Published in final edited form as:

IEEE Trans Biomed Eng. 2008 November ; 55(11): 2601–2607. doi:10.1109/TBME.2008.2001287.

A Versatile High-Permittivity Phantom for EIT

Tzu-Jen Kao [Member, IEEE],

Department of Biomedical Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180 USA (e-mail: kaot@rpi.edu)

Gary J. Saulnier [Senior Member, IEEE],

Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180 USA (e-mail: saulng@rpi.edu)

David Isaacson [Member, IEEE],

Department of Mathematical Sciences, Rensselaer Polytechnic Institute, Troy, NY 12180 USA (e-mail: isaacd@rpi.edu)

Tomas L. Szabo [Senior Member, IEEE], and

Department of Biomedical Engineering, Boston University, Boston, MA 02215 USA (e-mail: tlsxabo@bu.edu)

Jonathan C. Newell [Senior Member, IEEE]

Department of Biomedical Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180 USA (e-mail: newelj@rpi.edu)

Abstract

Phantoms are frequently used in medical imaging systems to test hardware, reconstruction algorithms, and the interpretation of data. This report describes and characterizes the use of powdered graphite as a means of adding a significant reactive component or permittivity to useful phantom media for electrical impedance imaging. The phantom materials produced have usable complex admittivity at the electrical impedance tomography (EIT) frequencies from a few kilohertz to 1 MHz, as measured by our EIT system (ACT4) and by a commercial bioimpedance analyzer (BIS 4000, Xitron). We have also studied a commercial ultrasound coupling gel, which is highly electrically conductive and semisolid but that permits objects to move within it. The mixture of agar-graphite and gel-graphite, increases in permittivity and conductivity are proportional to the graphite concentration. We also report the use of a porous polymer membrane to simulate skin. A thin layer of this membrane increased resistance and the characteristic frequency of the phantoms, providing a promising candidate to simulate the effect of skin and the layered structure of a breast or other anatomical structure. The graphite also provides a realistic level of “speckle” in ultrasound images of the phantom, which may be useful in developing dual-mode imaging systems with ultrasound and the EIT.

Index Terms

Electrical impedance tomography (EIT); graphite powder; high-permittivity phantom; porous polymer

I. INTRODUCTION

Phantom materials for imaging studies are used in the laboratory to simulate or reproduce the properties of the actual unknown materials under investigation. Useful electrical impedance tomography (EIT) phantoms have electrical and mechanical properties similar to those of the body region being imaged. The ideal phantom material would have conductivity and permittivity that could be adjusted independently over the ranges expected in tissue. Useful mechanical properties include having a shape and size similar to the subject, and being easy to handle, long lasting, and stable for at least several weeks. Of major importance in any phantom design is the ability to know its electrical properties either by design or by independent measurements so that it can be used to calibrate the actual EIT system.

One approach to establishing a known phantom is to build it from discrete electronic components [1]–[5]. This approach yields a phantom with well-known values, but that lacks the complexity of interactions among electrodes that a distributed model or a real tissue provides. It has long been recognized that sodium chloride solutions with a few percent agar or gelatin by weight can provide a material with many useful properties as EIT phantoms [6]–[8]. The principal disadvantage of agar/saline phantoms is that they do not simulate the permittivity of tissue. Conductivity is easily manipulated over the range of interest, but permittivity is far less than that of tissue. Attempts to overcome this shortcoming have made use of biological materials with cellular structure, such as banana or cucumber. The cell membranes of these materials contribute significant permittivity to the solid structure [9]–[11]. Their disadvantages include difficulty in controlling or reproducing their electrical properties, and the fact of their perishability. Other materials, such as TX 151 [12], [13] and polyacrilamide [14], [15] have been suggested for use at EIT and higher frequencies, but the technical difficulty of preparing phantoms from multiple and sometimes toxic ingredients have obstructed their widespread adoption.

A disadvantage of saline/agar phantoms is that they are solid objects once manufactured, and if different mechanical configurations are desired, a number of phantoms must be built. Tanks of liquid do not have this disadvantage, and permit inhomogeneities to be moved around at will, greatly facilitating some types of studies, including demonstration of real-time results.

One aspect of tissue that has received special attention in phantom development is skin. Because it is ubiquitous and of relatively high resistivity, it has an important role in most EIT studies [16]. A biological solution was sought by Tidswell [17], who reported that the skin of the vegetable marrow can be used to model skin in phantom studies. This useful observation does not appear to have been widely adopted.

