

Acoustic Reflectometry Profiles of Endotracheal and Esophageal Intubation

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Background: Acoustic reflectometry can be used to create a "one-dimensional image" of a cavity, such as the airway and lung, with the image displayed as an area-length curve. This pilot study was undertaken to determine whether acoustic reflectometry could be used to distinguish between an endotracheal and an esophageal intubation.

Methods: Ten adult patients underwent general endotracheal anesthesia and neuromuscular blockade. The reflectometer wavetube was attached to an endotracheal tube, and a reflectometric profile was obtained of the endotracheal tube and the airway and lung cavity. After confirmation of tracheal intubation, a second endotracheal tube was placed in the esophagus. After four breaths were administered, a reflectometric profile of the endotracheal tube-esophagus cavity was obtained.

Results: The acoustic reflectometric profiles for tracheal and esophageal intubation profiles were distinctive and characteristic. For an endotracheal tube-airway cavity, the profile shows a constant cross-sectional area throughout the length of the endotracheal tube, followed by a rapid rise in the area past the carina. For an esophageal intubation, the profile shows constant cross-sectional area throughout the length of the endotracheal tube, followed by a sudden decrease in the cross-sectional area to zero.

Conclusions: In this pilot study, acoustic reflectometry within seconds, and without resort to capnography, was able to generate characteristic and distinctive area-length profiles for both endotracheal and esophageal intubation. Acoustic reflectometry may have a role in the emergency imaging of the airway, and in the immediate detection of esophageal intubations, particularly in cases of cardiopulmonary arrest in which the usual techniques for confirmation of breathing tube placement fail. (Key words: Airway; cardiopulmonary arrest; lung imaging.)

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IN the prehospital setting, the incidence of unrecognized esophageal intubation has been reported to be as high as 1.8-2.0%.^{1,2} In cases of cardiopulmonary arrest the critical failure to recognize an esophageal intubation continues to pose a serious safety problem.

Acceptable methods of validation of correct tracheal intubation are direct visualization of passage of the endotracheal tube through the vocal cords, fiberoptic bronchoscopy, and detection of expired carbon dioxide.³⁻⁵ Direct visualization may not be possible in some patients, however, and fiberoptic bronchoscopy may not be available in emergency settings. Expired end-tidal carbon dioxide can be detected with a capnograph, a mass spectrometer, or a single-use end-tidal colorimetric device.⁷⁻⁹ Even these devices may provide spurious results. For example, for a patient in cardiopulmonary arrest there may be no characteristic color change in the colorimetric device, and a waveform may be absent in a capnograph or spectrometer trace.¹⁰⁻¹² Because the detection of expired carbon dioxide may not be possible in a patient in cardiac arrest, a major safety issue for emergency intubations is the development of a means whereby one can confirm proper placement of the endotracheal tube quickly, assuring that oxygenation and ventilation can proceed. Because an unrecognized esophageal intubation can have devastating clinical consequences, the development of a definitive diagnostic device that is capable of distinguishing *unequivocally* within seconds, between an endotracheal and an esophageal intubation in a patient in cardiopulmonary arrest, is of the highest importance. Such a diagnostic device should be compact, portable, and easy to use.

A recently developed airway adjunct is the esophageal detector device. This device consists of a syringe or suction bulb that, after intubation, attaches to an endotracheal tube circuit adapter.¹³⁻¹⁵ Studies have demonstrated the high reliability of the esophageal detector device in patients with normal airways. Reported drawbacks include, however, a slow inflation of the suction bulb, lasting as long as 30 s¹⁶; failure to confirm tracheal

