Published in final edited form as:
Breast Dis. 1998 August ; 10(3-4): 191–195.

The Potential for Hall Effect Breast Imaging

H. Wen and **R. S. Balaban**
Laboratory of Cardiac Energetics, National Heart, Lung and Blood Institute, National Institutes of Health, Bethesda, Maryland 20892

Abstract

Hall effect imaging is a non-invasive imaging method that combines ultrasound with a strong magnetic field to investigate the electrical properties of tissue. Although it is at an early stage of technical development, there is promise that it might be useful for detecting or characterizing pathologies in the breast and other organs. In vitro studies in the past showed that tissue electrical properties are closely related to its physiology and morphology. Hall effect imaging may become a new tool to study these electrical properties in the body and potentially provide unique diagnostic information.

Introduction of the imaging method

The electrical properties of the body depend on the physiological state and morphology of its structures. Research in this area for the past two decades yielded much understanding of this relationship, and motivated the long effort in using tissue electrical parameters to diagnose diseases. It has proven difficult to map these parameters non-invasively in the human body with direct electromagnetic means. This is because the body is a strong scatterer and absorber of electromagnetic fields, such that the interpretation of the measurements depends greatly on a priori knowledge of the electrical properties themselves. Recently a new imaging method, Hall effect imaging (HEI), was developed which may overcome this limitation. Hall effect imaging relies on the interaction between ultrasonic vibrations and strong magnetic fields to map the dielectric properties of the body. It holds the potential for real-time high contrast imaging of the electrical parameters, with spatial resolutions similar to diagnostic ultrasound. There is promise in applying this method to the breast, because the breast has wide acoustic windows for ultrasound signal detection, and some published results suggest that breast tumors trigger large changes in tissue electrical parameters(1,2).

Hall effect imaging evaluates an object's electrical and mechanical properties using a phenomenon called the Hall effect (3). The phenomenon is as follows, the positive and negative charges in a conductive object tend to separate when the object moves in a magnetic field as a result of the opposing Lorentz forces on the charges. This leads to an externally detectable voltage within the sample, the Hall voltage. One biological example of this effect are the artifacts detected in the EKG voltages when a subject is placed in a magnet for a magnetic resonance scan. These artifacts are Hall voltages generated by the flowing blood in the large arteries of the chest. Their magnitude is on the same order as the normal EKG. This example demonstrates that under physiological conditions, Hall voltage naturally arises within the body in the audio-frequency range and can be detected with external electrodes (i.e. EKG pads). Hall effect imaging relies on the generation of the Hall voltage at much higher frequencies with ultrasonic pulses instead of relying on physiological motions such as heartbeat or blood flow.

Corresponding author: H. Wen, Ph.D., Building 10, Room B1D-161, National Institutes of Health, Bethesda, MD 20892, Tel: (301) 496-2694, FAX: (301)402-2389, wen@zeus.nhlbi.nih.gov.

The amplitude of the Hall voltage is determined by the strength of the Lorentz force as well as the charge density and mobility. The Lorentz force is proportional to the magnetic field B_0 and the velocity of motion v, while the charge density and mobility are characterized by the apparent conductivity σ of the tissue. The apparent conductivity includes contributions from the conductivity and the dielectric constant of the medium. Overall, the Hall voltage V_h is proportional to the product $\sigma v B_0$.

Based on this relationship, a conductivity-based image of an object can be formed if the motion v is induced with ultrasonic pulses. An ultrasonic pulse is a localized packet of vibration that travels at a known speed. At any moment, the Hall voltage generated by the pulse is a signature of the position of the pulse. As the acoustic pulse moves through an object, the associated instantaneous Hall voltage reports the electrical properties it experiences. In other words, the scanning ultrasonic pulse converts spatial information along its path to the time record of the Hall voltage. This relation between space and time is similar to conventional ultrasound imaging. What is different here is that the Hall voltage is monitored almost instantaneously as it is created because electric field propagates at roughly the speed of light, in contrast a regular ultrasonic echo takes time to travel back to the sensor. With Hall effect imaging one also obtains additional information about the electrical properties of the object instead of the acoustic properties alone. A detailed discussion of the physics of image formation and the relationship between the contrast of an HEI image and the electrical parameters can be found in a prior publication (4).

The Hall effect is reciprocal. That is, a strong electrical field applied to a conductive object will produce an ultrasonic pulse if there are spatial variations in the conductivity. In practice it is advantageous to scan in this reverse mode, i.e., to pass an electrical impulse through the sample and detect the resulting ultrasound signal (4). Based on the reciprocity relation of a linear electro-mechanical system (5), the reverse mode produces identical images as the forward mode. The reverse mode is less susceptibility to electromagnetic interference in the environment, and allows the use of array transducers for fast 2-D or 3-D image formation, as is used in conventional ultrasound.

