

Biomedical Imaging Modalities

The introduction of advanced imaging techniques has improved significantly the quality of medical care available to patients. Noninvasive imaging modalities allow a physician to make increasingly accurate diagnoses and render precise and measured modes of treatment. A multitude of imaging modalities are available currently or subject of active and promising research. This chapter outlines those discussed in this book.

1.1 X-Ray Imaging and Computed Tomography

X-ray imaging is a transmission-based technique in which X-rays from a source pass through the patient and are detected either by film or an ionization chamber on the opposite side of the body. Contrast in the image between different tissues arises from differential attenuation of X-rays in the body. For example, X-ray attenuation is particularly efficient in bone, but less so in soft tissues. In planar X-ray radiography, the image produced is a simple two-dimensional projection of the tissues lying between the X-ray source and the film. Planar X-ray radiography is used for example to study the liver and the abdomen and to detect diseases of the lung or broken ribs.

Planar X-ray radiography of overlapping layers of soft tissue or complex bone structures can often be difficult to interpret. In these cases, X-ray computed tomography (CT) is used. In CT, the X-ray source is tightly collimated to interrogate a thin slice through the patient. The source and detectors rotate together around the patient, producing a series of one-dimensional projections at a number of different angles. These data are reconstructed to give a two-dimensional image and provide a reasonable contrast between soft tissues. The mathematical basis for reconstruction of an image from a series of projections is the Radon transform. Recent developments in spiral and multi-slice CT have enabled the acquisition of full three-dimensional images in a single patient breath-hold.

The biggest disadvantage of both X-ray and CT imaging is the fact that the technique uses ionizing radiation. Because ionizing radiation can cause tissue damage, there is a limit on the total radiation dose per year to which a patient can be exposed. Radiation dose is of particular concern in pediatric and obstetric radiology. Figure 1.1 shows an X-ray image of breast cancer.

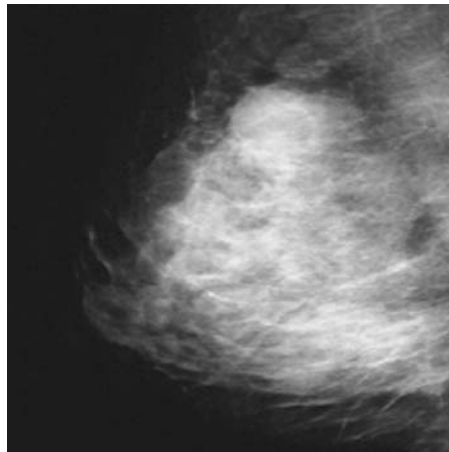


Fig. 1.1. X-ray image of breast cancer.

1.2 Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) is a non-ionizing technique with full three-dimensional capabilities, excellent soft-tissue contrast, and high spatial resolution (about 1mm). In general, the temporal resolution is much slower than for computed tomography, with scans typically lasting between 3 and 10 min, and MRI is therefore much more susceptible to patient motion. The cost of MRI scanners is relatively high, with the price of a typical clinical 1.5-T whole-body imager on the order of 1 million euros. The major uses of MRI are in the areas of assessing brain disease, spinal disorders, cardiac function, and musculoskeletal damage.

The MRI signal arises from protons in the body, primarily water, but also lipid. The patient is placed inside a strong magnet, which produces a static magnetic field typically more than 10^4 times stronger than the earth's magnetic field. Each proton, being a charged particle with angular momentum, can be considered as acting as a small magnet. The protons align in two configurations, with their internal magnetic fields aligned either parallel or anti-parallel to the direction of the large static magnetic field. The protons

process around the direction of the static magnetic field. The frequency of precession is proportional to the strength of the static magnetic field. Application of a weak radio-frequency field causes the protons to process coherently, and the sum of all the protons precessing is detected as an induced voltage in a tuned detector coil.

Spatial information is encoded into the image using magnetic field gradient. These impose a linear variation in all three dimensions in the magnetic field present within the patient. As a result of these variations, the precessional frequencies of the protons are also linearly dependent upon their spatial location. The frequency and the phase of the precessing magnetization is measured by the radio-frequency coil, and the analog signal is digitized. An inverse two-dimensional Fourier transform is performed to convert the signal into the spatial domain to produce the image. By varying the data acquisition parameters, differential contrast between soft tissues can be introduced with high spatial resolution. Figure 1.2 shows an MRI image of breast cancer. MRI has high sensitivity but low specificity. It is not capable of discriminating benign from malignant lesions.



