Tomographic Medical Imaging Modalities: a Short Conceptual Introduction

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ABSTRACT

This paper presents an overview of tomography and different tomographic imaging modalities. The goal of this paper is to provide an understanding of various imaging modalities; in particular, how the imaging is performed, working principles, and applications. It was not intended to provide the in-depth mathematical principles of these imaging modalities, rather this paper focuses on providing the knowledge in an easy-to-grasp manner for the readers' benefit. Imaging modalities are categorized based on the physics behind image generation. First, the paper explains the general tomography principle. Then explains Ultrasound Imaging, Electrical Impedance Tomography, Computed Tomography, Magnetic Resonance Imaging (MRI), Photoacoustic Tomography (PAT), and Positron Emission Tomography (PET). In the end, the paper provides the fundamentals and review of two relatively new imagining modalities, Diffuse Optical Tomography (DOT) and functional Near-infrared Spectroscopy (fNIRS).

Keywords Tomography, Medical Imaging; Ultrasound, EIT; CT Diffuse Optical Tomography; Magnetic Resonance Imaging; Photoacoustic; Positron Emission; fNIRS

1 Introduction to Tomography

The "Tomography" word comes from the Greek words "Tomos", referring to cross-section and graph refers to imaging. As the term is used today Tomography is concerned with reconstructing a higher-dimensional object from the measured projections obtained from the same onto a lower-dimensional space. In Tomography, using some probing method the information about the internal properties of an object is acquired, and then using the data containing the information and a mathematical model, an inverse problem is solved to generate an image of the property of the object. Karol Mayer was the first who suggested the idea of tomography in 1914 **?**. Using this idea, Bocage, Grossman, and Vallebona built equipment **?**. In 1931, Ziedses des Plantes conducted a thorough study and published comprehensive results on tomography **?**. However, it was in 1972 that Sir Godfrey Hounsfield developed and commercialized the first axial computer tomography. The invention of the computer tomographic (CT) scanner, which reconstructs a 3-D image of body parts from 2-D projections of the x-rays **?**. A probing beam, either x-ray or light, can be used to interrogate the object. The interaction of the probe beam with the object and its propagation through the object is modeled by appropriate equations, which help one estimate the projections onto a lower dimensional space, of this object. The instrument used to measure the projections is known as a "tomograph" and the reconstructed image is called a "tomogram". Computed tomography is known to be the most impacting innovation in the field of medical radiology after the discovery of X-rays. The model used in CT for x-ray propagation through the body is the integral form of Beer's law, which has a closed-form solution for the x-ray absorption coefficient distribution. For refraction tomography, the model is the eikonal equation of optical ray paths, for which there is no closed-form inversion formula available, and therefore iterative methods are used for reconstruction in refraction tomography.

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2 Different Medical Imaging Modalities

Depending on the nature of the probing beam, different imaging modalities are demonstrated. Tomograms are created using various physical phenomena, such as X-rays, nuclear magnetic resonance, positron-electron annihilation reactions, gamma rays, electrons, ultrasound, ions, and light. Depending upon the source and detector configuration tomography is classified into three categories, namely (1) reflection tomography, (2) transmission tomography, and (3) emission tomography. In transmission and reflection tomography source and detector are situated outside the object whereas, in the case of emission tomography, the source is inside the object. Each tomographic modality measures a different physical quantity. The concept of different imaging modalities for the cross-sectional imaging of objects is summarized in this paper. Finally, the paper focuses more on modern Diffuse Optical Tomography and functional near-infrared spectroscopy(fNIRS) imaging for various advantages.

2.1 Ultrasound Imaging

Ultrasound imaging, commonly known as sonography involves the use of a small probe containing ultrasound transducers and gel to interface the body with the probe for the high-frequency sound wave propagation **?**. Ultrasound imaging was developed from the principles of SONAR (which in turn is derived from nature, the principle which bats use to track objects). Ultrasound falls under reflection tomography. Ultrasound for medical purposes originated from the work of physicists researching sound wave energy. The pioneering work of Wild and Reid in 1950 led to the use of ultrasound in medical imaging **?**.