Currently HEI is still at laboratory stage with relatively low spatial resolution. Figure 1 shows 2-D images of phantoms and biological samples with a line scan method (4). With improvements in the electrical components, and the adaptation of up-to-date diagnostic ultrasound scanners, it is possible to significantly improve image qualities and achieve 1 mm resolution or better in the near future, to allow a realistic judgement of its value for medical applications. Besides technical issues, the question of how much diagnostic information can be obtained from tissue conductivity and/or dielectric constant remains to be answered, and HEI may provide an effective tool for this clinical evaluation.

What do the electrical parameters tell about the pathologies in the breast?

Tissue electrical properties are characterized by two parameters: the conductivity σ and the dielectric constant ε. Roughly speaking, σ measures the amount of instant current in a tissue in response to an external electric field, ε measures the amount of electrical polarization in the bulk and across membranes during the course of the applied electric field. Both parameters change with the frequency of the applied field. This frequency dependence is important in understanding the connection between electrical and physiological parameters.

At any frequency, σ and ε are determined by parts of the tissue structure that participate in electrical conduction (6). At audio frequencies (below 20 kHz) only extracellular space contribute to the bulk tissue conductivity and dielectric constant, since the cell membrane presents a high impedance. Above a certain frequency the impedance of the cell membrane decreases significantly, and the intracellular water and ions begin to contribute to the overall conductivity of the sample. This frequency is called the dispersion frequency of the cell membrane. It is dependent on the membrane capacitance and cell size, and is normally on the order of 1MHz. The smaller the cell, the higher the dispersion frequency. Going further up in the spectrum, the cell membranes become almost “transparent” to the electric field, and water even in the sub-cellular organelles begin to contribute. For instance the dispersion frequency of mitochondria is around 13 MHz, and their contributions to the electrical parameters depend on the volume fraction of mitochondria in the tissue. Figure 2 is a compiled chart of dispersion frequencies of various tissue components in rat liver. The dispersion frequency is approximately inversely proportional to the size of the structure.

With increasing frequencies smaller structures are included in the electrical parameters, until into the GHz range all compartments in the cell become “transparent” to the electric field. At GHz frequencies σ and ε measure the overall water, ion and protein contents of the tissue (7).

In vivo applications of Hall effect imaging will mostly occur in the radio-frequency (RF) range of 1 MHz - 10 MHz. This is because much below 1 MHz the spatial resolution of the images is poor, above 10 MHz the signal level is very low and signal attenuation in tissue is severe. In this frequency range, in addition to the contribution of extracellular water, intracellular water partially contribute to σ and ε. In breast imaging large HEI contrast between fatty and non-fatty regions is expected because of the differences in water content and water distribution. However it is not clear how much difference there is between normal non-fatty breast tissue and tumors in vivo. To date there have been two studies on excised human breast tissues at these frequencies. Surowiec et al (1) studied 28 specimen from 7 patients with known history and diagnosis of breast carcinoma. The measurements were all completed within 4 hrs of the excisional surgical procedure. Their results showed that malignant tumor regions had at least 4 times higher conductivity and dielectric constants than surrounding normal tissue. The dispersion frequencies of the tumor regions were 2 to 4 times lower than the surrounding area, consistent with the cells being larger in the tumor.

The elevated electrical constants in malignant breast tumors in Surowiec et al’s study could be explained by water distribution changes. Campbell and Land conducted dielectric measurements at 3.2 GHz of excised breast tissue specimen (7). By drying the samples at 105° C, they showed that the overall free water content of normal (non-fatty) breast tissue mostly fell between 45%-70% in volume, in malignant tumor it was 75-80%. This increase in overall saline content will lead to higher conductivity and dielectric constant in the RF range as well. However, benign tumor specimens had water content from 60% to 90%, significantly overlapping both normal and malignant tissues. Campbell and Land concluded that overall water content alone may not be able to distinguish between benign and malignant tumors.

In the RF range, σ and ε also depends on the distribution of water between the intra and extracellular compartments. There is evidence that this may change between normal and neoplastic tissues. Smith and Foster studied the electrical parameters of VX-2 carcinoma implanted in rabbit livers for the frequency range of 1 kHz to 13 MHz (8), and found that the fraction of extracellular water was much higher in the tumors. They concluded that in the tumors the number of intact cells decreased, and the extracellular water percentage reflected the sum of extracellular space and necrotic cells. This may also happen in breast tumors, and is corroborated by the lower dispersion frequencies, or appearingly larger cell sizes in malignant tissues in Surowiec et al’s study. Other changes in the extracellular matrix and gross changes in capillary density could also contribute to the higher conductivity and dielectric constant of tumors.