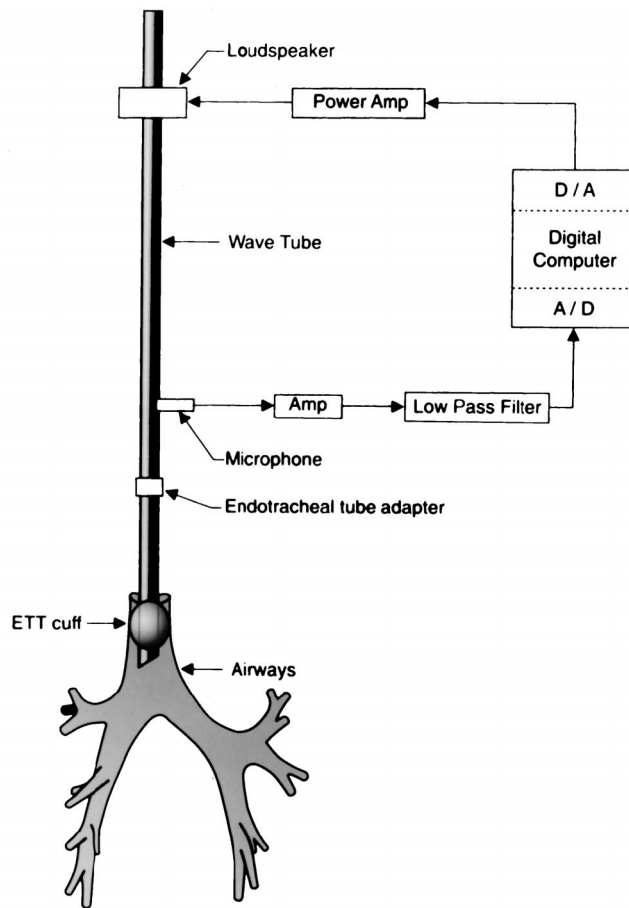


Fig. 1. An acoustic reflectometer. The loudspeaker within the wavetube emits a series of pulses that travel down the wavetube and into the airways of the lung. The microphone, located within the distal wavetube, is connected to a computer-based system that analyzes the reflections returning from the lungs.

intubation in the presence of airway obstruction (asthma, mediastinal mass)¹⁷; and inability to use the device in children younger than 1 yr of age, owing to a failure rate of 25% even with a small modified syringe.¹⁸

A method that has not been attempted to address the problem being discussed here is acoustic reflectometry (fig. 1).^{19,20} A reflectometer generates a series of acoustic impulses and analyzes the reflections from the cavity of interest to generate an area-distance curve. In essence, one obtains a "one-dimensional image" of the cavity of interest. I hypothesized that acoustic reflectometry could be used to distinguish between an esophageal and a tracheal intubation.

Materials and Methods

Ten adult patients provided informed consent in accordance with institutional review board protocol. After intravenous induction of general anesthesia, patients were intubated, paralyzed, and mechanically ventilated. Conventional laryngoscopy and tracheal intubation with an endotracheal tube were performed. In females, an endotracheal tube 7.0 mm ID was positioned at 21 cm at the teeth; in males, an 8.0-mm tube was positioned at 23 cm at the teeth. After confirmation of proper endotracheal tube placement using a capnograph, the presence of bilateral and equal breath sounds was confirmed in all patients.

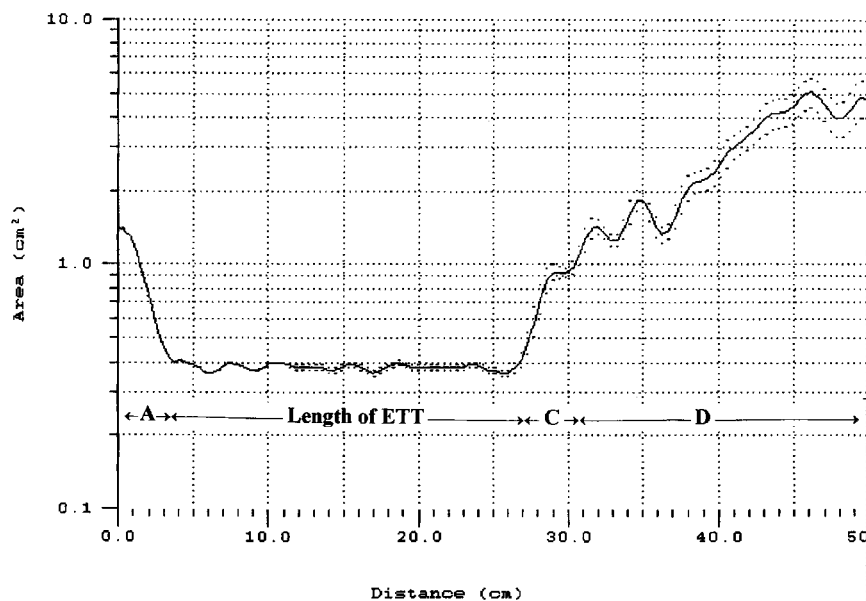
Acoustic reflectometric profiles were obtained *via* use of a customized, computer-based acoustic reflectometer (Hood Labs, Pembroke, MA), characterized by a maximum measurement distance of 50 cm from the distal end of the wavetube. The reflectometer impulse, 2 ms in duration, is characterized by a flat spectral range from 0–5,000 kHz (low-pass filter) and is repeated at the rate of 5 pulses/s.

