atrophy should hold for both muscles. For the overlying epithelial layer's electrical properties, we used an online data resource (Institute of Applied Physics (IFAC), 2007) based on previously published work by others (Gabriel et al., 1996). The *ex vivo* muscle data were obtained after mice were sacrificed at the end of the study via the use of an impedance measuring cell, as previously described (Jafarpoor et al., 2013). The muscle data obtained included anisotropic information, with separate longitudinal (conduction along the length of the fibers) and transverse values (conduction across the fibers). The epithelial layer data were isotropic. Institutional animal care and use committee approval had been previously obtained for all studies.

2.3. FEM development and analysis

The basic FEM model was based on available human anatomic tongue morphological data (Hopkin, 1967; Oliver and Evans, 1986) and was developed and analyzed using the AC/DC Module, Electric Currents Physics in Comsol Multiphysics software (Comsol, Inc, 5.0 Burlington, MA), as shown in Figure 1A. The proximal end of the model extended toward the base of the tongue and the distal end extended to and included the tip of the tongue. The

basic structure consisted of a superficial epidermal layer and an underlying muscle layer. More distant structures, such as the sublingual arteries and veins were not included, since, based on past work, electrical current would not be expected to penetrate that deeply (Jafarpour et al., 2013). The model included anisotropic data: longitudinal values in the sagittal plane and transverse data in both the axial and coronal planes. Thickness of the epidermal layer was identical throughout the model, whereas the muscle thickness increased moving posteriorly, consistent with its known anatomical structure. Electrodes identical in size and spacing to the electrode array shown in Figure 1B (0.15 cm² sized electrodes spaced 0.4 cm apart) were positioned anteriorly on the center of the tongue. The normal component of the electric current was assumed to be continuous for non-electrode boundaries. The electrodes were modeled as potential surfaces. No inter-electrode contact impedances were included, as they are several orders of magnitude smaller than the input impedance of the voltage sensors and likely inconsequential at the frequencies of interest. The electrode closest to the tip of the tongue served as the current source, the one most posterior served as the current sink, and the middle two provided voltage measurement. The mesh of linear elements was generated automatically with the Comsol software with the final construction consisting of between 14878 and 18760 tetrahedral elements (Figure 1C) and having a 3 to 4 s solution time, depending on thickness of tongue used.

The effective impedance values were calculated from 10 kHz to 1 MHz after solving the finite element problem. These values were calculated from the difference in voltage between the two sense electrodes, as previously described (Wang et al., 2011a). After this basic model was developed, the shape was altered by reducing the superior-inferior axis of the tongue. This allowed us to decrease its thickness while maintaining its width and length, the modeled EIM outcomes being recalculated for each of these different sizes.

2.4. Human subjects and human data collection

These modeled results were then compared to previously published human data (McIluff et al., 2015). Specifically, all human studies had been approved by Beth Israel Deaconess Medical Center's institutional review board and informed consent had been obtained from all subjects. Both healthy subjects and ALS patients with clinical evidence of bulbar dysfunction and tongue weakness on examination underwent EIM measurements utilizing the Imp SFB7® (Impedimed, Inc, Sydney, Australia). The data are based on an average of values from 27 normal subjects (14 male, 13 female) with mean age of 44.1 years, range 22–71 years and 3 ALS patients with clinical bulbar involvement and tongue weakness (2 female, 1 male), mean age 71.3 years, range 67–80 years.

3. RESULTS

3.1. FEM models and predictions

Figure 2 shows the modeled current flow through the tongue at 2 angles, the size of the arrows being proportional to the amount of current (i.e., current density) in any given region of the tongue. As can be seen, although the current flows through a fairly large area of the tongue, most of the current flows relatively superficially in the region of the electrodes.