At microwave frequencies, graphite has been found to be useful in simulating both conductivity and permittivity for phantoms [18]–[20]. An added benefit of using graphite is that it is suitable for use in building phantoms for ultrasound imaging [21]. Agar alone does not produce the “speckle” in an ultrasound image that is present in biological structures, but graphite adds that feature, resulting in more realistic ultrasound images [22]. Graphite would therefore be particularly attractive as a medium for phantom construction in a study of a dual-mode imaging system for EIT and ultrasound.

This paper addresses several of these issues. This paper is a report on the use of graphite for phantom construction at EIT frequencies from a few kilohertz to 1 MHz. We have also studied a commercial ultrasound coupling gel, which is highly electrically conductive and semisolid but permitting objects to move within it. Graphite is useful when added to phantoms based on saline/agar or on ultrasound gel. We also report on a conductive polymer [23]–[25] sheet material that may be suitable as a skin model in conjunction with these phantom materials.

II. METHODS

A. Test Instruments

Electrical properties of the tested materials were evaluated by two instruments, a commercial Bioimpedance Analyzer (BIS 4000, Xitron) and the ACT 4 instrument built in our laboratory [26], [27]. The BIS 4000 was repeatedly calibrated according to the manufacturer's instructions, using its 422 Ω test load, and used to measure complex admittivity at 50 discrete frequencies distributed evenly on a log scale from 5 kHz to 1 MHz. Although it is capable of four-electrode measurements, it was used in a two-electrode configuration. This instrument applies a current of 800 μ A, and measures the resulting voltages. Its operating range is 0–1000 Ω of load.

The ACT 4 instrument was used in a cell-test mode, which applies a voltage between two adjacent electrodes, and measures the resulting currents. It was configured to measure complex admittivity at 3.3, 10, 33, 100, 333, 500, and 1000 Ω kHz.

Both these instruments were tested using two test loads: the 422 Ω resistive load supplied with the BIS 4000 and an *RC* test load consisting of a 750 Ω resistor in parallel with a series combination of a 150 Ω resistor and a 9.6 nF capacitor. Fig. 1 shows the results of these tests, along with the calculated admittivity of the test load for comparison.

Substances to be tested were placed in a test cell 6 cm long, with 2 cm $\times$ 3 cm stainless steel electrodes that covered each end completely. Cell dimensions were chosen so that the area of each electrode in square centimeter was equal to the electrode separation in centimeter, so that $L/A = 1/\text{cm}$ where L is the length of the test cell and A is the size of the electrode. To evaluate the surface impedance of the stainless steel electrodes, we built a second similar test cell with titanium electrodes having a platinized, platinum–iridium surface. The effective surface area of this material is so high that its contact impedance is negligible. A test was then conducted with an agar/graphite mixture and the BIS 4000 and ACT 4 instruments, comparing the admittivity measured by the stainless steel electrodes with that seen by the platinum.

B. Biological Materials

In order to provide a rough basis for comparison, we prepared samples of a banana, a winter squash, and a cucumber to fit snugly into a test cell. There were three banana sections in the cell, with their axes vertical. In addition, we applied two electrodes to opposite sides of a subject's forearm and measured the spectrum of the transverse admittance between them.

C. Mixing Protocol

Saline of various conductivity levels was prepared by adding sodium chloride to deionized water at room temperature. The formula for this process is approximately 1 g of salt per liter per 190 mS/m of conductivity. Agar (Laboratory Grade, A360 Fisher Scientific) was added to deionized water or saline while the water was heated to 85 $^{\circ}$ C and stirred vigorously (the melting point of agar is about 78 $^{\circ}$ C). Graphite powder (Grade 38, G67 Fisher Scientific) was then added to the mixture with continued stirring. This was done as quickly as possible to minimize evaporative losses. The solution was then poured into the test cell(s) and allowed to cool to room temperature, while covered with a layer of Mylar (Saran, Dow Chemical).

In other experiments, commercial ultrasound gel (Other-Sonic, Pharmaceutical Innovations, Newark, NJ) was used in place of saline and agar. Deionized water was added to the gel to reduce its conductivity from 200 to 100 mS/m. Graphite powder in various concentrations up to 25% by weight was stirred into the diluted gel to produce a homogeneous mixture of the desired conductivity and permittivity.