The reflectometer profile is a semilogarithmic plot of area *versus* length. The horizontal coordinate in the profile corresponds to axial length, in centimeters, with the origin taken to be the distal end of the wavetube and the axial direction taken to be parallel to the longitudinal length of the wavetube. The vertical coordinate of the profile, indicated in square centimeters, corresponds to the coronal cross-sectional area of the structure at a given axial length.

To obtain a measurement, the endotracheal tube was disconnected momentarily from the breathing circuit at the junction between the endotracheal tube adapter and the breathing circuit. The wavetube was attached to the endotracheal tube adapter *via* a 1-in long connecting piece of medical-grade silicone tubing, and an acoustic reflectometric image of the endotracheal tube-airway system was obtained, typically within 15 s.

With an endotracheal tube already in place, assuring satisfactory patient ventilation, a second endotracheal tube of the same diameter was passed into the esophagus to the same depth (21 cm in females, 23 cm in males). Four breaths with a manual reservoir bag were given through this esophageally placed tube, in simulation of the usual ventilatory attempts that follow an intubation. An acoustic reflectometric profile of the endotracheal tube-esophagus system then was made, before and after the four reservoir-bag breaths.

Fig. 2. Acoustic reflectometric profile for an tracheal intubation. In this semilogarithmic plot, the origin is at the distal tip of the wavetube, with the horizontal coordinate parallel to the axial length of the wavetube. The vertical coordinate is the coronal cross-sectional area of the airway at the given axial length. In the positive axial direction, four segments are encountered: the short 1-in connector segment (A); the endotracheal tube segment (7.0-mm-ID endotracheal tube, cut to a length of 26 cm, and positioned at 21 cm at the teeth; B); the tracheal segment, from the distal endotracheal tube to the carina, approximately 5 cm long (C); and from the carina and beyond into the lung, with a corresponding rapid rise in the area (D).



Results

Acoustic Reflectometric Profile of an Endotracheal Intubation

The acoustic reflectometric profile for an tracheal intubation is shown in figure 2. As one proceeds in the direction of positive axial length, the following segments are encountered, in successive order:

1. The approximately 1-in long connector segment of silicone tubing (15.8 mm ID; calculated cross-sectional area of 1.96 cm²).
2. A segment of constant cross-sectional area, which reflects the fixed area throughout the length of the endotracheal tube, in this case a tube of 7.0 mm ID, positioned at 21 cm at the teeth and cut to a length of 26 cm. Because the area of the silicone connector is greater than the inner cross-sectional area of the 7.0-mm endotracheal tube (calculated cross-sectional area 0.385 cm²), there is a decrease in area in going from the former to the latter.
3. A sudden rise in cross-sectional area followed by the first plateau. The vertical height of the plateau corresponds to the fixed area of the trachea beyond the tube, *i.e.*, for a distance of approximately 5 cm extending from the distal end of the endotracheal tube to the yet more distal carina. The length of this segment is best estimated from the initiation of rise to the end of the plateau.
4. The exponentially increasing area beyond the carina, with ensuing successive area rises and plateaus that

are the result of successive bifurcations within the lung.

For a breathing tube correctly placed in the trachea the dominant and characteristic feature of the profile is the constant cross-sectional area segment corresponding to the length of the endotracheal tube, followed by a segment exhibiting a rapid rise in the area beyond the carina, as shown in figure 2.