Figure 3 shows the impact of altering tongue thickness with progressive thinning due to muscle atrophy, holding the epidermal thickness unchanged, at a single frequency of 50 kHz, using both the healthy mouse and ALS mouse data. Selected values are also provided in Table 1. This analysis showed that alterations in impedance data were non-linear, especially for resistance, with the greatest changes occurring as the tongue became severely thinned. It also showed that the alterations were relatively similar for both healthy and diseased muscle. The other point of interest here is that the phase value was the least impacted by tongue size. Indeed, the resistance values increase more than 20% for both the ALS and healthy muscle as the thickness of the muscle decreased; reactance shows a slightly smaller difference, being somewhat greater for the ALS mouse, changing 20.6%. The phase, in contrast, changed only slightly as the muscle size decreases (by approximately 5%). Also of interest, the phase decreased slightly with decreasing thickness, in contrast to both reactance and resistance, both of which increased.

Figure 4 shows the comparison between our modeled data using a proximal tongue thickness of 1.2 cm, a value based on reported atrophy in human tongue data, and those of the ALS and healthy subjects (Cha and Patten, 1989). As can be seen, there are substantial offsets, despite our including scaling factors of 0.5X for reactance and 0.235X for reactance. Nonetheless, the general character of the modeled curves followed that of the real data. For example, the resistance values were slightly higher for the healthy muscle at low frequencies and slightly lower at high frequencies for both the modeled and real data. Similarly, the reactance plots were characterized by prominent peaks (arrows), although the modeled data had lower frequency peaks and higher amplitudes than did the real data. An explanation for this discrepancy is provided below.

4. DISCUSSION

The major goal of this study was to gain insight into how changes in tongue size due to atrophy and its electrical material properties influence surface-measured EIM tongue data in ALS patients. The findings suggest that most of the impedance differences that are observed between diseased and healthy tongue data are due to the alteration in the inherent electrical material properties of tongue tissues, rather than as a mere consequence of muscle volume loss. This suggestion appears to be especially true for the phase value, which is expected since the phase is a geometric ratio (the arctangent (reactance/resistance)), with the size changes canceling out.

The lack of a substantial effect of tongue size on the impedance measures is explained partially by the findings displayed in Figure 2, which shows that most of the current is flowing superficially in the tongue. Thus, impedance measures may, therefore, only be affected by tongue atrophy when the tongue becomes severely thinned. The small inter-electrode distances in our electrode array likely minimized the effect of tongue thickness on impedance measures because it ensured that current flow did not penetrate too deeply. The farther apart the electrodes are spaced, the greater the current penetration and likely the greater the impact of tongue thickness. The length of our electrode array was intentionally short to minimize the likelihood of eliciting a gag reflex, which was a problem with the first-

generation tongue array (Shellikeri et al., 2015). The resulting short electrode distance may have also have fortuitously reduced the impact of tongue atrophy on the measurements.

The differences in the reactance peaks (as shown by the arrows in Figure 4) between the modeled and real data are of specific interest. The most likely explanation relates to muscle fiber size and the fact that we did not use actual tongue muscle in the model, but rather gastrocnemius muscle from the mouse. Human tongue muscle has considerably smaller muscle fiber size than appendicular muscles, even comparing that of the human to the mouse (mean anterior tongue muscle fiber size in an adult human is approximately 30 μm (Stål et al., 2003) as compared to 40–50 μm for an adult mouse gastrocnemius muscle fiber (Burkholder et al., 1994; Li et al., 2013a)). Due to the inherent resistive-capacitive aspects of tissue, smaller fiber size means that the tissue will have a higher frequency peak in reactance. Such cell size dependency of the impedance was actually the basis for early automated cell counting such as the Coulter counter (Grover et al., 1969). This effect can also be observed in both the modeled and real data comparing the ALS to the healthy values in Figure 4. As can be seen, there is a slight shift to the right in the ALS muscle, consistent with the presence of some atrophied (i.e., smaller-sized fibers).