Another study of malignant breast tumors was from Chaudhary et al. in the 3 MHz to 3 GHz range (2). Their data on the conductivity and dielectric constant of malignant tissue agreed with Surowiec et al's measurements, although they did not measure non-fatty normal breast tissue as a control. This is an important limitation since the fatty breast tissue has extremely low conductivity.

It is realized that measurements on excised tissue specimens include uncertainties from sample handling, such as loss of tissue water and blood during slicing or refrigeration. Nonetheless the many-fold increase in σ and ε between malignant tumor tissues and normal tissues suggest that HEI may be able to detect malignant tumors in the breast. Currently there is not sufficient data in the RF range to make a judgement on the possibility of distinguishing benign and malignant tumors with HEI. Another potential problem is that HEI depicts spatial changes of σ and ε. If the boundary between neoplastic and normal tissues is not well defined, detection may be difficult, or boundary definition may be fuzzy in the images. Furthermore, results in Surowiec et al's study contained large inter-patient variation. While tumor tissues have much higher σ and ε values than normal tissues, both sets of parameters varied over a wide range for specimens from different patients. This suggests that quantitative gradation of tumors based on electrical parameters alone may not be possible. In any event, HEI should provide a non-invasive tool of evaluating tissue conductivity in vivo, and may lead to useful insights into the diagnostic values of electrical parameters, and possibly yield some basic information about tumor structure and composition.

Summary and Discussion

Hall effect imaging may be applicable for the detection of breast tumors in the future. In vitro data suggest that the electrical properties of breast tumors are different from normal tissue, however, whether these electrical changes are specific enough for clinical use is unknown. One of the reasons that electrical properties of tissues in vivo have been relatively unexplored is the lack of good imaging techniques. Hopefully, HEI will provide a tool to fully explore these parameters in breast cancer as well as other tissues and pathologies.

To fully implement HEI several technical issues need to be addressed. A strong magnetic field is required for HEI, however the cost and size of these magnets will be much lower than MRI applications due to the 10,000 fold relaxation of specifications for field uniformity and stability. Many other engineering aspects of HEI are not yet optimized. Key components are the ultrasound and electrode arrays, which need to be developed for operation in high magnetic and electrical fields associated with HEI. This is the most unique technical development area since other aspects of image formation are basically available from conventional ultrasound technology. The geometry of a human imaging device is still in a conceptual stage with hopes of an operational prototype device in the next 2 years.

A basic question of how to interpret tissue electrical properties revealed from HEI, in vivo, is unknown and will require extensive investigation once the image quality begins to approach theoretical limits. Much like the magnetic relaxation properties of tissues that have been exploited in MRI, HEI should provide a physical sense of the tissue electrical properties, which may prove useful as a clinical tool in evaluating the breast as well as other tissues.

References

(1). Surowiec AJ, Stuchly SS, Barr JR, Swarup A. Dielectric Properties of Breast Carcinoma and the Surrounding Tissues. IEEE Trans. Biomed. Eng 1988;35(4):257–263. [PubMed: 2834285]

(2). Chaudhary SS, Mishra RK, Swarup A, Thomas JM. Dielectric Properties of Normal & Malignant Human Breast Tissues at Radiowave & Microwave Frequencies. Ind. J Biochem. Biophys 1984;21:76–79.

(3). Jackson, JD. Classical Electrodynamics. John Wiley & Sons; New York: 1975. p. 266ch. 6

(4). Wen H, Shah J, Balaban RS. Hall effect imaging. IEEE Trans. Biomed 1998;45(1):119–124.

(5). Ballantine S. Reciprocity in electromagnetic, mechanical, acoustical, and interconnected systems. Proceedings of the Institute of Radio Engineers 1929;17:929–951.

(6). Stoy RD, Foster KR, Schwan. Dielectric properties of mammalian tissues from 0.1 to 100 MHz: a summary of recent data. Phys. Med. Biol 1982;27(4):501–513. [PubMed: 7089048]

(7). Campbell AM, Land DV. Dielectric properties of female human breast tissue measured in vitro at 3.2 GHz. Phys. Med. Biol 1992;37(1):193–210. [PubMed: 1741424]

(8). Smith SR, Foster KR, Wolf GL. Dielectric Properties of VX-2 Carcinoma Versus Normal Liver Tissue. IEEE Trans. Biomed. Eng 1986;BME-33(5):522–524. [PubMed: 3710509]

