Effect of Skin Layer on Electric Impedance Scanning Imaging

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Abstract: In study of Electric Impedance Scanning Imaging (EISI), some scholars believe that low electrical impedance of skin layer will reduce detection sensitivity of imaging system. However, in the previous numerical model analysis, there is little work to analyze the influence of skin layer. Based on actual size, electrical parameters of Chinese female breasts and detection probe structure, static electric field equation was solved by finite element method. Results show that skin layer not only reduces current detected by probe, but also significantly reduces sensitivity of probe. The smaller the conductivity of skin layer, the more obvious decrease in sensitivity. In practice, if conductivity of skin layer can be improved by some means, sensitivity of probe can be increased. Furthermore, if thickness and conductivity parameters of skin layer can be accurately obtained, and then influence of skin layer in overall EISI image can be eliminated, imaging quality and detection sensitivity of system should be significantly improved.

1. Introduction
Breast cancer is one of the most susceptible malignant tumors in women. Due to the significant differences in electrical admittance between breast cancerous tissue and normal tissue, many corresponding breast cancer detection or diagnosis techniques have been developed, such as electrical impedance tomography, breast surface potential diagnosis technology, four-electrode impedance measurement and Electric Impedance Scanning Imaging (EISI). EISI inspection has been widely used in breast cancer detection and diagnosis due to its simple operation, comfortable and economical cost. In an EISI examination, a constant voltage with a low frequency is applied to the hand-held stainless-steel cylinder. The scan probe with a planar array of electrodes is placed on breast and all electrodes in array are kept at virtual ground. Due to good electrical conductivity of human pectoralis muscle, it can be regarded as an equivalent potential surface, and an approximate parallel electric field was established between pectoralis muscle and probe. When there is a cancerous lesion in breast tissue, due to differences in electrical conductivity, the electric field originally distributed in parallel will be disturbed, and the current distribution detected by probe will be disturbed [1].

Seo et al. modeled EISI as a semi-infinite space. Through boundary element method, the imaging characteristics of presence of cancerous lesion in breast were simulated. It was preliminarily pointed out that current disturbance has a close relationship with depth of cancerous lesion [2]. Since the model does not involve actual size of breast and actual structure of probe, it can’t reflect the boundary effects during imaging process. Scholz et al. modeled imaging process as a single volume conductor problem, and conducted a preliminary simulation analysis of imaging process based on finite element method [3]. However, Scholz's imaging model has following shortcomings: first, breast is equivalent to a single tissue, and skin layer is not considered; second, equivalent potential surface of pectoralis major muscle is regarded as same size as surface of probe, which reduces boundary effects to a certain
extent. In fact, equivalent potential surface of pectoralis muscle is same as size of breast, and is larger than surface of probe. Third, idealize surface of probe as an ideal zero potential surface, and boundary conditions at electrode spacing are not considered.

This paper constructs a breast imaging model that is closer to EISI. The current distribution of breast surface was obtained by using COMSOL software. The effect of skin layer on imaging is analyzed.

2. Methodology and modelling

Electrical parameter of human tissues can be regarded as electrical admittance form shown in equation (1), where \( \sigma \) is conductivity and \( \varepsilon_0 \) is dielectric constant in vacuum, and its value is \( 8.85 \times 10^{-12} \) F/m; \( \varepsilon \) is a relative dielectric constant, \( \omega = 2\pi f \) is angle frequency of excitation signal, and \( f \) is frequency of excitation signal.

\[
\sigma^* = \sigma + j \omega \varepsilon_0 \varepsilon
\]  

(1)

EISI detection process is through application of low-frequency sinusoidal excitation signal (excitation frequency <20 KHz), and then detect current on surface of breast. Considering that there is no current source inside breast, there is no current accumulation effect, so potential distribution inside breast satisfies the typical Laplace equation (2) [4, 5].

\[
-\nabla \cdot (\sigma^* \nabla \phi) = 0 \quad \text{in} \quad \Omega
\]  

(2)

