Electrically conductive synthetic vocal fold replicas for voice production research

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Abstract: A method of fabricating electrically conductive synthetic vocal fold replicas and monitoring their vibration via resistance measurement is presented. Normally non-conductive silicone replicas were coated with conductive graphite and subjected to long-term vibration tests. Synchronized resistance and imaging data using hemilarynx and full larynx configurations showed an inverse correlation between replica contact area and resistance during vibration, similar to clinical electroglottography (EGG) used to estimate vocal fold contact area. This method has potential for long-term replica vibration monitoring and studying basic physical relationships between resistance and contact area in vocal folds and vocal fold replicas.

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1. Introduction

Voice production research is frequently conducted using excised larynges and synthetic and computational models, each of which has inherent benefits and limitations.[1–3] Among the advantages of synthetic vocal fold replicas[4] is the ability to sustain vibration over long periods of time, a useful characteristic when studying, for example, flow dynamics[5–7] or cell function.[8] In such studies, replica vibration is often observed using high speed imaging, an approach that is highly informative, but costly and unsuitable for long-term monitoring.

The purpose of this letter is to demonstrate a new method of monitoring synthetic replica vibration based on electroglottography (EGG). EGG is a clinical tool for estimating vocal fold contact area during phonation based on electrical resistance across the neck at the level of the glottis.[9–11] During the closed phase of the glottal cycle, electrical resistance across the neck decreases due to increased contact area between the vocal folds. In a similar manner, synthetic EGG using electrically conductive vocal fold replicas could be used for long-term monitoring of vibrating replicas and to further study relationships between electrical conductivity and glottal area. For example, such long-term resistance monitoring could be useful in cases in which other monitoring methods (e.g., microphones or accelerometers) are not feasible due to background noise and vibration, which may be the case in some bioreactor designs. As with the human vocal folds, electrical resistance across electrically conductive synthetic replicas would be expected to be inversely related to the contact area between the replica medial surfaces. In this paper, the methods for fabricating electrically conductive synthetic vocal fold replicas and measuring resistance across the replicas are described, and results that successfully demonstrate the technique using vibrating replicas in both hemilarynx and full larynx configurations are presented.

2. Methods

2.1 Electrically conductive replica fabrication

Synthetic vocal fold replicas based on the M5 geometry of Scherer *et al.*[12] were fabricated. The replicas were composed of a single layer of EcoFlex 0030 addition-cure

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silicone mixed at a ratio of one part A:one part B:four parts Silicone Thinner (all materials from Smooth-On, Inc.) While more sophisticated replicas exist,[4] because the purpose of this work was to demonstrate the feasibility of monitoring resistance across electrically conductive vibrating replicas, the simpler homogeneous M5 replicas were sufficient.

Each replica was cured and mounted to an acrylic plate as in other studies.[4,13] Since silicone is not conductive, the outside surface of each replica was coated with 5-μm graphite powder (GRPM5, ChemicalStore.com) until it was visibly covered. Vocal fold replicas are typically coated with talcum powder to reduce surface tackiness. However, in the present case, no talcum powder was necessary since the graphite coating simultaneously reduced surface tackiness and created an electrically conductive surface. Attempts to mix graphite and other conductive particles within the silicone compounds prior to curing were attempted; however, when a sufficient quantity of particles had been added to achieve conductivity, the resulting material properties had been sufficiently altered such that phonomimetic flow-induced vibration would not have been possible.

Full and hemilarynx configurations were used to study resistance vs time waveforms for vibrating replicas. In the full larynx configuration, electrical leads were placed in contact with the superior surface of each replica, toward the lateral margins. In the hemilarynx configuration, one replica was replaced with a 50 mm × 50 mm × 1 mm indium tin oxide (ITO)–coated conductive transparent glass plate (www.adafruit.com, Product 1310). One electrical lead was placed in contact with the superior surface of the replica and the other lead was attached to the conductive glass. Conductive transparent glass in hemilarynx studies enables synchronous EGG measurements and medial surface imaging, as has been recently demonstrated in an excised hemilarynx study.[14]