There are a variety of limitations to this study. The first is the use of online data and mouse gastrocnemius to build the model; mouse tongue was unavailable and there were barriers to obtaining human cadaveric tongue. Despite this, we believe that the assumptions underlying this choice of values are reasonable and sufficient for the sake of this simple model. Second, it is difficult to accurately incorporate the anisotropic properties of the tongue given its very complex fiber structure as compared to most appendicular muscles where the orientation is generally simpler; thus, inevitably this also contributed to inconsistencies between the models. Third, the geometric shape we developed is also obviously simplified and discrepancies between that and a real tongue will lead to further inaccuracies in the modeled data. Fourth, we did not include in the model electrical material properties of less-severely diseased ALS tissue (e.g., tissue from mice with less advanced disease). Theoretically, we could have incorporated less diseased tissue into models with corresponding thicknesses between those of a healthy tongue and severely diseased tongue. This would have resulted in a gradient of EIM values that corresponded with disease progression and would be useful in evaluating the progression of ALS early in the disease course. However, the purpose of this study was for proof of concept and such an analysis is well beyond its scope. Nevertheless, future work could address this interesting concept more specifically. Finally, the impedance-measuring device, the SFB7, has certain limitations, including having impedances with greater offsets at high frequencies (likely due to parasitic currents within the device itself). This is, no doubt, also contributing to some of the observed inconsistencies between real and modeled data at higher frequencies.

The main purpose of this study was to better understand the mechanism of impedance alteration in ALS. Much of the observed change appears to be due to alterations in the impedance characteristics of the tissue and not simple volume effects. This supports the possibility that localized impedance measurements could be used to assist in diagnosis of lower motor neuron bulbar disease, possibly before clear tongue atrophy is present. The modeling completed here will also assist in the development of improved arrays for tongue

measurement. For example, it suggests that close electrode spacing is advantageous when measuring the tongue. It may thus be possible to create a two-dimensional array to attempt to obtain multidirectional tongue data. Such an array may be able to provide a more complete and possibly more sensitive impedance measure of tongue involvement in ALS. Further work exploring this possibility and the broader application of EIM to bulbar ALS assessment is currently ongoing.

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References

- Burkholder TJ, Fingado B, Baron S, Lieber RL. Relationship between muscle fiber types and sizes and muscle architectural properties in the mouse hindlimb. *J Morphol.* 1994; 221:177–90. [PubMed: 7932768]
- Caroscio JT, Mulvihill MN, Sterling R, Abrams B. Amyotrophic lateral sclerosis. Its natural history. *Neurol Clin.* 1987; 5:1–8. [PubMed: 3561382]
- Cedarbaum JM, Stambler N, Malta E, Fuller C, Hilt D, Thurmond B, et al. The ALSFRS-R: a revised ALS functional rating scale that incorporates assessments of respiratory function. BDNF ALS Study Group (Phase III). *J Neurol Sci.* 1999; 169:13–21. [PubMed: 10540002]
- Cha CH, Patten BM. Amyotrophic lateral sclerosis: abnormalities of the tongue on magnetic resonance imaging. *Ann Neurol.* 1989; 25:468–72. [PubMed: 2774487]
- Gabriel S, Lau RW, Gabriel C. The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz. *Phys Med Biol.* 1996; 41:2251–69. [PubMed: 8938025]
- Green JR, Yunusova Y, Kuruvilla MS, Wang J, Pattee GL, Synhorst L, et al. Bulbar and speech motor assessment in ALS: Challenges and future directions. *Amyotroph Lateral Scler Frontotemporal Degener.* 2013; 14:494–500. [PubMed: 23898888]
- Grover NB, Naaman J, Ben-Sasson S, Doljanski F, Nadav E. Electrical sizing of particles in suspensions. I. Theory. *Biophys J.* 1969; 9:1398–414. [PubMed: 5353144]
- Gubbay SS, Kahana E, Zilber N, Cooper G, Pintov S, Leibowitz Y. Amyotrophic lateral sclerosis. A study of its presentation and prognosis. *J Neurol.* 1985; 232:295–300. [PubMed: 4056836]
- Hopkin GB. Neonatal and Adult Tongue Dimensions. *Angle Orthod.* 1967; 37:132–3. [PubMed: 5229084]
- Jafarpour M, Li J, White JK, Rutkove SB. Optimizing electrode configuration for electrical impedance measurements of muscle via the finite element method. *IEEE Trans Biomed Eng.* 2013; 60:1446–52. [PubMed: 23314763]
- Jenkins TM, Burness C, Connolly DJ, Rao DG, Hoggard N, Mawson S, et al. A prospective pilot study measuring muscle volumetric change in amyotrophic lateral sclerosis. *Amyotroph Lateral Scler Frontotemporal Degener.* 2013; 14:414–23. [PubMed: 23705876]
- Langmore SE, Lehman ME. Physiologic deficits in the orofacial system underlying dysarthria in amyotrophic lateral sclerosis. *J Speech Hear Res.* 1994; 37:28–37. [PubMed: 8170127]
- Li J, Geisbush TR, Rosen GD, Lachey J, Mulivor A, Rutkove SB. Electrical impedance myography for the in and ex vivo assessment of muscular dystrophy (mdx) mouse muscle. *Muscle Nerve.* 2013a; 49:829–35. [PubMed: 24752469]
- Li J, Jafarpour M, Bouxsein M, Rutkove SB. Distinguishing neuromuscular disorders based on the passive electrical material properties of muscle. *Muscle Nerve.* 2014; 51:49–55. [PubMed: 24752678]
- Li J, Sung M, Rutkove SB. Electrophysiologic biomarkers for assessing disease progression and the effect of riluzole in SOD1 G93A ALS mice. *PLoS One.* 2013b; 8:e65976. [PubMed: 23762454]