D. Admittivity Spectra

With the test cell containing the phantom material at room temperature, admittivity scans were made using both instruments. When this was complete, a layer of phantom skin, consisting of a 0.25-mm-thick sheet of porous polyethersulfone polymer (Omega Ultrafiltration Membrane, Pall Corporation) was introduced between each of the electrodes and the agar phantom. Four different polymer sheets were studied, OT30K, OT50K, OT100K, and OT300K. These designations denote the size of the pores in the membrane; the 30 K membrane will pass molecules of molecular weight 30 kDa and below, excluding larger molecules. The larger pores in the 300 K membrane will allow passage of molecules up to 300 kDa to pass. There were two layers of the test membrane, in addition to the agar/graphite block in the cell during all phantom skin studies.

III. RESULTS

A. Test Equipment

Fig. 1 shows the complex admittance spectrum measured by the BIS 4000 and the ACT 4 instrument of an RC test load consisting of a $750\ \Omega$ resistor in parallel with a series combination of a $150\ \Omega$ resistor and a $9.6\ \text{nF}$ capacitor. The dynamic range of the Xitron instrument extends to only $1000\ \Omega$ of load, so it was overloaded by this test load at frequencies below about $20\ \text{kHz}$, where the admittance magnitude was below $1\ \text{mS}$.

B. Test Cells

The test for possible “surface impedance” or “contact impedance” associated with the stainless steel electrodes showed no evidence of such an effect below $150\ \text{kHz}$, and up to a 0.7% decrease in conductivity below $1\ \text{MHz}$ (Fig. 2). This conclusion follows from the observation that the stainless steel electrodes used throughout the study had virtually the same admittivity as the platinized, platinum–iridium electrodes. Since these latter electrodes have a functional surface area hundreds of times that of their apparent gross size, their contact impedance is much less than a plain stainless steel surface. Since the stainless steel electrodes’ impedance was not significantly higher, they both must have been extremely low.

In Fig. 2 and most subsequent figures, we plot susceptibility as the parameter to best express the value of permittivity. Susceptivity is the reactive component of complex admittivity. Its relation to permittivity is $\text{susceptivity} = \omega\epsilon$, where ω is angular frequency in per second, it is used because it has the same units as conductivity, millisiemens per meter.

C. Biological Materials

The admittivity spectra of the banana, winter squash, cucumber, and admittance of the arm segment are plotted in Fig. 3. The assumed geometry of the arm segment, to allow it to be plotted on these axes, was $L/A = 1\ \text{cm}^{-1}$. We do not intend to interpret these as generalized findings in these structures, but they are intended as examples of the approximate range of admittivities that the present phantom materials are meant to duplicate. The critical frequency of the arm and the cucumber was in the vicinity of $100\ \text{kHz}$. The squash and banana frequencies were higher, around $300\ \text{kHz}$.

D. Agar/Graphite Phantoms

Conductivity of agar alone was nearly constant across frequency, at about $150\ \text{mS/m}$. This likely demonstrates the effect of some electrolytes present in the agar powder, raising conductivity from the $100\ \text{mS/m}$ of the saline. With the addition of graphite, conductivity increased at all frequencies, and did so to a greater extent at higher frequencies (Fig. 4, upper left). Susceptivity of agar alone was nearly zero at all frequencies below $100\ \text{kHz}$, and fell

below zero as frequency increased from 100 to 1000 kHz, as measured by the BIS 4000 instrument. The addition of graphite caused a nearly proportional increase in susceptibility at lower frequencies. Above 100 kHz, susceptibility decreased with frequency and became negative above about 700 kHz for all graphite concentrations (Fig. 4, upper right).

In order to facilitate the interpretation of these curves in terms of the material properties, we have calculated the relative permittivity implicit in these susceptibility data (Fig. 4, lower right). Relative permittivity values in excess of 60 000 are seen at lower frequencies with graphite concentrations above 10%.

These data are presented in the form of a “Cole–Cole” plot of susceptibility versus conductivity in Fig. 5. This figure shows the results from the BIS 4000 on the left and from the ACT 4 on the right, with the same axis scales.

The results shown in Fig. 4 suggest that both the real and imaginary components of admittivity are approximately proportional to graphite concentration. To test this hypothesis, we plotted conductivity and susceptibility versus graphite concentration at 33 kHz (Fig. 6). At this frequency, conductivity and susceptibility were very close to 3.0 mS/m per percent graphite up to 20% graphite.

E. Stability of Admittivity

Four samples of agar/graphite mixtures were examined repeatedly after being produced. Spectra were obtained on days 1, 4, 7, 10, and 14 following introduction of the graphite to the agar. A plot of complex admittivity similar to Fig. 5 was produced on the first day (Fig. 7). The data from the later times are also plotted as individual points in this figure. There were only small, unsystematic variations over this two-week period.