During vibration the resistance across the replicas (or between the replica and the conductive glass plate in the hemilarynx configuration) varied from relatively low values during closed phases to relatively high values during open phases. To measure this change in resistance, the electrical leads were connected to form one arm of a Wheatstone bridge (i.e., in a quarter-bridge configuration) such that resistance across the replica could be calculated as follows:

$$R_x = \frac{R_2 R_3 + R_3(R_1 + R_2)\dfrac{V_B}{V_{in}}}{R_1 - (R_1 + R_2)\dfrac{V_B}{V_{in}}}, \tag{1}$$

where R_x is the resistance across the replica sensed using the electrical leads, R_1, R_2, and R_3 are fixed resistors, each with the same nominal value, V_B is the measured voltage across the replica, and V_{in} is the bridge source voltage. Because the resistance values were found to generally be in the range of 100 to 800 kΩ, fixed 330 kΩ resistors were used for R_1, R_2, and R_3. An excitation voltage of 10 V was applied to the bridge, and the bridge output (V_B) was measured using a data acquisition system (National Instruments cDAQ-9176 with NI 9218 module) and custom LabView VI. The output resistance waveforms were then calculated using the measured voltage waveforms via Eq. (1).

2.2 Experimental setup and procedure

Images of the vibrating replicas were synchronized with resistance data using still frames from a Nikon D5100 SLR camera (shutter speed 0.5 s, f/stop 4.5, ISO 400), two strobe lights (GenRad 1546 Digital Stroboscopes, IET Labs), and a function generator (GFG-8015G, GW Instek). The camera was mounted directly above the replicas to image the glottal opening. Strobe lights were placed above and below the replicas. A function generator with an approximately 1.8 Hz square wave triggered the strobe lights and the camera. The square wave was also recorded in LabVIEW simultaneously with the Wheatstone bridge data. The room was darkened. Upon receiving the trigger from the function generator, the camera shutter would open, the strobes would flash once for approximately 2 μs, and after 0.5 s, the camera shutter would close. Using the trigger signal that was recorded with the Wheatstone bridge signal, each image was subsequently matched to its corresponding position in the resistance waveform. The images were then reordered to reconstruct a representative sequence of images of glottal opening.

Air flow from a pump (AMETEK model DR083DC9Y/081572) was used to initiate flow-induced vibration of the replicas. For the hemilarynx configuration, vibration onset and offset occurred at 2.3 and 2.1 kPa, respectively. For the full configuration, onset and offset occurred at 2.5 and 2.1 kPa, respectively. In both cases, resistance and area tests were performed at the onset pressure. The tube between the pump and the replicas contained a "T" valve for rapidly turning the airflow to the replicas on and off in order to readily observe changes in resistance before and after vibration commencement.

Tests proceeded as follows. The pump was turned on with the valve in a position such that no air reached the replicas. As the valve was adjusted to increase subglottal pressure and initiate replica vibration, voltage measurements across the replicas were acquired at a rate of 10 kHz to capture the change in resistance as vibration commenced from rest. After vibration onset, data were collected at an increased sample rate of 25 kHz for improved temporal resolution of the resistance waveform, and images were acquired during oscillation. After sustaining vibration over a period of time (around 10 min), another 25 kHz dataset was acquired, followed by 10 kHz data acquisition while the pump was turned off and the replicas returned to their no-flow positions.

3. Results

3.1 Replica conductivity

In the hemilarynx configuration with no flow, the medial surface of the replica was in contact with the conductive glass plate. In this state, the resistance between the replica and the glass plate was approximately 170 kΩ. In the full larynx configuration in the absence of flow, the medial surfaces of opposing coated replicas were touching, in which case the resistance across the replicas was approximately 235 kΩ. These baseline values demonstrate conductivity of the graphite-coated replicas, but in general are expected to vary from replica to replica based on variables such as graphite particle shape and size, material stiffness, coating density, and so on. Thus, as in EGG, relative—rather than absolute—resistance throughout vibration is of primary interest.

Tests during vibration demonstrated that the graphite powder adhered to the replica surfaces sufficient for long-term resistance waveform monitoring. Resistance over time throughout the onset, testing, and offset phases are shown in Fig. 1 for the hemilarynx and full larynx configurations. Shown are the initial ramp-up phases as the airflow was turned on, a detailed view of the resistance waveforms during vibration toward both the beginning and the end of the test, and the ramp-down phases as the airflow was turned off. Note that the data are not continuous, but had a break in time during which the imaging took place. Some drift in the waveforms is evident in both cases, particularly that of the full larynx configuration, and is attributed to factors such as replica material relaxation, changes in supply pressure, and temperature