Fig. 1.2. MRI image of breast cancer.

1.3 Electrical Impedance Tomography

Electrical impedance tomography (EIT) uses low-frequency electrical current to probe a body; the method is sensitive to changes in electrical conductivity. By injecting known amounts of current and measuring the resulting electrical potential field at points on the boundary of the body, it is possible to “invert” such data to determine the conductivity or resistivity of the region of the body probed by the currents. This method can also be used in principle to image changes in dielectric constant at higher frequencies, which is why the

method is often called “impedance” tomography rather than “conductivity” or “resistivity” tomography. However, the aspect of the method that is most fully developed to date is the imaging of conductivity/resistivity. Potential applications of EIT include determination of cardiac output, monitoring for pulmonary edema, and screening for breast cancer.

There is a formal mathematical analogy between EIT and CT, since in either case data must be processed to produce the desired image of interior structure and, furthermore, the imaging is often performed on two-dimensional slices through the body. EIT uses diffusion of current to deduce conductivity distribution, unlike MRI and CT.

EIT is expected to have relatively poor resolution compared to MRI, and CT. However, at the present time, EIT is the only method known that images electrical conductivity, although MRI and electromagnetic methods also have some potential to measure conductivity. So, for applications requiring knowledge of the distribution of this parameter through a body, EIT is an important method to consider for medical imaging, regardless of its resolving power.

On the other hand, EIT has some very attractive features. The technology for doing electrical impedance imaging is safe and inexpensive, and therefore could be made available at multiple locations (for example, at bedside) in hospitals. At the low current levels needed for this imaging technique, the method is not known to cause any long-term harm to the patient, and therefore could be used to do continuous (or frequent, but intermittent) monitoring of bedridden patients.

The impedance imaging problem is nonlinear and extremely ill posed, which means that large changes in interior properties can result in only small changes in the measurements. The classical image reconstruction algorithms view EIT as an optimization problem. An initial conductivity distribution is iteratively updated, so as to minimize in the least-squares sense the difference between measured and computed boundary voltages. This approach is quite greedy in computational time, yet produces images with deceptively poor accuracy and spatial resolution.

In the 1980’s, Barber and Brown introduced a back-projection algorithm, that was the first fast and efficient algorithm for EIT, although it provides images with very low resolution. Since this algorithm is inspired from computed tomography, it can be viewed as a generalized Radon transform method.

A third technique is dynamical electrical impedance imaging to produce images of changes in conductivity due to cardiac or respiratory functions. Its main idea consists in viewing the conductivity as the sum of a static term plus a perturbation. The mathematical problem here is to visualize the perturbation term by an EIT system. Although this algorithm provides accurate images if the initial guess of the background conductivity is good, its resolution does not completely satisfy practitioners especially when screening for breast cancer.

1.4 T-Scan Electrical Impedance Imaging System for Anomaly Detection

Recently, a commercial system called TransScan TS2000 (TransScan Medical, Ltd, Migdal Ha'Emek, Israel) has been released for adjunctive clinical uses with X-ray mammography in the diagnostic of breast cancer. Interestingly, the TransScan system is similar to the frontal plane impedance camera that initiated EIT research early in 1978. The mathematical model of the TransScan can be viewed as a realistic or practical version of the general EIT system, so any theory developed for this model can be applied to other areas in EIT, especially to detection of anomalies. In the TransScan, a patient holds a metallic cylindrical reference electrode, through which a constant voltage of 1 to 2.5 V, with frequencies spanning 100 Hz-100 KHz, is applied. A scanning probe with a planar array of electrodes, kept at ground potential, is placed on the breast. The voltage difference between the hand and the probe induces a current flow through the breast, from which information about the impedance distribution in the breast can be extracted. See Fig. 1.3

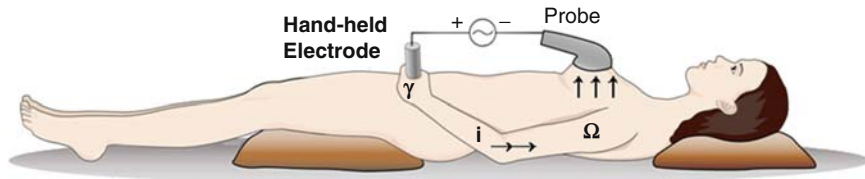


Fig. 1.3. Tscan.