F. Gel/Graphite Phantoms

The admittivity of diluted and undiluted ultrasound gel alone was similar to that observed for agar in saline. Low susceptibility and conductivity near 100 mS/m were seen, as expected in the diluted gel. Admittivity spectra of ultrasound gel/graphite phantoms (Fig. 8) were similar to those made with agar/graphite (Fig. 5).

G. Independence/Interaction of Effects

In order to examine the interaction between the graphite, which contributes to both conductivity and permittivity, and the saline, which contributes only conductivity when used alone, we made samples of 5% graphite and 4% agar mixed with the saline solutions with conductivity 100, 200, 400, and 800 mS/m. There was evidence of interaction among these factors, since the susceptibility increased in rough proportion to the increase in saline conductivity (Fig. 9). The observed susceptibility increased from about 13 to 40 mS/m at a frequency of 33 kHz when the saline conductivity was increased from about 100 to 800 mS/m. In addition, the frequency at which the susceptibility reached its maximum, f_c , decreased from about 100 kHz with less conductive saline to 33 kHz with the most conductive saline.

H. Skin-Like Layer of Polymer

The introduction of a layer of polymer between each of the electrodes and the material in the test cell decreased the measured conductivity, but had little effect on the measured susceptibility (Fig. 10). The characteristic frequency was increased by the polymer layers from about 50 to about 600 kHz. The conductivity change was nearly independent of the pore size of the polymer. The results for the OT50K, OT100K, and OT300K polymers are not plotted for clarity, since they were nearly superimposed over the results for the OT30K polymer shown.

IV. DISCUSSION

One of the advantages of using phantoms is illustrated in Fig. 1. Both the ACT 4 and the Xitron instruments have an anomalous behavior at high frequencies, where they report that the reactive term of admittance changes sign and becomes an inductance-like load. This phenomenon was reported by Patterson and Latterell [28] and Bolton *et al.* [29]. These authors suggested that phase shifts in the electronic circuits, in conjunction with stray capacitances of the connecting cables, might explain the result in the Xitron instrument. We agree, and expect that a similar cause affects the ACT 4 instrument as well, although to a lesser extent. It is helpful to know this characteristic of the instrumentation in interpreting the later reports of the properties of the materials studied.

The range of complex admittivities shown in Fig. 3 for biological materials is roughly comparable to that reported previously by Bagshaw *et al.* [30], who found a phase angle for cucumber, for example, of $29 \pm 5^\circ$ at 40 kHz. Fig. 3 shows a phase of 45° for cucumber around that frequency.

We have not explored the properties of the graphite used, which may influence its permittivity. However, it seems likely that charges at the surface of the immobilized graphite granules account for the displacement currents. If this is so, it might be possible to achieve higher permittivity by using finer graphite powder than the standard laboratory grade used here. The manufacturer reports that 97% of a sample of this material passes through a -320 mesh. This is a mesh with pores 44 μm in diameter.

We tested the long-term stability of the embedded graphite, to see if a slow hydration or other process might alter the electrical properties. The changes seen over the course of two weeks storage at room temperature were random, small, and nonsystematic. We do caution that a similar degree of stability of saline with agar may not occur when in proximity to a different conductivity medium. It is generally known that salt migrates down its concentration gradient between agar blocks, altering the conductivity at the junction and for some distance into the bulk phase. We have not studied this systematically, but caution that small embedded agar inhomogeneities may not retain their contrast over time. We expect that this difficulty would be minimized if the gradients were of graphite, rather than sodium chloride.

The results of using ultrasound gel and agar as a semifluid medium facilitate the study of small embedded inhomogeneities. Since solid objects can be introduced temporarily into this gel, contamination due to salt migration can be minimized by completing data collection promptly. This gel has the added advantage of allowing motion of targets, which greatly facilitates studies of spatial resolution as well as demonstration of real-time EIT displays.

The decrease in conductivity in the test cell when two layers of polymer membrane were introduced was expected, but the observation that the decrease was nearly identical in all four membranes tested was unexpected. These membranes are intended to be used as filters for molecules of different sizes. The present observation suggests that the pore density is different among membranes of different pore sizes, such that the total pore area is approximately the same among all types. A larger number of smaller pores might balance the smaller number of larger pores. The manufacturer's data show differing hydraulic conductivities for water, but do not appear to address this issue, and the manufacturer was unable to supply further details of the membrane.