In an ultrasound scanning, a transducer is placed on the skin on top of the region of interest. The transducer emits high-frequency ultrasound waves and waves that are reflected back from the internal body structures are measured using the same probe. When the sound waves enter the body and reach the tissue boundaries, for example, fluid-soft tissue, soft tissue-bone. Some of the sound waves return back to the probe after a reflection at a boundary and some travel further and reach another boundary for another reflection. The returning sound waves, or echoes, are displayed as an image on a monitor forming a two-dimensional image. The images can be reconstructed based on the change in frequency and strength of the reflected sound signal, and also the time of flight. Ultrasound imaging has been widely used for over 30 years and has an excellent safety record. Ultrasound is a non-ionizing radiation, and hence it poses no risk unlike x-rays radiation or other ionizing imaging modalities. Ultrasound imaging serves as a simple, fast, and inexpensive medical imaging modality for imaging soft tissues such as objects of interest in obstetrics.

Figure 1: Ultrasound image of a fetus.

2.2 Electrical Impedance Tomography

Electrical impedance tomography (EIT) is a non-invasive imaging method used for reconstructing conductivity and/or permittivity distribution in tissues. The EIT can image the physiological changes by imaging the electrical impedance properties of tissue due to those changes. The working principle of EIT is that injecting a constant current across a body, and measuring the voltage distribution on the surface of the body will probe the internal impedance distribution. So, EIT utilizes low-frequency currents to image the body. Adhesive electrodes are placed on the skin and a few milliamperes of alternating electric current (frequency of 5-120 kHz) is applied between electrodes **?**. The voltage across a few electrodes is also measured. The recorded voltages are then sent to a computer to mathematically reconstruct EIT images and display the images. The inventor of the EIT medical imaging method is John G. Webster **?** and the work publish in a paper in 1978. However, the first practical application of EIT for medical imaging was presented in 1984 by David C. Barber and Brian H. Brown **?**. EIT has some advantages for medical applications, for example, it can be

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used to monitor the functionality of lungs, detection of skin cancer and breast cancer, hyperthermia monitoring, and imaging of brain activity.

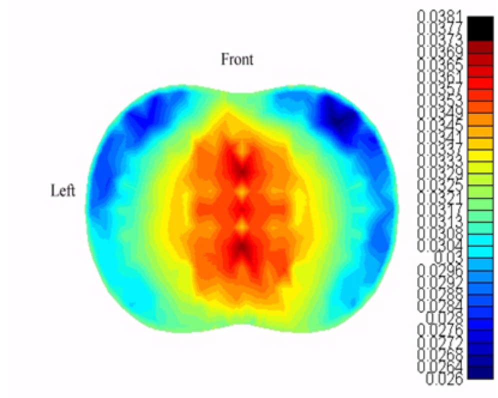

Figure 2: A time-averaged cross sectional EIT image of a human chest.

2.3 Computed Tomography

Computed Tomography (CT) can non-destructively produce 2-D cross-sectional images and 3-D volumetric images of a body from X-ray images. It is the implementation of the principle proposed by Johann Radon in 1917. According to this principle, the image of a 3-dimensional body can be reconstructed from 2-dimensional projections of the body (with a finite number of projections) **?**. The first CT scanner came to light in 1972 and was patented by Godfrey N. Hounsfield **?**. The imaging object is kept on a rotating stage and between a radiation source and detectors of the imaging system. The rotating stage and the detectors are controlled by a computer to correlate the collected x-ray images to the position of the object. The imaging system gives a 2-D shadowgraph of the object similar to a radiograph. A mathematical model in the computer produces cross-sectional CT images of the object. CT creates volumetric data that can be manipulated by the windowing process. A CT scan can produce a detailed image of a body, for example, the brain, spine, chest, and abdomen. The imaging can be used to diagnose a disease, guide a surgical procedure, assist in a biopsy, locate tumors and cancer, and examine blood vessels. CT produces high-contrast images and can differentiate tissues that differ in density by less than 1%.