1.5 Electrical and Magnetic Source Imaging

Electrical source imaging (ESI) is an emerging technique for reconstructing brain or cardiac electrical activity from electrical potentials measured away from the brain or heart. The concept of ESI is to improve on electroencephalography (EEG) or electrocardiography (ECG) by determining the locations of sources of current in the body from measurements of voltages. ESI could improve diagnoses and guide therapy related to epilepsy and heart conduction abnormalities through its capability for locating an electrical abnormality that is to be removed. Differences in potential within the brain, heart, and other tissues reflect the segregation of electrical charges at certain locations within these three-dimensional conductors as nerves are excited, causing cell membrane potentials to change. While the potential measured at

some distance from an electrical charge generally decreases with increasing distance, the situation is more complex within the body; generators of the EEG, for example, are not simple point-like charge accumulations but rather are dipole-like layers. Moreover, these layers are convoluted and enmeshed in a volume conductor with spatially heterogeneous conductivity. The particular geometry and orientation of these layers determines the potential distribution within or at the surface of the body. The classical approach to studying brain electrical activity involves recognizing patterns in a set of waveforms showing voltage as a function of time, acquired from about 20 electrodes placed on the scalp. While frequency analysis methods can indicate probable Alzheimer's disease by the abnormal distribution of spatial frequency bands true distribution of neuronal activity, knowledge of which could lead to more refined diagnoses, is masked or blurred by the conducting tissue layers between the central cortex and the electrodes. Cardiac electrical activity is likewise spatially complex, and involves the propagation of excitation wave fronts in the heart. Standard electrocardiographic techniques such as electrocardiography (ECG) and vectorcardiography (VCG) are very limited in their ability to provide information on regional electrical activity and to localize bioelectrical events in the heart. In fact, VCG lumps all cardiac wave fronts into a single dipole located at the center of the heart and known as the heart vector. Traditional ECG and VCG employ a small number of electrodes to measure potentials from the body surface, and the patterns of electrical activity cannot give the information required for characterizing the electrical activity of the heart. Non-invasive electrocardiography requires simultaneous recordings of electrical potential from 100 to 250 torso sites in order to map the body surface potential. These body surface potential maps (BSPMs) reflect the regional time course of electrical activity of the heart, information that is important for clinical treatment. Body surface potential distribution is a very low resolution projection of cardiac electrical activity, and details of regional electrical activity in the heart cannot be determined merely from visual inspection of the BSPMs. A mathematical method of reconstructing endocardial potentials is greatly needed.

Ion currents arising in the neurons of the heart and the brain produce magnetic fields outside the body that can be measured by arrays of SQUID (superconducting quantum interference device) detectors placed near the chest or head; the recording of these magnetic fields is known as magnetocardiography (MCG) or magnetoencephalography (MEG). Magnetic source imaging (MSI) is the reconstruction of the current sources in the heart or brain from these recorded magnetic fields. These fields result from the synchronous activity of tens or hundreds of thousands of neurons. Both magnetic source imaging and electrical source imaging seek to determine the location, orientation, and magnitude of current sources within the body. The magnetic field at the surface is most strongly determined by current sources directed parallel to the surface, but the electrical potentials are determined by current sources directed perpendicular to the surface. Other than the signal distortion from

the heterogeneity of tissue conductivity, there is no clear physical reason that the clinical information produced by biomagnetic measurements could not as well be obtained from electrical potential mapping. An advantage of MSI over ESI is that all body tissues are magnetically transparent and the magnetic fields propagate to the surface without distortion. The electrical potentials at the surface, on the other hand, are distorted by variations in conductivity within the body; this is especially true in the head, where the low conductivity of the skull both distorts and hides the electrical activity of the brain. A disadvantage of MSI is that the need for cryogenic cooling and a magnetically shielded room makes the procedure cumbersome with the present technology.