The curves in Fig. 9 demonstrate an interaction between the graphite and the sodium chloride. At a fixed level of 5% graphite and 4% agar, the addition of sodium chloride to increase conductivity would be expected to shift the admittivity plot horizontally to the right. The observed shift is to the right as expected, but each curve is also shifted upward. The increase

in susceptibility is approximately 4 mS/m for each 100 mS/m increase in conductivity. We conjecture that this added displacement current results from the increased availability of bound charges at the surfaces of the graphite particles. These charges, which must be in equilibrium with the free ions in the saline/agar, may be denser, providing increased displacement current. A related observation is that there is also a change in the characteristic frequency of the material f_c the frequency at which the permittivity is its maximum. This is 100 kHz when the agar conductivity is 100 mS/m, but shifts steadily downward as conductivity increases, reaching 33 kHz when the conductivity is 800 mS/m.

The underlying physical explanation for the high permittivity observed in this study is not certain. We hypothesize that it is related to charges within each graphite particle that are free to move, but don't leave the particle. The particle density is not likely to be high enough to allow contact among them. We estimate that their density in this experiment is of the order of $200000/\text{mm}^3$ at a concentration of 10%. The hypothesized mechanism is that described by Pethig [31, p 160] under "complex conductivity." "In non-ideal dielectric mixtures there will be the usual polarization processes exhibited by ideal dielectric materials ... together with polarizations resulting from the displacement of free charge carriers under the influence of the applied electric field. If the size of the conducting dielectric components is large, then the induced dipole moments created by these displaced free charges will be enormous compared with normal molecular dipole moments, and the resulting polarization may dominate over all other polarization processes." By this hypothesis, graphite is seen as a non-ideal dielectric. It is usually called a conductor, but its resistivity is 500–3000 times that of copper, so it may not behave as an ideal conductor.

Some interaction at the graphite particle surface may also be important, and it is likely that the shape of the particle has a role in this. Analytical studies have been done for embedded insulators of spherical shape, but we have not found a study of small, disk-shaped semiconductors embedded in a semiconducting medium.

In summary, we have described and characterized the use of powdered graphite as a means of adding a significant reactive component or permittivity to media useful as phantoms for electrical impedance imaging. Graphite has the added advantage of simulating the speckle seen in tissues by ultrasound imaging. Since graphite concentration can be varied over a wide range, and saline concentration is similarly flexible, the possibility is demonstrated of creating tissue-mimicking phantoms of solid agar or semifluid gel, with desired levels of permittivity and conductivity for EIT studies.

Acknowledgments

The authors would like to thank Teratech, Burlington, MA for generously providing us with an ultrasound imaging system for our research.

This work was supported in part by the Center for Subsurface Sensing and Imaging Systems (CenSSIS) under the Engineering Research Centers Program of the National Science Foundation Award EEC-9986821 and in part by the National Cancer Institute–National Institute of Health (NIH) under Grant R21 CA 109962-01.

REFERENCES

1. Hartinger AE, Gagnon H, Guardo R. Accounting for hardware imperfections in EIT image reconstruction algorithms. *Physiol. Meas* 2007;vol. 28:S13–S27. [PubMed: 17664631]
2. Griffiths H. A phantom for electrical impedance tomography. *Clin. Phys. Physiol. Meas* 1988;vol. 9:15–20. [PubMed: 3240643]
3. Griffiths H. A cole phantom for EIT. *Physiol. Meas* 1995;vol. 16(no 3A):A29–A38. [PubMed: 8528124]