Among equation (2), \( \Omega \) represents the breast to be detect, \( \phi \) is the potential value inside breast. During EISI inspection, a sinusoidal excitation voltage is introduced into pectoralis major muscle by electrode rod held by patient (with good electrical conductivity). Then it flows out via breast tissue from probe electrode (both electrodes are virtual grounded) on surface of breast. Therefore, in addition to satisfy equation (2), it is also necessary to meet Dirichlet boundary condition shown in formula (3). Dirichlet boundary \( r_1 \) includes surface of probe (including surface of measuring electrode and guard electrode) and plane where pectoralis muscle is located. The boundary conditions are \( U = 0 \) and \( U = 2.0 \) V, respectively (EISI excitation voltage amplitude).

\[
\phi = U \quad \text{on} \quad \Gamma_1
\]  

(3)

With exception of boundary \( r_1 \), other surfaces are collectively referred to as Newman boundary \( r_2 \). Outer material in contact with boundary \( r_2 \) is air. Taking into account that electrical conductivity of skin is much greater than that of air, therefore, there is no boundary current at boundary \( r_2 \). Distribution of electric fields described in equation (2) still needs to satisfy Newman boundary conditions (i.e., electrical isolation conditions) shown in equation (4) [4]:

\[
\sigma^* \frac{\partial \phi}{\partial n} = 0 \quad \text{on} \quad \Gamma_2
\]  

(4)

By solving equations (2)-(4), potential distribution \( \phi \) of EISI can be obtained. On surface of probe, considering that electrode can be considered as an ideal conductor, it can be regarded as an isopotential body, and its electric field tangent component is zero. Therefore, on contact surface of probe and breast, electric field strength in tissue is only normal component [4]. Current density distribution of electrode surface is calculated by means of equation (5). Current of measuring electrode can be achieved by integrals with equation (6).

\[
J = -\sigma^* \frac{\partial \phi}{\partial n}
\]  

(5)

\[
I = \int_{s} J ds
\]  

(6)

When excitation frequency is less than 100 KHz, conduction current in human tissue is much larger than displacement current, so dielectric effect can be ignored. EISI’s measuring frequency is in range of 200-20KHz, so only conductivity value is considered in subsequent simulations.

Female breast consists of breast tissue and surface skin. Breast tissue consists of glands and fats. Young women have dense breasts and breast tissue is dominated by glands. As age grows, glands gradually degenerate, and breast tissue gradually takes fat as main component. The size distribution of women's breasts in China is 100-170 mm [6], flat posture breast thickness between 30-60 mm [7].
Average thickness of breast skin is 5 mm and conductivity is 0.01 S/m. During EISI, breast is examined by a physician after pressing and smoothing, so it can be approximated as a square column with a side length of 100-170 mm and a thickness of 30-60 mm. The column has two layers of structure. The surface is skin layer. Fig.1 is a computational example. Fig.1 (a) is a breast EISI measuring model with a diameter of 100 mm. There is a tumor with a radius of 15 mm within breast tissue, and its depth is 20 mm; tumor tissue conductivity is 0.7 S/m, mammary tissue is fat, conductivity is 0.04 S/m, thickness of skin layer is 5 mm, and conductivity is 0.01 S/m. Fig.1 (b) is a grid model, measuring electrodes and guard electrode are manufactured by PCB copper coating process with a thickness of 100 um. Fig.1 (c) shows distribution of electric field lines. To solve equation (2)-(6), current distribution of measuring electrode on surface of probe can be obtained as shown in Fig.1 (d). In order to reduce current disturbance caused by larger breast than probe, guard electrode is designed around measuring electrodes (Square, side length of 3 mm, and interval space of 1 mm). This reduces interference of boundary effect on measuring electrodes to some extent. It is helpful to highlight current disturbance introduced by difference of electrical conductivity between tumor lesion and surrounding normal tissue.

Figure 1 (a) EISI measuring model
Figure 1 (b) Grid model for EISI measuring model
Figure 1 (c) Electric field line of EISI
Figure 1 (d) Current of EISI electrodes, unit with A