- McIllduff CE, Yim S, Pacheck A, Geisbush T, Mijailovic ARS. An Improved Electrical Impedance Myography Tongue Array for Use in Clinical Trials. *Clin Neurophysiol.* 2015;106:1016/j.clinph.2015.06.021
- Oliver RG, Evans SP. Tongue size, oral cavity size and speech. *Angle Orthod.* 1986; 56:234–43. [PubMed: 3461733]
- Robbins J. Swallowing in ALS and motor neuron disorders. *Neurol Clin.* 1987; 5:213–29. [PubMed: 11681400]
- Rutkove SB, Caress JB, Cartwright MS, Burns TM, Warder J, David WS, et al. Electrical impedance myography as a biomarker to assess ALS progression. *Amyotroph Lateral Scler.* 2012; 13:439–45. [PubMed: 22670883]
- Shefner JM, Watson ML, Simionescu L, Caress JB, Burns TM, Maragakis NJ, et al. Multipoint incremental motor unit number estimation as an outcome measure in ALS. *Neurology.* 2011; 77:235–41. [PubMed: 21676915]
- Shellikeri S, Yunusova Y, Green JR, Pattee GL, Berry JD, Rutkove SB, et al. Electrical impedance myography in the evaluation of the tongue musculature in amyotrophic lateral sclerosis. *Muscle Nerve.* 2015; 52:584–91. [PubMed: 25580728]
- Stål P, Marklund S, Thornell LE, De Paul R, Eriksson PO. Fibre composition of human intrinsic tongue muscles. *Cells Tissues Organs.* 2003; 173:147–61. [PubMed: 12673097]
- Tankisi H, Otto M, Pugsahl K, Fuglsang-Frederiksen A. Spontaneous electromyographic activity of the tongue in amyotrophic lateral sclerosis. *Muscle and Nerve.* 2013; 48:296–8. [PubMed: 23813640]
- Wang LL, Ahad M, McEwan A, Li J, Jafarpour M, Rutkove SB. Assessment of alterations in the electrical impedance of muscle after experimental nerve injury via finite-element analysis. *IEEE Trans Biomed Eng.* 2011a; 58:1585–91. [PubMed: 21224171]
- Wang LL, Spieker AJ, Li J, Rutkove SB. Electrical impedance myography for monitoring motor neuron loss in the SOD1 G93A amyotrophic lateral sclerosis rat. *Clin Neurophysiol.* 2011b; 122:2505–11. [PubMed: 21612980]
- Yorkston, K.; Beukelman, D.; Hakel, M.; Dorsey, M. Speech intelligibility test for Windows [computer software]. Lincoln, NE: Institute for Rehabilitation Science and Engineering at Madonna Rehabilitation Hospital; 2007.
- Yunusova Y, Green JR, Greenwood L, Wang J, Pattee GL, Zinman L. Tongue movements and their acoustic consequences in amyotrophic lateral sclerosis. *Folia Phoniatr Logop.* 2012; 64:94–102. [PubMed: 22555651]
- Institute of Applied Physics (IFAC). Dielectric Properties of Body Tissues [Internet]. 2007. Available from: <http://niremf.ifac.cnr.it/tissprop/>