4. Schneider ID, Kleffel R, Jennings D, Courtenay AJ. Design of an electrical impedance tomography phantom using active elements. *Med. Biol. Eng. Comput* 2000;vol. 38:390–394. [PubMed: 10984936]
5. Rigaud, B.; Chauveau, N.; Ayeva, B.; Fargues, F.; Martinez, E.; Morucci, J-P. Modular cole phantom for parametric electrical impedance tomography. *Proc. IEEE 18th Annu. Int. Conf. Eng. Med. Biol. Soc.*; Oct. 31–Nov. 3; Amsterdam, The Netherlands. 1996. p. 794-795.
6. Grimnes, S.; Martinsen, OG. *Bioimpedance and Bioelectricity Basics*. London, U.K.: Academic; 2000.
7. Oh TI, Lee J, Seo JK, Kim SW, Woo EJ. Feasibility of breast cancer lesion detection using a multifrequency trans-admittance scanner (TAS) with 10 Hz to 500 kHz bandwidth. *Physiol. Meas* 2007;vol. 28:S71–S84. [PubMed: 17664649]
8. Newell JC, Saulnier GJ, Edic PM, Isaacson D, Cheney M, Gisser DG, Cook RD. Electrical impedance imaging. *BMES Bull* 1993;vol. 17(no 2):19–23.
9. Holder D, Hanquan Y, Rao A. Some practical biological phantoms for calibrating multifrequency electrical impedance tomography. *Physiol. Meas* 1996;vol. 17:A167–A177. [PubMed: 9001615]
10. Oh SH, Lee BI, Woo EJ, Lee SY, Kim T-S, Kon O, Seo JK. Electrical conductivity images of biological tissue phantoms in MREIT. *Physiol. Meas* 2005;vol. 26:S279–S288. [PubMed: 15798241]
11. Tidswell AT, Gibson A, Bayford RH, Holder DS. Validation of a 3-D reconstruction algorithm for EIT of human brain function in a realistic head-shaped tank. *Physiol. Meas* 2001;vol. 22:177–185. [PubMed: 11236878]
12. Lee, KH.; Kim, YT.; Oh, TI.; Woo, EJ. Complex conductivity spectra of seven materials and phantom design for EIT. *Proc. 13th Int. Conf. Electr. Bioimpedance 8th Conf. Electr. Impedance Tomograph., ICEBI*; Aug.–Sep.; Graz, Austria. 2007. p. 344-347.
13. Woo EJ. Impedance spectroscopy and multifrequency electrical impedance tomography. *IJBEM* 2007;vol. 9(no 2):101–102.
14. Holder D, Kahn A. Use of polyacrilamide gels in a saline-filled tank to determine the linearity of the Sheffield Mark 1 electrical impedance tomography (EIT) system in measuring impedance disturbances. *Physiol. Meas* 1994;vol. 15:A45–A50. [PubMed: 8087049]
15. Chou C-K, Chen G-W, Guy AW, Luk KH. Formulas for preparing phantom muscle tissue at various radiofrequencies. *Bioelectromagnetics* 1984;vol. 5:435–441. [PubMed: 6517962]
16. Raicu V, Kitagawa N, Irimajiri A. A quantitative approach to the dielectric properties of the skin. *Phys. Med. Biol* 2000;vol. 45:L1–L4. [PubMed: 10701501]
17. Tidswell AT, Bagshaw AP, Holder DS, Yerworth RJ, Eadie I, Murray S, Morgan I, Bayford RH. A comparison of headnet electrode arrays for electrical impedance tomography of the human head. *Physiol. Meas* 2003;vol. 24:527–544. [PubMed: 12812436]
18. Chang JT, Fanning MW, Meaney PM, Paulsen KD. A conductive plastic for simulating biological tissue at microwave frequencies. *IEEE Trans. Electromagn. Compat* 2000 Feb;vol. 42(no 1):76–81.
19. Gabriel C. Tissue equivalent material for hand phantoms. *Phys. Med. Biol* 2007;vol. 52:4205–4210. [PubMed: 17664603]
20. Tamura H, Ishikawa Y, Kobayashi T, Nojima T. A dry phantom material composed of ceramic and graphite powder. *IEEE Trans. Electromagn. Compat* 1997 May;vol. 39(no 2):132–137.
21. Szabo, TL. *Diagnostic Ultrasound Imaging: Inside Out*. New York: Academic; 2004.
22. Burelew MM, Madsen EL, Zagzebski JA, Banjavic RA, Sum SWA. New ultrasound tissue–equivalent material. *Radiat. Phys* 1980;vol. 134:517–520.
23. Nam J-D, Hwang SD, Choi HR, Lee JH, Kim KJ, Heo S. Electrostrictive polymer nanocomposites exhibiting tunable electrical properties. *Smart Mater. Struct* 2004;vol. 14:87–90.
24. Pusch W, Walch A. Synthetic membranes—preparation, structure, and application. *Angew. Chem. Int. Ed* 1982;vol. 21:660–685.
25. Zhang QM, Li H, Pho M, Xia F, Cheng Z-Y, Xu H, Huang C. An all-organic composite actuator material with a high dielectric constant. *Nature* 2002;vol. 419:284–287. [PubMed: 12239563]
26. Ross AS, Saulnier GJ, Isaacson D, Newell JC. Current source design for electrical impedance tomography. *Physiol. Meas* 2003;vol. 24(no 2):509–516. [PubMed: 12812434]
27. Saulnier, GJ.; Liu, N.; Tamma, C.; Xia, H.; Kao, T-J.; Newell, JC.; Isaacson, D. An electrical impedance spectroscopy system for breast cancer detection. *Proc. 29th Annu. Int. Conf. IEEE EMBS*; 2007. p. 4154-4157.

