Photoacoustic Imaging in Biomedicine

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Introduction

Photoacoustic imaging (PA Imaging) is the basic idea of imaging by measuring the amount of electromagnetic energy or light that is absorbed by the target. It's typically used in imaging organs or small animals. [2]. Photoacoustic imaging is possible due to the findings by Alexander Gram Bell, who in 1880, showed that when a beam of high intensity light comes in contact with something it emits sounds (~5% of it is converted). Therefore, Photoacoustic imaging is often coupled with a laser source (532nm wavelength) and an ultrasonic device. The thermodynamics of this process follow a simple algorithm. When matter is exposed to high frequency pulses of light, most of the light's energy will be absorbed by the molecules in the incident matter. As the energy from the light is converted to heat, the molecules become thermally excited. Heat waves then radiate away from the matter producing sound waves due to pressure variations in the environment around the medium—this is the motivation behind computed tomography. These sound waves can then be detected by acoustic devices such as ultrasound. [3]. Currently the biggest applications for Photoacoustic imaging include depth profiling in layered media, scanning tomography with focused ultrasonic transducers, image forming with acoustic lenses, and computed tomography. These applications are discussed in depth in this paper.

Paper Selection

This project uses the principle of the Photoacoustic effect to revolutionize Laparoscopic Partial Nephrectomy surgical procedures. It is therefore important that the

project group be familiar with not only the basis of Photoacoustic imaging, but also all modern techniques and applications associated with PA imaging. This paper is a review of all modern theoretical and quantitative approaches of PA imaging. It provides a thorough introduction to the quantitative approaches of Computer Tomography—most common area of application of PA imaging. Finally, this paper is an excellent review article on the current state of the PA imaging field including promising biomedical applications (breast cancer and small animal imaging) and recent experiments. This paper was used as the primary source for the groups' understanding of the PA effect and its corresponding imaging techniques.

Summary

Non-ionizing waves (lasers, rf, etc) are often used to excite MHz sound waves (PA signals) in biological tissues. The motivation behind PA imaging is to couple ultrasonic resolution with high contrast light due to a laser source, or rf, absorption. Current optical imaging technologies can only provide a maximum spatial resolution of ~1cm; PA imaging overcomes this and can provide resolution of ~0.1mm. Xu and Wang provide significant background information on the optical properties of tissues, as these properties are the primary reason that PA imaging is possible. Optical properties include absorption and scattering. Scattering details architectural changes at the cellular/sub-cellular levels of the tissue. Absorption properties can be used to quantify angiogenesis and hypermetabolism ("hallmarks of cancer"). These optical properties can be used to determine light propagation in tissues by performing a Monte Carlo Simulation. PA imaging has a greater spatial resolution because ultrasound scattering is 2-3 orders of magnitude greater than optical scattering. As a result PA imaging that relies on optical properties can be used to deduce physiological parameters (such as O_2 levels, concentration of hemoglobin, etc); this

can be used to quantitatively identify angiogenesis and hypermetabolism, hence functioning as an early indicator for cancer.

An important application of PA imaging involve laser based microscopic imaging. A laser system can generate pulses of 10ns durations. These are small enough to excite PA signals at high frequencies (100 MHz). Therefore PA images can be obtained in large soft-tissue areas with good SNR. Average laser-based PA scanning tomography can produce images with axial resolutions of 30μm. This is used quite often in procedures involving imaging early stages of squamous-cell carcinoma in the oral mucous of golden hamsters *in vivo.*

More than 90% of papers that exist on PA imaging are on computational approaches and algorithms for tomography (PA Tomography). Tomography is the basic idea of imaging by sections or layers of the entire image. The weighted sum of all of these sections provides the full reconstruction. The emphasis is on reconstruction-based PAT, this is so because its more flexible in dealing with PA signal because you don't have fixed lenses or transducers with limited (and fixed) imaging regions. It's also easier to obtain temporal measurements by measuring the PA signal at various detection positions. It can help to easily obtain a complete 3D reconstruction by combining these temporal and 2D spatial measurements. The Inverse Source Problem is the primary motivator of PAT reconstruction. The partial differential equation to model this phenomenon is given in equation (4) of [1]. Let H(r,t) be the heat source, and p(r,t) be the pressure at position r; this obeys a linear wave equation. The key to the PAT reconstruction is the difference between the initial source pressure Po(r) and the measured data Pd(r, t)—this is the same pressure gradient which is crated when the laser if fired at the incident matter. This can be solved by using the free-space Green's function.

The algorithms discussed in detail in this paper include the Radon Transform; also knows as the "Energy Deposition Function" – it provides a "decent" reconstruction of an object located near the center of spherical detection geometry. The main idea is to represent projections on the detector as integrals over spherical shell geometry. It fails when the source is not located near the center of the spherical geometry (often the case). Xu and Wang borrowed mathematical techniques from ultrasonic reflectivity imaging to derive the Fourier domain representation for the spherical geometry. This was done because it is often too difficult to solve these problems analytically in the time domain.

Breast Cancer is the leading cause of death among women all around the world. X-Ray mammography is still the Gold Standard for cancer detection, though it may miss up to 20% of existing lesions. Additionally, it provides a number of false positives. PAT has several advantages over X-Ray, these include: Nonionizing radiation is not harmful to humans (unlike x-ray mammography), its better at early cancer detection b/c light absorption is very sensitive to tissue abnormality. It's able to provide sub millimeter spatial resolution. No breast compression is necessary (compression is painful). Coupled with a US detection array it can be applied *in vivo* for real-time imaging. The propagation speed needed for human tissue is perfectly right. PA signals are excited internally through EM absorption so only one way propagation of waves (rather than round-trip pulse echo methods of ultrasound imaging). Used to image animal or human organs where angiogenesis networks, blood vessels, and blood perfusion can be measured. Finally, it is much cheaper.

Criticisms

This is an excellent review paper on the current state of PA imaging as well as its application to computed tomography. There are however, a few shortcomings to this paper.

The paper does a good job at citing the clinical relevance of PA imaging and its current use in breast cancer. However, it doesn't really provide any clinically relevant data or experiments that have been done in a large scale clinical trial. Though, it is important that the computational techniques of computer tomography be discussed in detail, that's one of the only things that the paper does indeed discuss. The paper highlights the fact that no real clinical trials have been done employing PA imaging, therefore, though the techniques work in theory, they may not be viable in a large scale clinical scenario (which is what PA imaging is trying to do). Finally, though the authors provide significant detail in the mathematics used, it would seem trivial that the math be done anylitically. It would seem a much simpler task to perform the calculations numerically. The paper gets away by passing this off as a theoretical approach to computed tomography, "computed" tomography implies the use of computers to numerically solve problems. It would be useful if the authors cite specific mathematical packages—such as MATLAB, or Mathematica—used primarily in the field of computed tomography. The next major step from this paper would be full scale employment of PA imaging in a large clinical trial. The theory, in practice, is good, but it's impossible to tell, as of current, its potency in a clinical setting.

References

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