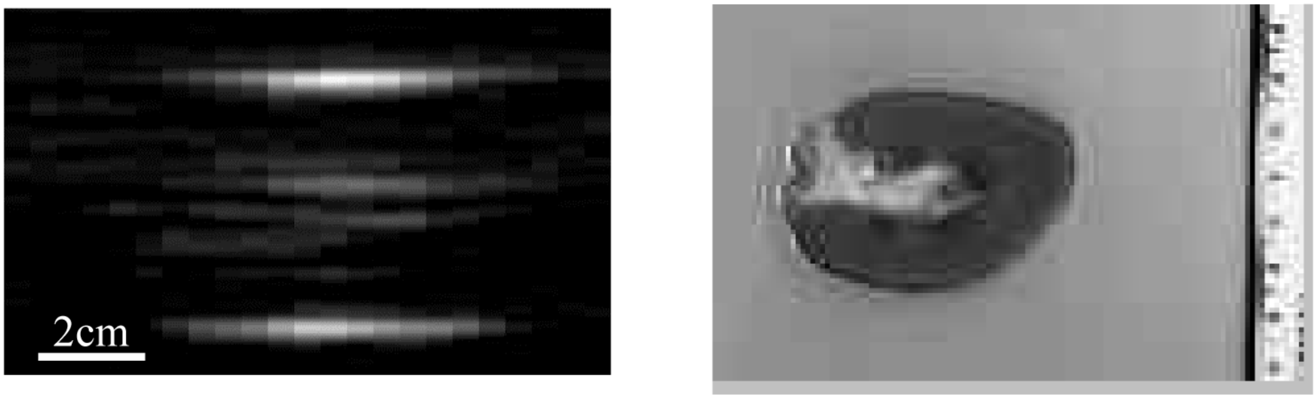

Fig. 1.

A Hall effect image of a canine kidney immersed in a saline tank.

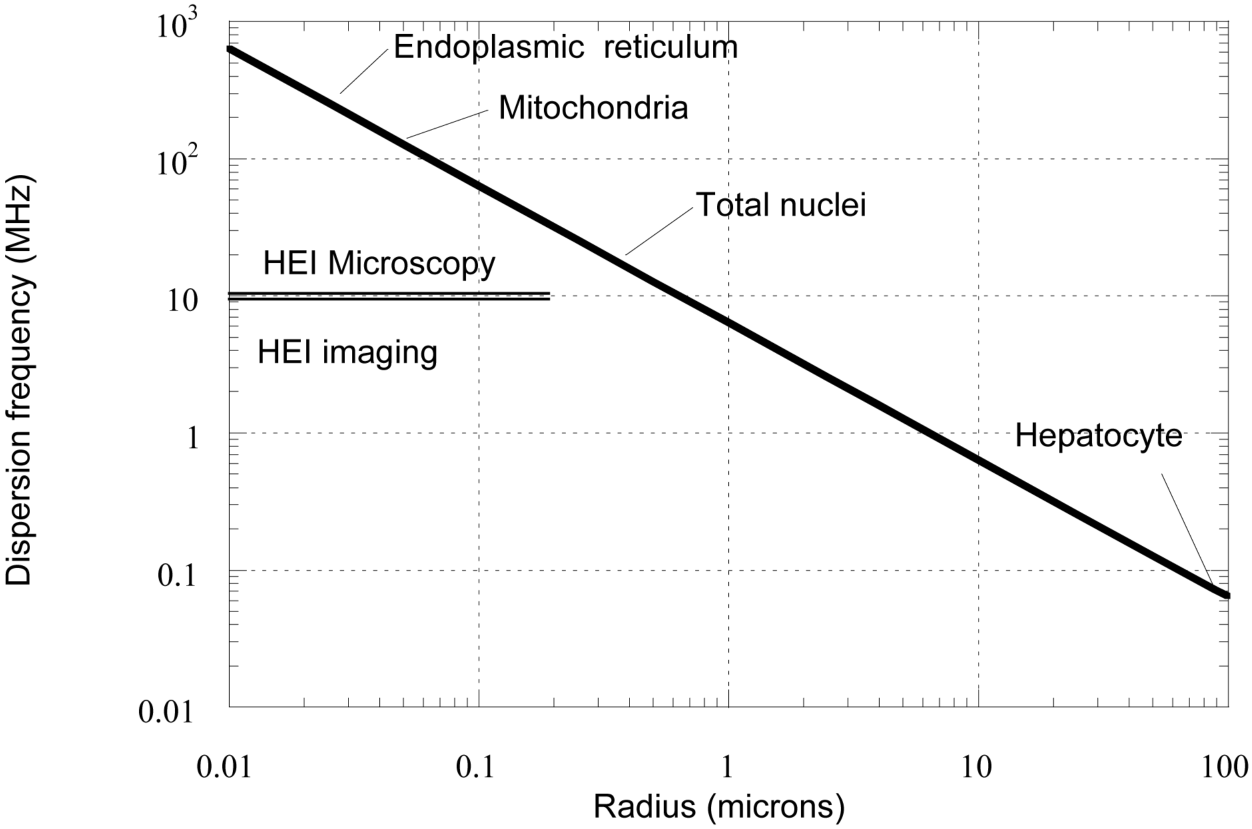

Fig. 2.
The dispersion frequency of cellular components of rat liver cells vs. their radii.