28. Patterson, R.; Latterell, T. Evaluation of a commercial impedance spectroscopy instrument: inaccuracies and their corrections. *Proc. IEEE 17th Annu. Int. Conf. Eng. Med. Biol. Soc.*; Sep 20–23; 1995. p. 651-652.
29. Bolton MP, Ward LC, Khan A, Campbell I, Nightingale P, Dewit O, Elia M. Sources of error in bioimpedance spectroscopy. *Physiol. Meas* 1998;vol. 19:235–245. [PubMed: 9626688]
30. Bagshaw, AP.; Holder, DS.; Bayford, RH. Development of a realistic head phantom with marrow to simulate skin impedance. presented at the Biomed. Appl. EIT, 3rd EPSRC Eng. Netw. Meet., Univ. College; London, U.K.. 2001 Apr. p. 4-6.
31. Pethig, R. *Dielectric and Electronic Properties of Biological Materials*. New York: Wiley; 1979. ch. 5; p. 150-187.

Biographies

Tzu-Jen Kao (M'06) received the B. Sc. degree in computer science and engineering from Tatung Institute of Technology, Tatung University, Taipei, Taiwan, R.O.C., in 1993, the Bachelor of Medicine degree from Beijing Medical University, Peking University Health Science Center, Beijing, China, in 1998, and the M.S. and the Ph. D. degrees in biomedical engineering from Rensselaer Polytechnic Institute, Troy, NY, in 2002 and 2005, respectively.

In 1998, he was a medical intern in the Department of Thoracic Surgery in Peking University 3rd Hospital. After using various surgical equipments, he decided to study abroad to learn

medical instrument design. From 2000 to 2006, he was a Research Assistant, Postdoctoral Research Associate, and Research Associate in the Electrical Impedance Imaging Group at Rensselaer Polytechnic Institute. His current research interests included body surface potential for cardiac detection, electrical impedance imaging for cancer detection, and treatment and combined electrical impedance tomography (EIT) with other modalities such as X-ray and ultrasound.

Gary J. Saulnier (S'80–M'84–SM'95) received the B.S., M.E., and the Ph.D. degrees in electrical engineering from Rensselaer Polytechnic Institute, Troy, NY in 1980, 1982, and 1985, respectively.

Since 1986, he has been on the faculty of the Electrical, Computer, and Systems Engineering Department at Rensselaer Polytechnic Institute, where he is currently an Associate Professor. His current research interests include modulation and coding, with an emphasis on spread spectrum, orthogonal frequency-division multiplexing (OFDM) and multiple-input and multiple-output (MIMO) systems, and the development of electronic instrumentation for biomedical applications.

Dr. Saulnier has been an Associate Editor for the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, since 2002.

David Isaacson (M'86) received the Ph.D. degree in mathematics from Courant Institute of Mathematical Sciences (CIMS), New York University, New York, in 1976.

He is currently a Professor of mathematical sciences at Rensselaer Polytechnic Institute, Troy NY. In the early years of his career, he was engaged in developing numerical methods to approximately solve problems arising in statistical mechanics, quantum mechanics, and quantum field theory. Since 1986, he has devoted his career to applying mathematics to the solution of problems in medicine and biology. Along with his collaborators at Rensselaer Polytechnic Institute, Troy, NY, he has developed adaptive current tomography systems for monitoring heart and lung function. He is collaborating on the construction of an electrical impedance tomography system specifically designed to improve the diagnosis of breast cancer.

Thomas L. Szabo (S'63–SM'99) received the B.S. degree from the University of Virginia, Charlottesville, the M.S. degree from the University of Rochester, Rochester, NY, both in

electrical engineering, and the Ph.D. degree in physics from the University of Bath, Bath, U.K. in 1966, 1968, and 1993, respectively.