Acoustic Reflectometric Profile of an Esophageal Intubation

For an endotracheal tube in the esophagus, the characteristic reflectometric profile (fig. 3) consists of a segment of constant cross-sectional area corresponding to the length of the endotracheal tube (7.0 mm internal diameter, 34 cm length including adapter, positioned at 21 cm at the teeth), followed by an immediate decrease in the cross-sectional area to zero; this occurs because the esophageal lumen normally is closed immediately beyond the tip of the endotracheal tube. After the application of the four reservoir-bag breaths, a separate acoustic reflectometric profile of the endotracheal tube-esophagus was made, but there was no detectable difference in the resulting profile.

A spike artifact is noted in some of the esophageal intubation profiles. That this spike is an artifact is evident from the stretch of zero-area axial length (caused by complete closure of the esophageal lumen) proximal to the spike.

Figure 4 shows three more pairs of endotracheal and

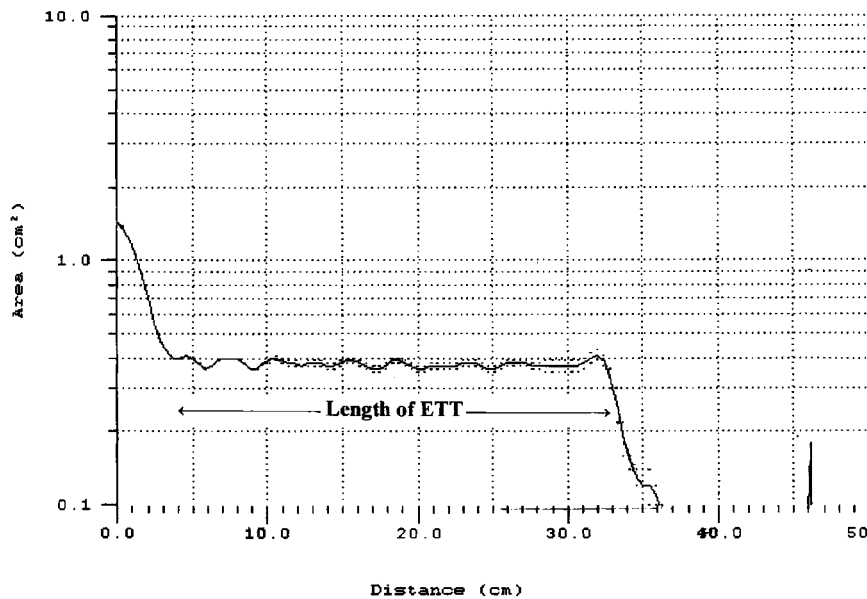


Fig. 3. Acoustic reflectometric profile of an esophageal intubation. For the same patient as in figure 1, the first two segments encountered are the connector segment and the endotracheal tube segment (7.0-mm-ID endotracheal tube of length 34 cm, positioned at 21 cm at the teeth); however, slightly beyond the tip of the endotracheal tube, the area profile immediately goes to zero because of the usual closure of the esophageal lumen.

esophageal intubation profiles, which are unequivocal as to what type of intubation has occurred. All 10 patients exhibited the same characteristic endotracheal and esophageal intubation profiles.

Discussion

Distinction between a tracheal intubation and an esophageal intubation is possible through the use of acoustic reflectometry because the cartilaginous trachea is usually patent, whereas the nonrigid esophagus normally has a closed lumen. In the esophagus, the compliant walls close around the distal end of the endotracheal tube. The closed esophageal lumen prevents further transmission of the acoustic impulse down the cavity, and the reflectometer profile area value goes to zero. The observed spike in the esophageal profile, possibly because of aliasing (using too low a sampling frequency, such that the spectral detection device mistakes multiples of the sampling frequency as inherent to the system), should be removable by better analog filtering.

The creation of one-dimensional acoustic reflectometric images, which allow the distinction to be made between endotracheal and esophageal intubation, does not depend on ventilation, nor does it depend on the presence of exhaled carbon dioxide. The shape and size of the one-dimensional image depend solely on the physical dimensions of the cavity being studied, *i.e.*, on the underlying human anatomy, be it esophagus or trachea, to which the reflectometer-breathing tube system is

attached. In view of this unusual capability, acoustic reflectometry has the potential to become a new gold standard, much like fiberoptic bronchoscopy, in determining whether proper tube placement has occurred.

