

Expanding Your Materials Horizons

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Abstract: Materials and their related properties are intrinsically fundamental to the creation, development and solution of viable exploratory models when using numerical analysis software. In many cases, simply determining the location, availability and relative accuracy of the necessary material parameters for the physical behavior of even commonly employed design materials can be very difficult and time consuming.

This paper demonstrates the application of a new consolidated materials properties data source in the development of a first principles Electrical Impedance Tomography (EIT) model for Ovine (sheep) lung function.

Keywords: materials properties database, electrical impedance tomography, lung function, electrical tissue properties.

1. Introduction

EIT is a non-invasive sensing technology that potentially applies currents over a range of frequencies, measures the resulting voltages on the surface of a body (inanimate, animate, etc.) and infers relative impedances from those data. EIT technology has been and is currently being developed independently in several diverse areas of study (geophysics {1}, industrial process imaging {2} and medical imaging {3}, to name a few). As a result of this on-going broad interest, substantially the same technology has come to be known by several different names in the literature (e.g. electrical resistivity tomography, electrical resistance tomography, electrical impedance tomography, etc.). EIT technology is widely applied in the above-mentioned areas. It is one of the most promising broadly applicable non-invasive measurement techniques currently available.

2. Use of COMSOL Multiphysics

This paper explores the potential opportunity available through the use of COMSOL Multiphysics software and a currently available third-party materials properties data source {4}

to expand the modeling horizons of COMSOL Multiphysics modelers into many such diverse applications. This paper discusses one such methodology and technique for the location of materials properties data, its acquisition and its incorporation into a critical COMSOL model. In this case, the following EIT model is the prime demonstration platform. As an example, one of the multiphysics solutions obtained from the first principles EIT model can be seen in Figure 1 below.

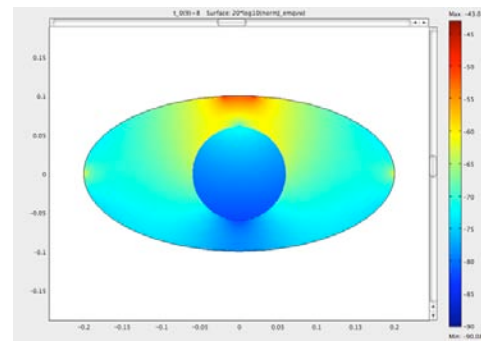


Figure 1 Lung Function Model

Typically, EIT Models {5} can be built that employ different alternating currents from a range of possible values (AC to radio frequency). Those currents may use frequencies that range from 1Hz to 1×10^{10} Hz {6, 7}. This range of frequencies is used to allow the exploration of materials properties (conductivity, permeability, etc.) over the broadest possible value variation in such complex materials as mammalian tissue (human, sheep, cow, pig, etc.).

The current in the EIT technology is applied to the material(s) of the modeled body to determine the location of volumetric regions that differ in impedance from the impedance of the normal tissue (primary tissue) by monitoring the local impedance. (This statement is also true, whatever the composition of the primary modeling material, as long as the resolution of the model and the materials differences are sufficient.)

The EIT model presented herein operates at 1.0×10^4 Hz, in consideration of the electrical limitation imposed by the conductivity of the tissue and the associated electrical skin depth effect. This model simulates the location of a fluctuating difference in an air-filled-void volume (lung), as might be seen in a medical application measuring lung function. In this case, as a first approximation, the model comprises only the muscle tissue, the lung tissue and the volume of air, as would be found within a typical lung. Only one lung is modeled, to reduce the complexity of the model, remove redundancy and reduce the computation time.

This model was created using COMSOL Multiphysics software Version 3.5.a, the AC/DC Module (2D Small In-Plane Currents application mode) and the PKS-MPD materials properties database Version 1.0.

3. Geometry

Figure 2 below shows the geometry developed for this model. The geometry shown is a composite object that comprises an ellipse (the main body muscle/lung region) and a small rectangle (electrode contact area) on the upper edge of the ellipse.