Biomagnetic source imaging offers a tool to study processes where electrical function is important. Promising results have been obtained in the fields of cardiology and epilepsy. An exciting research on challenging signal processing issues for EEG and MEG data analysis is being conducted at Laboratoire de Neurosciences Cognitives & Imagerie Cérébrale in Paris (<http://cogimage.dsi.cnrs.fr/index.htm>). A comprehensive set of tools dedicated to MEG and EEG data visualization and processing is available at <http://neuroimage.usc.edu/brainstorm/>. Figure 1.4 shows a MEG imaging system and a MEG reconstruction of electrical brain activity coherent with the speed of hand movements.

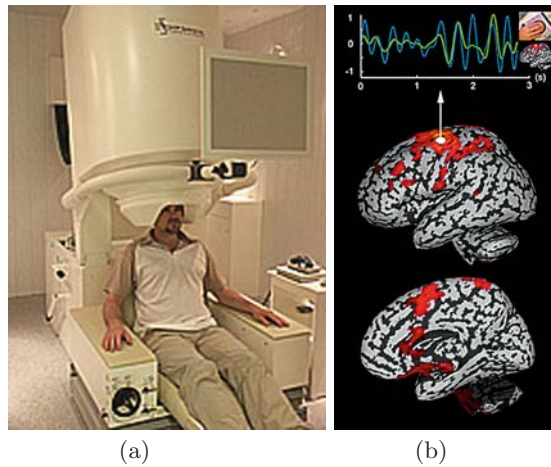


Fig. 1.4. (a) MEG imaging system; (b) Electrical brain activity coherent with the speed of hand movements.

1.6 Magnetic Resonance Electrical Impedance Tomography

Since all the present EIT technologies are only practically applicable in feature extraction of anomalies, improving EIT calls for innovative measurement

techniques that incorporate structural information. A very promising direction of research is the recent magnetic resonance imaging technique, called current density imaging, which measures the internal current density distribution.

When one injects a current into a subject, it produces a magnetic field as well as an electric field. In EIT, one utilizes only the electrical quantities. Furthermore, since there is no noninvasive way of getting measurements of electrical quantities from inside the subject, we are limited in EIT by the boundary current-voltage data which is insensitive to internal conductivity perturbations. Using a magnetic resonance imaging scanner, one can enrich the EIT data by measuring the internal magnetic flux density. This technique called magnetic resonance current magnetic resonance electrical impedance tomography (MREIT) perceives the distortion of current pathways due to the conductivity distribution to be imaged and overcomes the severe ill-posedness character of EIT. It provides high-resolution conductivity images. However, it has a number of disadvantages, among which the lack of portability and a potentially long imaging time. Moreover, it uses an expensive magnetic resonance imaging scanner.

MREIT has been developed at the Impedance Imaging Research Center in Seoul (<http://iirc.khu.ac.kr/>). See Fig. 1.5.



Fig. 1.5. MREIT imaging system.

1.7 Impediography

Another mathematical direction for future EIT research in view of biomedical applications, without eliminating the most important merits of EIT (real time imaging, low cost, portability). The method named impediography is

based on the simultaneous measurement of an electric current and of acoustic vibrations induced by ultrasound waves. The core idea of impediography is to extract more information about the conductivity from data that has been enriched by coupling the electric measurements to localized elastic perturbations. Its intrinsic resolution depends on the size of the focal spot of the acoustic perturbation, and thus it provides high resolution images.

Impediography is being developed at Laboratoire Ondes et Acoustique (LOA) in Paris (<http://www.espci.loa.fr>).

1.8 Ultrasound Imaging

Ultrasound imaging is a noninvasive, easily portable, and relatively inexpensive diagnostic modality which finds extensive use in the clinic. The major clinical applications of ultrasound include many aspects of obstetrics and gynecology involving the assessment of fetal health, intra-abdominal imaging of the liver, kidney, and the detection of compromised blood flow in veins and arteries.

Operating typically at frequencies between 1 and 10 MHz, ultrasound imaging produces images via the backscattering of mechanical energy from interfaces between tissues and small structures within tissue. It has high spatial resolution, particularly at high frequencies, and involves no ionizing radiation. The weakness of the technique include the relatively poor soft-tissue contrast and the fact that gas and bone impede the passage of ultrasound waves, meaning that certain organs can not easily be imaged. Figure 1.6 shows an ultrasound probe and an ultrasound image of breast cancer. Compared to Fig. 1.2, it is with much lower sensitivity.