In 2 of 10 patients, it was thought that cutting the endotracheal tube to a shorter length (and thus increasing the airway area seen in the profile) would enhance the decision-making process regarding proper endotracheal tube placement. This enhancing maneuver turned out to be unnecessary, however, because the decision could be made readily even with an uncut endotracheal tube, and the maneuver was not used in the other eight patients. Use of a reflectometer with only a 40-cm axial length range would have been sufficient to identify the position of a 30-cm-long endotracheal tube.

A validation study with a much larger number of patients is necessary to determine the sensitivity and specificity of acoustic reflectometry in the detection and confirmation of proper endotracheal tube placement. Clearly, the vast majority of patients exhibit normal airways, and in these patients acoustic reflectometry would be expected to distinguish readily between an endotracheal and an esophageal intubation. A special effort would have to be made to recruit study patients with aberrant tracheal and esophageal anatomy (*e.g.*, esophageal dilatation), with markedly altered pathophysiology (*e.g.*, pulmonary edema), or who are otherwise at risk for airway injury or obstruction (*e.g.*, mediastinal mass compressing the trachea). Should such a study validate the reliability of acoustic reflectometry, which seems to al-

ACOUSTIC REFLECTOMETRY AND INTUBATION

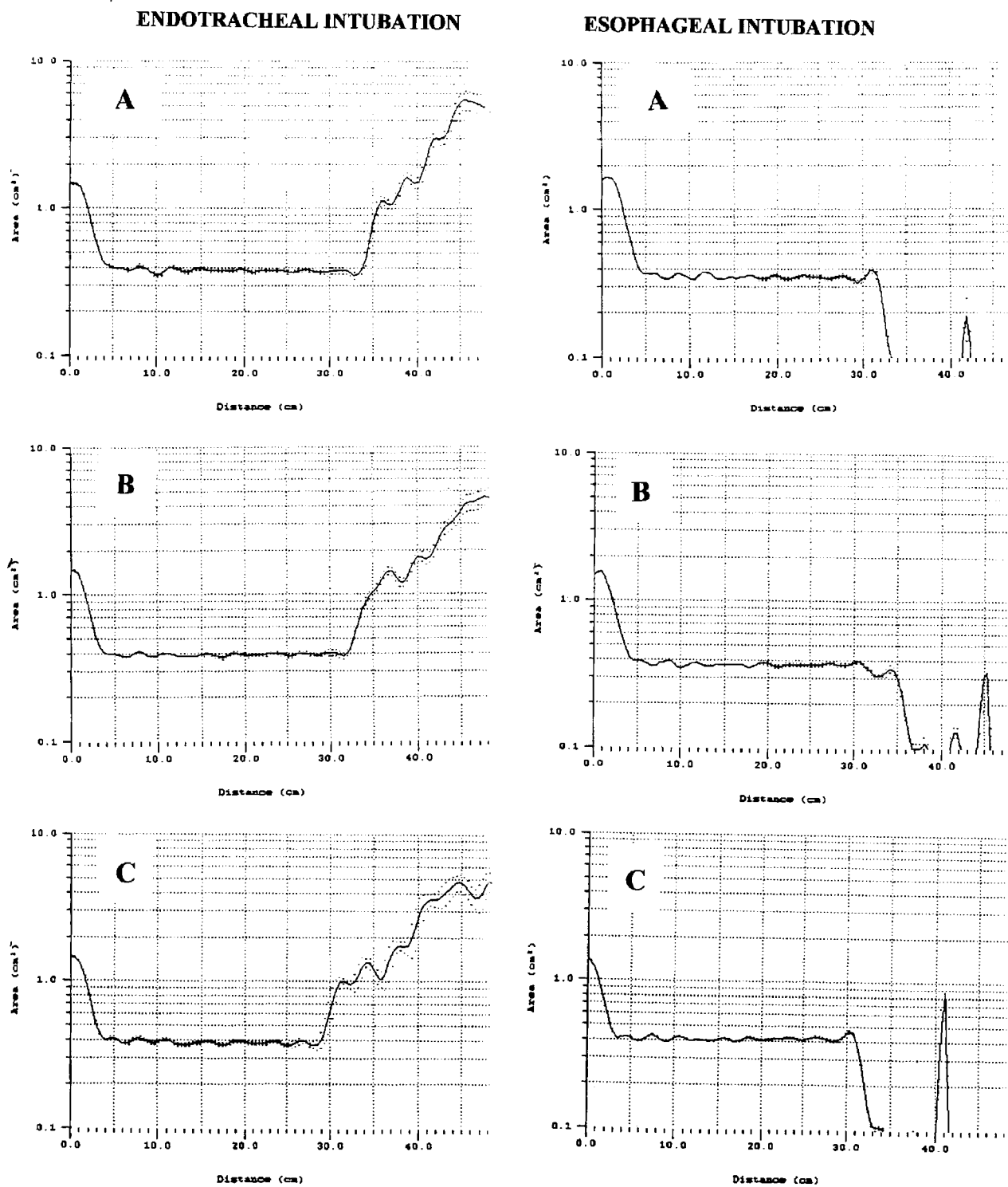


Fig. 4. Three more pairs of patient endotracheal and esophageal intubations. The profiles are distinctive and characteristic.

low the rapid determination of proper breathing tube placement with an extraordinary degree of certainty, the implications would be highly significant in terms of its potential use by paramedical personnel in the field in the setting of cardiopulmonary arrest, by emergency room physicians, and by anesthesiologists.

The reflectometer generates an impulse that propagates down the reflectometer wavetube, through the endotracheal tube, and into the cavity of interest. Using a computer-based data acquisition and analysis system, the pressure amplitudes of the acoustic reflections, which return from the cavity back to a microphone within the distal part of the wavetube, are analyzed by the Gopillaud-Ware-Aki algorithm,^{19,20} which breaks up the axial length into small segments, such that the travel time of the impulse is the same in each segment. The algorithm is thus a layer-stripping process in that it goes from one segment to the immediately more distal