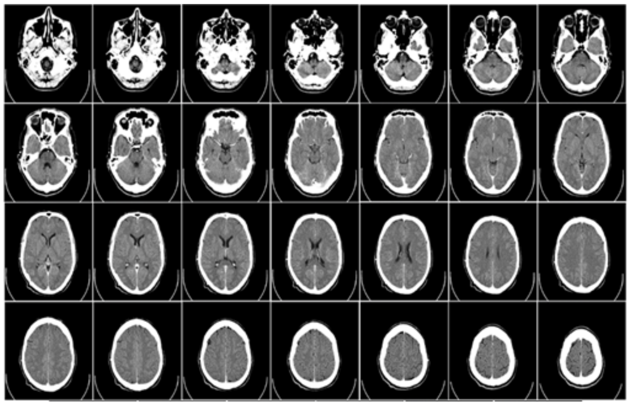

Figure 3: Computed tomography image of human brain.

2.4 Magnetic Resonance Imaging (MRI)

Magnetic Resonance Imaging (MRI) is based on the NMR (Nuclear Magnetic Resonance) principle where a powerful magnetic field is used to generate images of various elements of a body. As the human body predominantly consists of water, MRI is used to image hydrogen atoms in the body. Raymond Vahan Damadian, a physician of the Downstate Medical Center in Brooklyn, demonstrated the world's first MRI machine in 1972 **?**. This is used for tumor imaging, by

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injecting paramagnetic chemical agents, which have an affinity for tumorous tissue, into the living bodies to enhance the contrast of specific tissues. An MRI scanner accommodates a patient to lie inside a cave surrounded by a powerful magnet. The magnetic field aligns the magnetization of atomic nuclei inside the patient. A radio frequency is used to alter the magnetic fields that also alter the alignment of this magnetization of atomic nuclei inside the patient. The rotating magnetic field of the nuclei is detected by the scanner. And this information is used to produce an image of the scanning area of the patient. Due to magnetic field gradients, the nuclei at different locations have different speeds, and hence, it allows for the recovery of spatial information utilizing Fourier analysis of the recorded signal. By using magnetic field gradients in different orientations, 2D or 3D images can be reconstructed. The MRI provides superior image quality and also can provide functional information by using external contrast agents. In MRI, continuous monitoring is impossible because of the waiting time for the distribution of the chemicals in target organs as well as the need for fixed gantries and superconducting magnets to generate strong magnetic fields making instruments bulky.

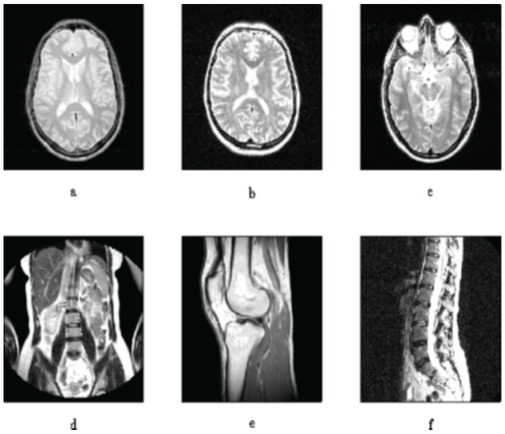

Figure 4: MRI images showing various parts of a human body demonstrating its capability to produce superior images of tissue.