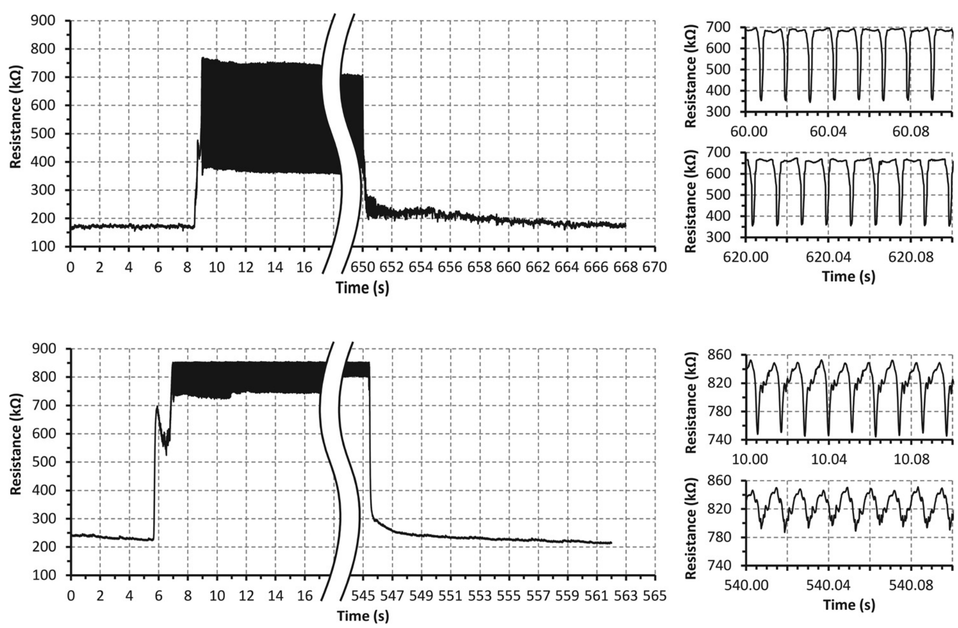

Fig. 1. (Left) Resistance vs time measurements before, during, and after replica vibration with hemilarynx (top) and full larynx (bottom) configurations. (Right) Close-ups of corresponding waveforms at selected times during oscillation.

variation. Phenomena such as these have been noted in other similar vocal fold replica studies.[15] Further explorations of these and other factors, including possible changes in electrical resistance over time, are needed. Nevertheless, it is noted that in both cases, the initial resistance before the airflow was turned on was very similar to the final resistance after the airflow had been shut off. This consistency in resistance before and after several minutes of oscillation suggests that the replicas maintained similar electrical properties throughout testing.

3.2 Resistance waveforms

Waveforms of resistance vs time toward the beginning and the end of the testing phases are also shown in Fig. 1. The frequency was about 83 Hz for both configurations. The waveform details show typical glottal cycle shapes over the duration of the tests with clear variation between open and closed phases. It is presumed that the closed phase resistance is higher than the baseline, no-flow resistance due to the replica medial surfaces (or the medial surface and the glass plate in the hemilarynx configuration) experiencing contact over a smaller area than that which existed at rest. The hemilarynx replica experienced a greater intra-cycle change in resistance than the full larynx replica, presumably due to differences in vibration patterns. The waveform from the hemilarynx configuration remained fairly consistent over the course of the vibration testing (approximately 10 min), with a small decrease in amplitude possibly caused by material relaxation of the single vibrating replica. The full larynx configuration experienced a more significant decrease in amplitude, which is not surprising given that in this case, two replicas were each presumably undergoing material relaxation.

3.3 Synchronization of resistance and image data

Simultaneous resistance and imaging data acquired during vibration demonstrate that the resistance across the conductive replicas varied with contact area. Figure 2 shows these data for a representative glottal cycle during vibration for the hemilarynx and full larynx configurations. On the left of the figure are sample waveforms of resistance vs time. On the right are images that approximately coincide with the labeled points on the waveforms. Because of the nature of the image acquisition (single-frame SLR images with synchronized strobe light illumination), the images do not exactly coincide