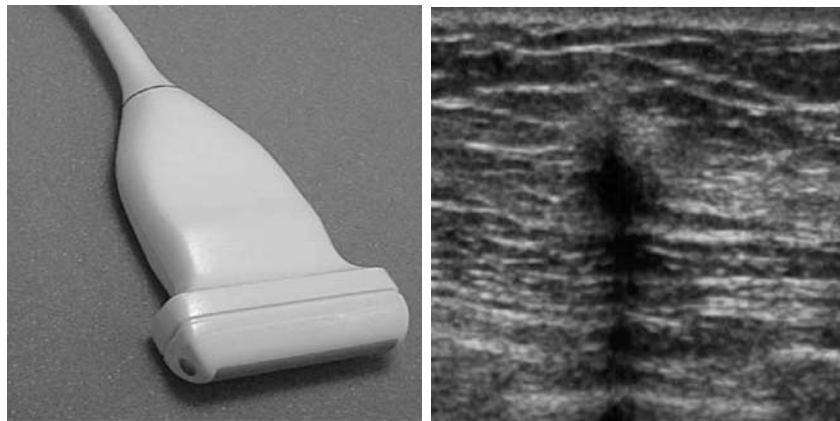


Fig. 1.6. Ultrasound image of breast cancer.

1.9 Microwave Imaging

Ultrasound specificity in breast cancer characterization is low as a result of the overlapping acoustic characteristics of benign and malignant lesions. Recently, microwave imaging is emerging as a new promising modality for the detection of breast cancer because of the high electrical contrasts between malignant tumors and normal breast tissue. Microwaves interact with biological tissues primarily according to the tissue water content, a fundamentally different mechanism from ultrasound. Due to the high vascular content or water content related to tumor angiogenesis, malignant tumors have significantly larger microwave scattering cross sections than normal fatty breast tissues.

1.10 Elastic Imaging

The mechanical properties of soft tissues are important indicators for biomedical research and diagnosis since they are generally correlated with the tissue pathological changes. Although different in terms of elastic stiffness, some tumors are not readily detectable by conventional imaging modalities such as CT, ultrasound imaging, and MRI. Palpation is frequently used to find firm lesions. However, deep lesions in large breasts may not be palpable until they grow large and become incurable. Recognizing that the elastic modulus stiffness change of tissues could indicate the tissue pathological evolution, elastic imaging was developed to detect and characterize tumors by combining some forms of tissue excitation techniques with methods for detection of tissue response.

1.11 Magnetic Resonance Elastography

Magnetic resonance elastography (MRE) is a recently developed technique that can directly visualize and quantitatively measure propagating acoustic strain waves in tissue-like materials subjected to harmonic mechanical excitation. Elastic waves at frequencies in the 10–1000 Hz range are used as a probe because they are much less attenuated than at higher frequencies, their wavelength in tissue-like materials is in the useful range of millimeters to tens of millimeters. A phase-contrast MRI technique is used to spatially map and measure the wave displacement patterns. From these data, local quantitative values of shear modulus can be calculated and images that depict tissue elasticity or stiffness can be generated. Very active research on MRE is being conducted at LOA. See Fig. 1.7.

It is worth pointing out that implediography, MREIT, and MRE are not yet established as standard imaging tools in medicine, and that they are still the subject of mainly academic research.



Fig. 1.7. MRE imaging system.

1.12 Optical Tomography

Optical tomography is a new technique being developed to estimate the optical properties of the body. It is based on the discovery that human tissue has a relative transparency to infra red light in the region 700-1000nm over the highly attenuated visible spectrum. Its principle is to use multiple movable light sources and detectors attached to the tissue surface to collect information on light attenuation, and to reconstruct the internal absorption and scattering distributions. Unusual growths inside the tissue may be discerned from the recovered optical densities because tumorous tissue has different scattering and absorption properties.

Applications of this emerging imaging technique also include a monitoring of cerebral blood and tissue oxygenation of newborn infants and functional mapping of brain activation during physical or mental exercise.

The most comprehensive mathematical model for optical tomography is the radiation transfer equation for the particle flux. When the tissue is strongly scattering, the signal propagation in the medium is diffuse and the particle flux is essentially isotropic a small distance away from the sources. In this case, the diffusion approximation can be used.

Single photon emission computed tomography (SPECT) and positron emission tomography (PET) are not discussed in this book.

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Ammari, H.

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