3. Results and discussions

3.1 Effect of presence or absence of skin layer on EISI

Combined with model and simulation method in previous section, skin effect on EISI was analyzed. Breast size was 100 mm, depth of lesion was 20 mm, radius of lesion was 15 mm, and conductivity of lesion was 0.7 S/m. On this basis, four situations are simulated respectively. Fig.2 (a) is case without considering skin layer, that is, thickness of breast tissue is 50 mm; breast tissue was of fat type, and conductivity was 0.04 S/m. Fig.2 (b) compared with Fig.2 (a), only skin layer was considered. Thickness of skin layer was 5 mm, and conductivity of skin layer was 0.01 S/m. Fig.2 (c) shows that skin layer is not considered, but breast tissue is a mixture of fat and gland, with a conductivity of 0.3 S/m. Similarly, in Fig.2 (d), only skin layer was considered. Thickness of skin layer was 5 mm, and conductivity of skin layer was 0.01 S/m. In order to objectively evaluate degree of current disturbance caused by cancerous lesions, this paper defined a breast cancer significance measure (BCSM):
BCSM = \frac{\left( \sum_{i=1}^{4} I_{i,4} \right) / 4}{\left( \sum_{i=7}^{10} I_{i,7} \right) / 28}

(7)

BCSM represents ratio between average detection current of four electrodes at center of probe and average detection current of 28 electrodes at four edges of probe. If BCSM is less than 1, it means that disturbance brought by cancerous lesion is submerged in boundary effect, and disturbance is difficult to be recognized. If breast tissue was fat, BCSM was 1.6939 without considering skin layer. If skin layer is taken into account, BCSM drops significantly to 1.2244. If breast tissue is dominated by glands, its conductivity significantly increases, and conductance ratio between cancerous lesion and breast tissue decreases, disturbance degree will be further reduced, and BCSM value is 1.1576. If skin layer is taken into account, BCSM value is only 1.0285, and it is difficult to detect current disturbance caused by cancerous lesion in Fig. 2 (d).

3.2 Effect of electrical conductivity of skin layer on EISI

Basic parameters of model are shown in Fig. 1. Conductivity of breast tissue is 0.3 S/m, radius of cancerous lesion is 15 mm, depth of cancerous lesion is 20 mm, conductivity of cancer lesion is 0.7 S/m, and thickness of skin layer is 5 mm. Conductivity of skin layer was 0.01, 0.02, 0.03 and 0.04 S/m, respectively. Fig. 3 shows current distribution detected by probe in four cases and corresponding BCSM values. It can be seen from Fig. 3, skin conductivity directly affects detection sensitivity. The higher conductivity of skin layer, the higher current detected by probe, and the higher BCSM value of image.
3.3 Effect of skin thickness on EISI

Basic parameters of model remain unchanged as shown in Fig. 1. Conductivity of breast tissue is 0.3 S/m, radius of cancerous lesion is 15 mm, depth of cancerous lesion is 20 mm, conductivity of cancerous lesion is 0.7 S/m, and conductivity of skin layer is 0.03 S/m. Thickness of skin layer is 3.0 mm, 3.5 mm, 4.0 mm and 5.0 mm respectively. Fig. 4 shows current distribution detected by probe in four cases and corresponding BCSM values. It can be seen from Fig. 4, the thicker of skin layer, and the smaller current detected by probe. However, there was no significant correlation between skin thickness and sensitivity of probe, and skin thickness had little effect on BCSM value.
4. Conclusion

In EISI, skin layer has a great influence on imaging. Based on results and discussions presented above, conclusions are obtained as below:

1. Under same conditions, sensitivity of probe to detection of cancerous lesion is greatly reduced because conductivity of skin layer is very low. Presence of skin layer greatly reduces current detected by probe, thus greatly reducing degree of current disturbance caused by cancerous lesion.
2. Conductivity of skin layer directly affects sensitivity of EISI. The higher conductivity of skin layer, the higher sensitivity of detection. Conversely, lower sensitivity.
3. There was no significant correlation between skin thickness and sensitivity.

In practice, if skin is moistened with physiological saline before detection, conductivity value of skin layer can be improved, which helps to improve sensitivity of EISI. If conductivity and thickness of skin layer can be accurately measured, effect of skin layer can be eliminated in impedance image and sensitivity of system can be improved. In addition, it can be seen from Fig.1 (c) that boundary effect of probe leads to a larger current detected by electrode at edge of probe, which further reduces current disturbance originally caused by cancerous lesion and decreases detection sensitivity of EISI. In next step, relationship between parameters such as width of guard electrode and space between guard electrode and outermost measuring electrodes and detection sensitivity of EISI should be further analyzed to improve system through optimization design.

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