From 1981 to 2000, he was involved in research and development on diagnostic ultrasound imaging systems at Hewlett Packard and Agilent Technologies, Pao Alto, CA. Since 2001, he has been a Research Professor at Boston University, Boston, MA, where he is now with the Biomedical Engineering Department. He is the author of a textbook, *Diagnostic Ultrasound Imaging: Inside Out* (Elsevier, 2004). His current research interests include applications of ultrasound to emergency medicine and to characterizing physiology, image fusion, and high-intensity therapeutic ultrasound.

Prof. Szabo is a Fellow of the Acoustical Society of America and the American Institute of Ultrasound in Medicine.

Jonathan C. Newell (S'64–M'69) received the B.S. and M.S. degrees in electrical engineering from Rensselaer Polytechnic Institute, Troy, NY, in 1968, and the Ph.D. degree in physiology from Albany Medical College, Albany, NY, in 1974.

He is currently a Research Professor of Biomedical Engineering at Rensselaer Polytechnic Institute. His current research interests include the regulation of the pulmonary circulation and pulmonary gas exchange in injured patients with acute respiratory failure. More recently, he has been developing a multi-frequency adaptive system for electrical impedance imaging, and applying it to the diagnosis of breast cancer.

Fig. 1.

Susceptance versus conductance for an electronic dummy load in the frequency range from 3 kHz to 1 MHz as measured by the BIS 4000 (Xitron) analyzer (circles, 5–1000 kHz, and the ACT 4 impedance imaging system (squares 3–1000 kHz). Numbers at specific points on each curve specify the frequency in kilohertz of that point. Theoretical values based on the component values are plotted as diamonds.

Fig. 2.

Cole–Cole admittivity plots of Xitron data for the test cells with platinized platinum–iridium surfaces and stainless steel surface, with 4% agar and 12% graphite. 50 discrete frequencies distributed evenly on a log scale from 5 kHz to 1 MHz from left to right.

Fig. 3.

Susceptivity versus conductivity of banana, cucumber, squash, and a normal human forearm. At the right are illustrated a schematic of the test cell, with a separation between the electrodes (L) of 6 cm, and a surface area (A) of each of $2 \times 3 = 6 \text{ cm}^2$. The photograph shows the banana segments in place. The seven points plotted for each curve correspond to frequencies of 3.3, 10, 33, 100, 333, 500, and 1000 kHz from left to right.

Fig. 4.

Susceptivity (right) and conductivity (left) of a 4% agar in saline block with differing concentrations of graphite added. The agar was mixed with saline having a conductivity of 100 mS/m. The susceptibility values in the upper panel correspond to relative permittivity values shown in the lower panel. 50 discrete frequencies distributed evenly on a log scale from 5 kHz to 1 MHz from left to right in the figures.

Fig. 5.

Cole–Cole admittivity plots for 4% agar with various concentrations of graphite added. The agar was mixed with saline having a conductivity of 100 mS/m. In the left figure, 50 discrete frequencies distributed evenly on a log scale from 5 kHz to 1 MHz from left to right. The seven points plotted for each curve in the right figure correspond to frequencies of 3.3, 10, 33, 100, 333, 500, and 1000 kHz, from left to right.

Fig. 6.
Conductivity and susceptibility versus graphite concentration at a frequency of 33 kHz.

Fig. 7.

Cole-Cole admittivity plots for saline/agar with various concentrations of graphite added. The solid curve connects points measured on the first day. Data obtained after four days (squares), after seven days (diamonds) after ten days (circles) and after fourteen days (triangles) are plotted individually. The seven points plotted for each curve correspond to frequencies of 3.3, 10, 33, 100, 333, 500, and 1000 kHz from left to right.

Fig. 8.

Cole–Cole admittance plots for pure (squares), and diluted (triangles) ultrasound gel. Susceptivity increased with the addition of 3% Graphite (circles). The gel was diluted with water to have a conductivity of 100 mS/m. The seven points plotted for each curve correspond to frequencies of 3.3, 10, 33, 100, 333, 500, and 1000 kHz from left to right.

Fig. 9.

Cole–Cole admittivity plots for 5% graphite mixed with 4% agar with four different concentrations of saline. The control sample at the bottom left was made with no graphite, only 4% agar mixed with 100 mS/m saline. There are seven points plotted for each curve, corresponding to frequencies of 3.3, 10, 33, 100, 333, 500, and 1000 kHz from left to right.

Fig. 10.

Cole–Cole admittance plots for 4% agar with 6% graphite added, before and after introduction of two layers of OK30 K polymer, one at each end of the test cell. The characteristic frequency is about 600 kHz for agar/graphite+polymer and 50 kHz for agar/graphite alone.