segment. The known impedance at one axial segment is used, in conjunction with the known pressure reflections at the microphone, to generate iteratively the impedance value at the next successive axial segment, and so forth. Through this process, an equivalent total cross-sectional area is determined for each point of characteristic impedance at a given axial length from the end of the wavetube.

Consequently, in this algorithm, errors tend to accumulate as one proceeds distally into the cavity. To assure that the cumulative error is minimal and that measurements are always valid, a limit must be preset for the maximal axial length (customized to 50 cm in this study) at which specific impedance measurements can be made.

Clinical studies with acoustic reflectometry, with the patient using a mouthpiece, have focused on the nasopharyngeal cavity,²¹ the glottal area,²² the difficult airway,²³ the imaging of the upper airway and the trachea,²⁴ area changes in asthma patients,^{25,26} and the narrowing of the distal endotracheal tube as a result of accumulation of mucus in chronically intubated patients.²⁷ The reproducibility and accuracy of the reflectometric data reportedly exhibit a within-run variability of $10 \pm 4\%$ and a mean intrasubject day-today variability of $9 \pm 4\%$.²⁸

The specific reflectometer used for this study is impractically long (1 m) and is unlikely to be accepted widely. A two-microphone reflectometer^{29,30} recently has been developed, however, which is 30 cm long and which has a maximal measurement distance of 60 cm. This two-microphone reflectometer may be adaptable

for day-to-day clinical practice in the emergency and operating room settings. Nonetheless, further development of the reflectometer is needed to make the instrument smaller, lighter, and more user friendly.

In summary, in this limited pilot study, the technique of acoustic reflectometry generated characteristic signature images that allowed the unequivocal distinction between an endotracheal and an esophageal intubation, to be made within seconds, and without resort to capnography. Pending further validation of the technique in a large series of patients, this pilot study suggests that acoustic reflectometry may have a useful role in the emergency imaging of the airway, particularly in the detection of esophageal intubations in the cardiopulmonary arrest setting if the usual techniques for confirmation of tube placement fail.

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ACOUSTIC REFLECTOMETRY AND INTUBATION

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