2.5 Photoacoustic Tomography (PAT)

It is a non-invasive, nonionizing imaging modality based upon reconstructing the photoacoustic source spatial distribution inside the body from the measurements recorded by ultrasound detectors over a boundary surface of the body. It was Alexander Graham Bell who first reported on the photoacoustic effect in 1880. The Photoacoustic effect is the physics behind Photoacoustic imaging. It is the generation of acoustic waves due to the absorption of electromagnetic energy (EM), such as optical or radio frequency (RF) **?**. PAT combines the advantages of high ultrasonic resolution and strong optical contrast in a single modality. It can provide high-resolution functional, structural, and molecular imaging in vivo in optically scattering biological medium. The PAT can overcome the high optical photons scattering inside the biological tissue by utilizing the photoacoustic effect. In PAT, the tissue is irradiated by a short-pulsed laser beam that produces thermal and acoustic impulse responses. The absorbed light gets converted into heat locally, which in turn rise the pressure via thermoelastic expansion of the local irradiated tissue. The pressure rise is dependent on the local optical energy injection and absorption and also the other thermal and mechanical properties of the tissue as an ultrasonic wave. The photoacoustic wave is recorded using ultrasonic transducers on the tissue surface. The recorded electric signals are further amplified and digitized, to transfer to the computer. After that, the computer software then reconstructs a PAT image. PAT imaging depends on both scattered or unscattered absorbed photons that produce photoacoustic signals by relaxing thermally.

2.6 Positron Emission Tomography (PET)

Positron Emission Tomography (PET) involves the use of an injected radioactive isotope that decays producing a positron. It falls under transmission tomography. The positron recombines almost immediately with a nearby electron in the surrounding medium, producing two photons that travel in opposite directions with equal momentum **?**. The PET system detects pairs of gamma rays that are emitted indirectly by a positron-emitting radionuclide, known as a tracer. The tracer is injected into the body prior to imaging. Radioactive molecules are made from radioactive isotopes and have short half-lives such as 11C, 15O, or 13N. These molecules can be injected into the body and they release positrons due to radioactive decay. The two gamma photons are simultaneously detected by a ring of detectors (scintillator crystal and photomultiplier tube) and used for tomographic Imaging. The three-dimensional concentration distribution of the

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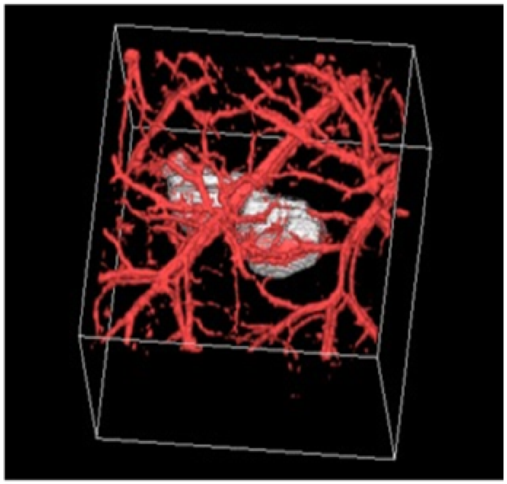

Figure 5: Photoacoustic image of skin cancer.

tracer within the body is then constructed in a computer. The PET can be used to image brain function, diagnose cancer, heart problems, and brain disorders, or the progress of cancer and spreading, and visualize the blood volume and flow into the heart. This method is expensive due to the short half-life of Isotope preparation and bulky cyclotron and hence cannot be used at the bedside.

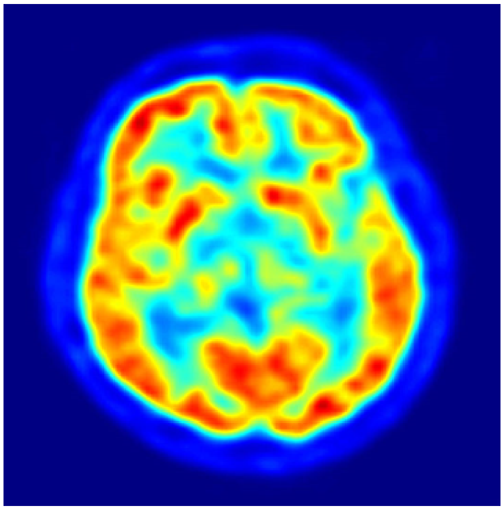

Figure 6: PET scan of human brain.