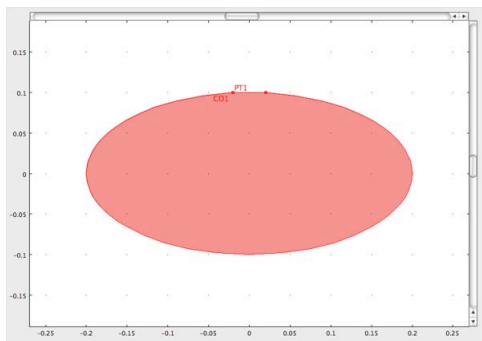


Figure 2 Lung Function Geometry

The two edges of the contact electrode are defined by points placed at the left and right lateral bounds of the upper surface of the rectangular region of the composite figure.

4. Constants

The required materials property constants are the conductivity and the permittivity for muscle

tissue, lung tissue and air at 1.0×10^4 Hz and at 37°C . Additionally, at non-breakdown voltages, for frequencies in this range, the conductivity of air is essentially zero (0). However, entry of a zero (0) value for this property will cause a mathematical singularity problem. Thus, the value $1\text{e-}15$ S/m is chosen as a nominal value that is adequately close to zero (0). The other property values are easily obtained by using the PKS-MPD materials database, as shown in Figures 3, 4 and 5 below.

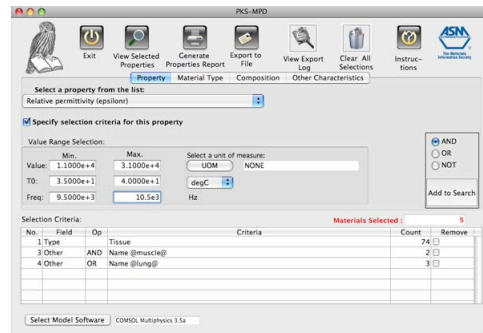


Figure 3 Tissue Relative Permittivity Retrieval

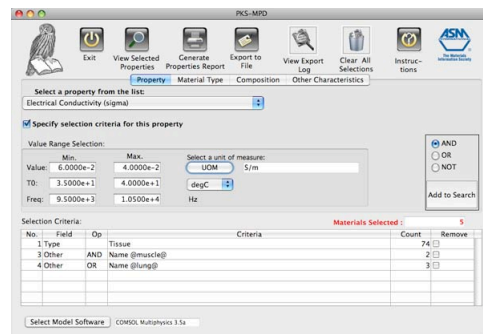


Figure 4 Tissue Electrical Conductivity Retrieval

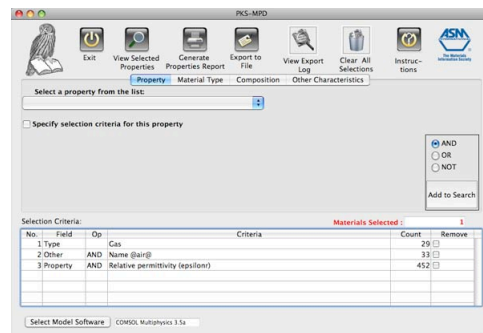


Figure 5 Air Relative Permittivity Retrieval

Figure 3 shows the retrieval of relative permittivity values for muscle and lung tissue. Figure 4 shows the retrieval of electrical conductivity values for muscle and lung tissue. Figure 5 shows the retrieval of relative permittivity values for air.

After each property's information set has been selected, the PKS-MPD database will generate a library file suitable for incorporation into the model library through the COMSOL Add Library function. The values for the model constants are as shown below in Table 1.

Table 1: EIT Model Constants Values

Variable	Value	Parameter
sig_m	0.3621[S/m]	Muscle conductivity
eps_r_m	3.043e4	Muscle relative permittivity
x_0	0.0[m]	x position of cavity center
y_0	0.0[m]	y position of cavity center
r_0	0.05[m]	Cavity radius
t_0	0.0[s]	Time init
sig_L	0.06366[S/m]	Lung inflated conductivity
eps_r_L	1.634e4	Lung inflated relative permittivity
freq_01	1.0e4[Hz]	Frequency
sig_air	1e-15	Conductivity of air
eps_r_air	1	Relative permittivity of air

5. Equations

This model could have built by using multiple Subdomains and employing a moving-mesh (ALE) type of calculation. However, since this is a first approximation type calculation, a simpler approach was deemed to be adequate. In this case, the muscle-lung-air interfaces are defined and manipulated through the use of a set of scalar equations.