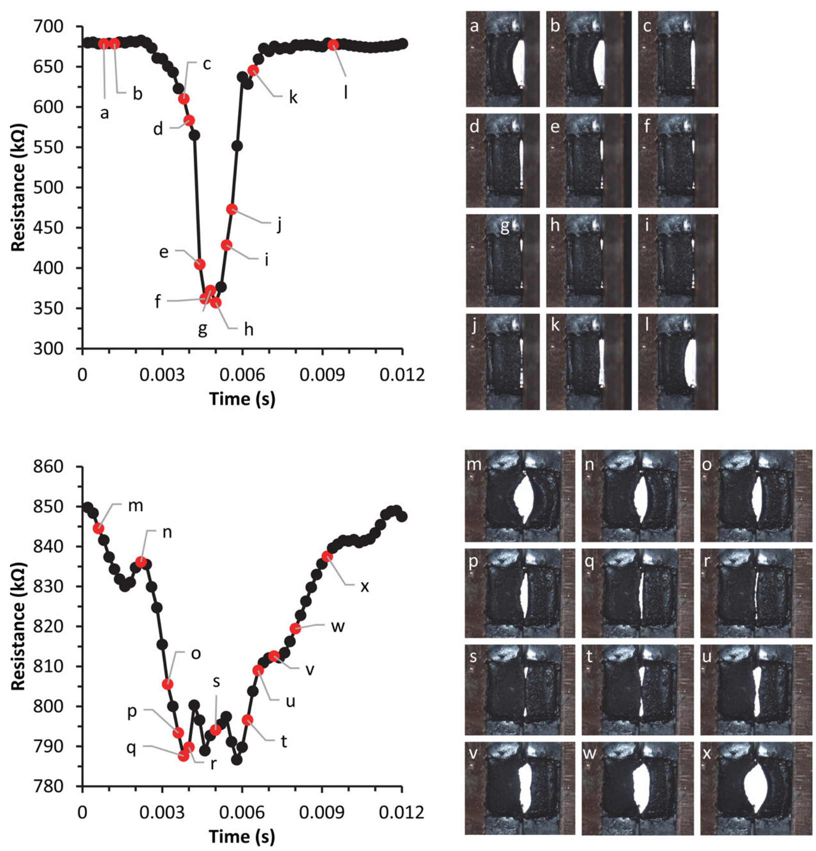

Fig. 2. (Color online) Characteristic resistance waveforms (left) and still images (right) for the hemilarynx configuration (top row) and full larynx configuration (bottom row).

with the resistance waveforms. However, since the imaging trigger was acquired in LabVIEW with the resistance data, the image and resistance acquisition times were matched with each other, and thus were able to be re-ordered and mapped to the characteristic resistance waveforms shown here.

By mapping the images to the resistance waveforms, it is possible to qualitatively correlate changes in resistance with glottal opening, and by inference, contact area. In Fig. 2, images a and b are near the time of hemilarynx maximum opening, showing that an open glottis coincided with the highest resistance values. As the orifice began to close (images c and d), the anterior-posterior edges of the replica began to make contact with the copper plate and resistance began to decrease. Images e through h show the replica beginning to contact the plate near the anterior-posterior midplane, with the largest decreases in resistance (indicating greatest contact areas) occurring at these phases. Finally, images i through k show the replica opening (with increasing resistance), with the replica returning to the open phase (image l).

The full larynx configuration results show similar trends. For example, images m, n, and x show an open glottis at the times of highest resistance, whereas images s and t show maximum contact and corresponding lower resistance values. In contrast with the hemilarynx configuration, more variation in contact area at the anterior-posterior edges of the replicas may be evident in the full larynx configuration images. This may have contributed to the greater amount of noise in the full larynx resistance waveforms. As discussed further below, more work is needed to explore noise and other phenomena seen in the images and waveform data.

4. Conclusions and future work

A method of monitoring synthetic vocal fold replica vibration through the use of electrical resistance has been introduced and demonstrated. Powdered graphite applied to the replica surfaces yielded electrically conductive replicas. Resistance and imaging results using hemilarynx and full larynx configurations showed an inverse correlation between electrical resistance and contact area during vibration, similar to the EGG signal used to monitor vocal fold contact area *in vivo*. The use of a conductive glass plate in the hemilarynx configuration allows for future simultaneous measurements of resistance and contact area. This method demonstrates the potential for tracking vocal fold motion over long periods of time using only resistance measurements, as well as for studying basic physical relationships between resistance and contact area with possible application to EGG methodologies.

Work is needed to further study and refine this technique. Longer-duration measurements of replicas with and without graphite powder, coupled with intermittent high-speed data, should be acquired to study drift in replica vibration (e.g., due to material relaxation) and resistance (e.g., due to possible changes in conductivity) over time. Tests with static replicas to correlate changes in resistance with contact area and contact force, as well as tests with vibrating replicas with more sophisticated geometries and layered structures, are advised. Finally, since the images shown here were only of the superior surfaces and were acquired at intermittent intervals throughout vibration using synchronized strobe illumination, additional imaging techniques, such as imaging through the conductive glass plate, synchronized medial and superior-view imaging, and high-speed imaging are needed to more fully characterize contact area vs resistance relationships during vibration and to explore and quantify sources of noise and uncertainty.

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