2.7 Diffuse Optical Tomography

Diffuse optical tomography (DOT) is an imaging modality that uses light to image internal structural maps and functional information of tissue **???**. It uses a model-based image reconstruction method and is also capable of providing hemoglobin concentration, water concentration, and lipid concentration inside the tissue. The fundamental principle of DOT is that it measures the Near-infrared (NIR) light transmitted or reflected from the deep tissue to probe the optical properties of the imaging tissues. Multiplexing techniques are used for high-speed light and detector switching and to acquire data **?** and hardware calibration is done to correct errors in the system **?**. From the spatial measurement data on the skin surface, the optical properties distribution can be reconstructed in optical tomographic images. The mathematical model of retrieval of the spatial distribution of tissue from the measured data at the tissue boundary is known as the inverse problem. In DOT tissue is irradiated with harmless NIR light one at a location and scattered light at the boundary is measured with a few detectors, and then an image reconstruction model is used to form images localizing the optical properties of the tissue. Most importantly, DOT can provide functional images of the tissue as the light absorption by the tissue constituents are wavelength dependent, and using more than one wavelengths light source in the nonionizing NIR range (600-1000 nm) **??** the concentration changes of the constituents can be measured. Specifically, brain and breast imaging are the applications of DOT. The challenge is in the estimation of internal optical properties of tissue using a few measurements on the tissue boundary **??**. Due to highly scattering of NIR light inside the tissue, the estimation problem (inverse problem) is nonlinear, ill-posed, and sometimes underdetermined **?**.

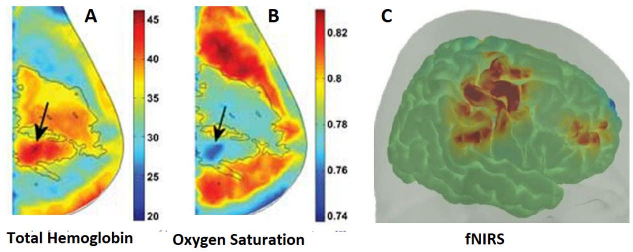

Figure 7: (A-B) Diffuse Optical Tomography measuring hemoglobin concentration of breast, and (C) functional near-infrared spectroscopy.

However, there are algorithms developed for high-speed 3D DOT image reconstruction **?**. Some utilization were on GPU and multiple GPUs for even faster image reconstruction **?**. Real-time imaging of DOT is also attempted **?**. Method for scanning a particular region of the tissue for high-speed tissue screening was proposed **??**. The DOT instruments are bulky and slow. There are efforts by researchers to reduce the instrument cost by implementing LEDs and photodetectors **?**. It was also shown that DOT can be used as a point-of-care imaging system **???**. Some of the systems are developed for educational purposes **?**. While collecting data the noise from the superficial layer of the tissue is often added to the signal of interest (signal from deep tissue). An empirical method-based superficial noise reduction technique for DOT was demonstrated **?**.

Another simplified imaging method based on DOT is functional near-infrared spectroscopy (fNIRS) where instead of fully tomographic image reconstruction channel wise measurements are observed. fNIRS is widely used for brain imaging, for example, to measure mental workload **?**. fNIRS system can be built with limited hardware. fNIRS patch for brain imaging was also demonstrated **??**. The light sources and detectors are called optodes and the signal quality depends on the optode design **?**. Portable fNIRS systems are also widely studied **?**. New technologies such as internet-of-things bases architecture were also implemented in fNIRS system development **???**. In addition, machine learning applied on fNIRS can allow for automatic classification of the brain function in real-time **??**. The applications of fNIRS for brain imaging are still in the early stage and the research in this field is growing and have great future potential.

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