In this model, the location of the muscle/lung tissue boundaries is controlled logically by a set of Scalar Equations. The entire single Subdomain is muscle tissue, except that region in the Subdomain that is designated to be either lung tissue or air by the set of Scalar Equations. Those control equations are shown in Table 2.

Table 2: EIT Model Scalar Equation Values

Equation	Value	Parameter
sigma_0	$(\text{sig_m} * ((x - x_0)^2 + (y - y_0)^2) > r_{00}^2) + (\text{sig_L} * (r_{00}^2 \geq ((x - x_0)^2 + (y - y_0)^2) > r_{02}^2) + (\text{sig_air} * ((x - x_0)^2 + (y - y_0)^2) < r_{02}^2))$	Model conductivity
epsilon_r_0	$1 + (\text{eps_r_m} - 1) * (((x - x_0)^2 + (y - y_0)^2) > r_{00}^2) + (\text{eps_r_L} - 1) * (r_{00}^2 \geq ((x - x_0)^2 + (y - y_0)^2) > r_{02}^2) + (\text{eps_r_air} * (((x - x_0)^2 + (y - y_0)^2) < r_{02}^2))$	Model permittivity
r_00	$r_0 * (1.4 - \cos((t_0 [1/s] * \pi) / 8)) / 2$	Lung Outer Wall Radius
r_02	$r_0 - 0.01$	Lung Inner Wall Radius

6. Subdomain Settings

The Subdomain settings, $\sigma = \text{sigma}_0$ and $\epsilon_r = \text{epsilon_r}_0$, are shown in Figure 6 below.

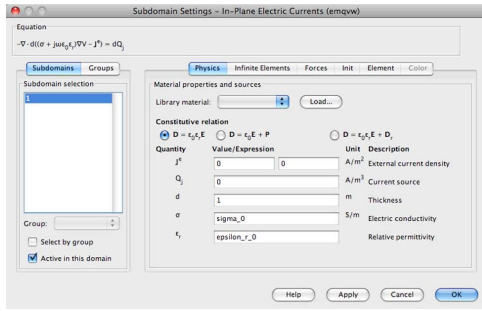


Figure 6 Subdomain Settings

6. Boundary Settings

The Boundary settings are shown in Table 3 and Figure 7 below.

Table 3: EIT Model Boundary Settings

Boundary	Setting
1,4,5,8 (blue)	Electrical Insulation
2,3 (green)	Port
6,7 (red)	Ground
Port Tab	Setting
Port Number	1
Input property	Fixed current density
Use port as input	Check Checkbox
Input current	1e-4 [A]

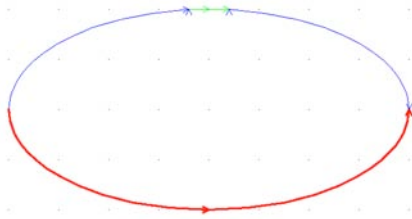


Figure 7 Boundary Settings

7. Mesh

This model was meshed with an elemental size limit of 0.001, using a Triangle (advancing front) mesh.

8. Solution

This model was solved using a parametric solver. The parameter varied was t_0 , with a Parameter value equation of range(0,32/32,32). This equation yields two inflation/deflation (2) cycles.

9. Postprocessing

Figure 8, Figure 9 and Figure 10 show the Cross-Section Plot of the solved model at full expansion, half expansion and fully deflated. The vertical axis value of the plot is $20 \cdot \log_{10}(\text{normJ_emqvw})$ (log current) and the horizontal axis value is x (distance from the center of the model).