Highlights

1. Computer modeling shows electrical impedance myography (EIM) values reflect changes in intrinsic muscle electrical properties.
2. Tongue thickness, unrelated to tongue health, has limited impact on the EIM data.
3. Given these findings, EIM of the tongue appears to hold potential to serve as a useful biomarker of disease progression in ALS clinical trials.

Figure 1.

A. Basic geometric model of tongue with electrodes on surface. **B.** Tongue electrode array used in the developed finite element model, using the same design as in McIllduff, et al. (McIllduff, CE, Yim S, Pacheck A, Geisbush T, Mijailovic A 2015) **C.** Same model as in A, now with finite element mesh added.

Figure 2. Current flow through the tongue with EIM measurement. The size of the arrows is proportional to the current density in that region. The current source electrode is the one closest to the tip of the tongue; the sink is the one most proximal. The two inner electrodes are voltage-measuring. Note that most of the current flows superficially through the tongue.

Figure 3.

Relationship between tongue thickness and modeled impedance values at 50 kHz using healthy mouse electrical material property values. Note that both reactance and resistance show marked elevations as the tongue thins, but phase remains relatively stable and decreases as atrophy progresses. This analysis supports that much of the change in phase values is due to the primary change in the intrinsic properties of the tongue and not simple volume loss.

Figure 4.

Comparison of modeled and real impedance data in both healthy and ALS-affected tongue. Gray shading in the human data indicates the standard error of the mean for each group. Scaling factors of 0.5X for resistance and 0.235X for reactance were also included such that the normal value peak matched the normal value peak of the actual data; ALS data was scaled based on that same factor. Note that the peaks in the reactance data (arrows) are shifted to the left (i.e., lower frequency) in the modeled data compared to the real data, consistent with the fact that mouse gastrocnemius muscle fibers are larger than tongue fibers. Similarly, both ALS plots (modeled and real) have peaks that are shifted slightly to the right of normal, likely secondary to ALS-associated muscle fiber atrophy.

Table 1

Effects of tongue thickness on modeled EIM data.

Tongue Thickness	2.0 cm	1.5 cm	1.0 cm
Resistance-Healthy	78.8 Ω	82.9 Ω (5.2 %)	94.6 Ω (20.1 %)
Resistance-ALS	67.2 Ω	72.1 Ω (7.3 %)	85.5 Ω (27.1 %)
Reactance -Healthy	48.1 Ω	49.3 Ω (2.6 %)	53.7 Ω (11.7 %)
Reactance ALS	27.0 Ω	28.3 Ω (4.8 %)	32.6 Ω (20.6 %)
Phase-Healthy	31.4 Ω	30.8 Ω (2.0 %)	29.6 Ω (5.8 %)
Phase-ALS	21.9 Ω	21.4 Ω (2.0 %)	20.9 Ω (4.7 %)