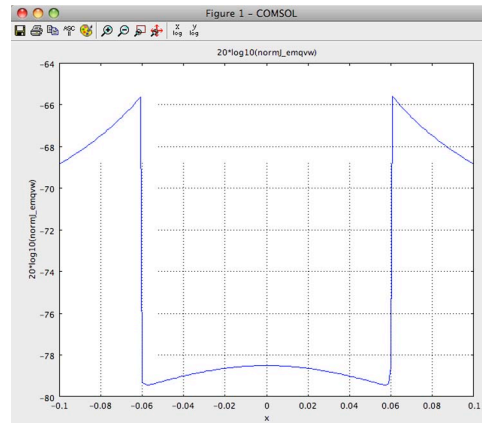


Figure 8 Cross-Section Plot, Full Inflation

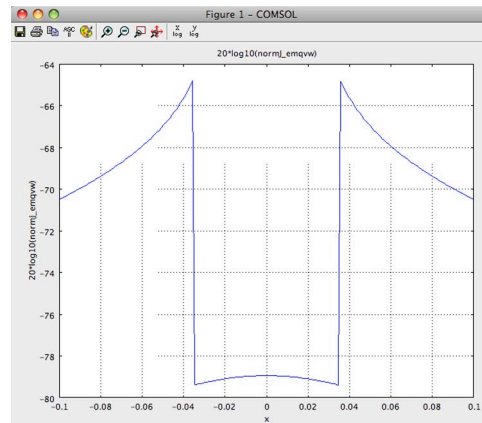


Figure 9 Cross-Section Plot, Half Inflation

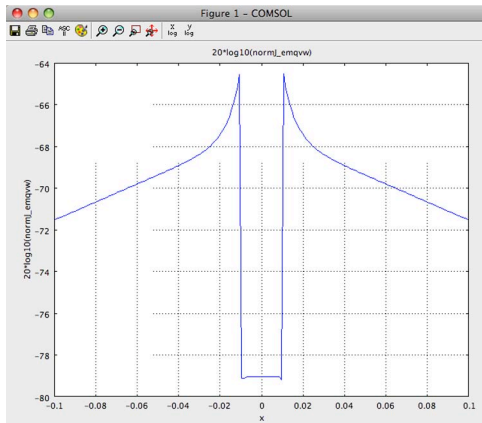


Figure 10 Cross-Section Plot, Full Deflation

10. Conclusions

Ongoing EIT research in the scientific community continues to explore the application of this measurement technique to the detection of breast cancer {8}, detailed lung function {9}, brain function {10} and other such areas of current interest.

This paper has demonstrated the ease of materials property acquisition and model building using the new consolidated materials properties data source {11} in the development of a first principles Electrical Impedance Tomography (EIT) model for Ovine (sheep) lung function. The same easy approach is readily applied to other modeling areas and types of models, both simple and complex.

11. References

1. http://en.wikipedia.org/wiki/Electrical_resistivity_tomography
2. http://en.wikipedia.org/wiki/Industrial_process_imaging
3. http://en.wikipedia.org/wiki/Electrical_impedance_tomography

4. Roger W. Pryor, Chapter 2, **Multiphysics Modeling Using COMSOL**, October 2009, Jones and Bartlett Publishers, Sudbury, MA, ISBN 9780763779993.

5. Roger W. Pryor, Chapter 7, **Multiphysics Modeling Using COMSOL**, October 2009, Jones and Bartlett Publishers, Sudbury, MA, ISBN 9780763779993.

6. http://en.wikipedia.org/wiki/Radio_frequency

7. http://en.wikipedia.org/wiki/Alternating_current

8. P. Manwaring, et al., Proceedings 30th Annual International IEEE EMBS Conference, pp 1178-1180

9. X. Chen, et al., Proceedings FMTC 2008-IEEE International Instrumentation and Measurement Technology Conference, pp 1531-1536

10. D.S. Holder, Proceedings Automation Congress 2008, pp 1-6

11. PKS-MPD, <http://www.pks-mpd.com>