

MODERN MEDICAL IMAGING AND IMAGE-GUIDED THERAPY

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Abstract: The paper is all about the recent advances in 4-D medical imaging (4DMI) and 4-D radiation therapy (4DRT), which study, characterize, and minimize patient motion during the processes of imaging and radiotherapy. The development of ultrasound contrast agents, containing encapsulated microbubbles, which has increased the possibilities for diagnostic imaging. Terahertz pulse medical imaging (TPI), an alternative to x-ray and, non-invasive technique to obtain quantitative and highly sensitive measurements of burn depth using terahertz tomography. Intensity modulated radiation therapy (IMRT) using computer-generated 3-D images of CT scans. Image-guided therapy- chemoembolization, Minimal-invasive procedures guided by fluoroscopy, CT, ultrasound and MRI have virtually replaced open surgical biopsy for bone and other tumours. Robotic technology is enhancing surgery by image-guided procedures. Phantoms are important tools for verifying simulated data, planning radionuclide treatments, and demonstrating the quality of imaging instruments.

Keywords: Microbubbles, Chemoembolization, Minimal-invasive, terahertz pulse imaging, phantoms

1. INTRODUCTION

1.1 The major discoveries in the last decade of nineteenth century revolutionized medical imaging and therapy. They were the discovery of x-ray and radioactivity in 1896 by Roentgen and Becquerel respectively. Until 1896 no means existed to examine or measure the hidden internal world of the living human body. Roentgen's discovery of the penetrating X-ray started a revolution in medical imaging. Specialized X-ray diagnostic and therapeutic methods developed throughout the century and, up until about 1960, X-ray methods completely dominated non-invasive medical diagnosis [1]. In some areas, such as mammography, X-rays provide the gold standard for the early detection of breast cancer. Dentistry relies almost entirely on X-rays. X-rays were also used for therapy and the first curing of cancer had been claimed.

1.2 Due to limitations of the traditional x-ray second revolution in imaging began in 1972 with Hounsfield's announcement of a practical computer-assisted X-ray tomographic scanner, the CAT scanner, which is now called X-ray CT or simply CT. This was actually the first radical change in the medical use of X-rays since Roentgen's discovery. One important motivation for the development of CT was the location of tumours and stroke damage within the brain [1]. The high level of X-ray absorption by the surrounding skull generally made this task very difficult for the projection radiograph. CT has some important drawbacks: it entails a relatively large dose of ionizing radiation to the patient and there are practical limits on spatial resolution brought about by the very small differences

in X-ray contrast between different types of soft tissue.

1.3 MRI is a wholly tomographic technique, just like X-ray CT, but it has no associated ionizing radiation hazard. It provides a wider range of contrast mechanisms than X-rays and very much better spatial resolution in many applications.

1.4 All of nuclear medicine, including diagnostic gamma imaging, became a practical possibility in 1942 with Fermi's first successful operation of a uranium fission chain reaction. Ansell and Rotblat obtained the first point-by-point image of a thyroid gland in 1948. Wren reported the first measurements of positron annihilation as early as 1951 and crude scanning arrangements for imaging were described by Brownell and Sweet in 1953[1].

1.5 Application to foetal imaging began in 1961 shortly after the introduction of the first commercial two-dimensional imaging system-ultrasound. Today, ultrasound imaging is second only to the use of X-rays in its frequency of clinical use.

1.6 Tomographic, SPECT gamma images, obtained by translations or rotations of a gamma camera, were first reported in 1963 by Kuhl and Edwards [9].

2. MODERN IMAGING TECHNIQUES

2.1 The evolving dimension from single projection 2-D image to 4-D images and now the 5-D images in medical imaging has enhanced the volumetric imaging techniques. Patient motion is inevitably present during imaging, producing artifacts and uncertainties in target (lesion) identification, delineation, and localization. 4DMI includes time-resolved volumetric CT, MRI,

PET, PET/CT, SPECT, and US imaging. To enhance the performance of these volumetric imaging techniques, parallel multi-detector array has been employed for acquiring image projections and the volumetric image reconstruction has been advanced from the 2-D to the 3-D tomography paradigm.

2.2 The time information required for motion characterization in 4D imaging can be obtained either prospectively or retrospectively using respiratory gating or motion tracking techniques [15]. The former acquires snapshot projections for reconstructing a motion-free image. The latter acquires image projections continuously with an associated timestamp indicating respiratory phases using external surrogates and sorts these projections into bins that represent different respiratory phases prior to reconstructing the cyclical series of 3D images. These methodologies generally work for all imaging modalities with variations in detailed implementation.

2.3 In 4-D CT imaging, both multi-slice CT (MSCT) and cone-beam CT (CBCT) are applicable in 4-D imaging. In 4-D MR imaging, parallel imaging with multi-coil-detectors has made 4D volumetric MRI possible. In 4-D PET and SPECT, rigid and non-rigid motions can be corrected with aid of rigid and deformable registration, respectively, without suffering from low statistics due to signal binning. In 4-D PET/CT and SPECT/CT, a single set of 4-D images can be utilized for motion-free image creation, intrinsic registration, and attenuation correction. In 4-D US, volumetric ultrasonography can be employed to monitor fetal heart beating with relatively high temporal resolution [16].

2.4 4-D Radiation Therapy aims to track and compensate for target motion during radiation treatment, minimizing normal tissue injury, especially critical structures adjacent to the target, and/or maximizing radiation dose to the target. 4DRT requires 4-DMI, 4-D radiation treatment planning (4-D RTP), and 4-D radiation treatment delivery (4-D RTD). Many concepts in 4-DRT are borrowed, adapted and extended from existing image-guided radiation therapy (IGRT) and adaptive radiation therapy (ART) [15].

3. TERAHERTZ MEDICAL IMAGING

3.1 Many living tissues emit terahertz waves, each having its own frequency pattern as a kind of “fingerprint” permitting them to be imaged, identified & analyzed. The application of terahertz images in medical diagnosis came to life when European space agency (ESA) captured first terahertz picture of a human hand in September 2002. The research in terahertz radiation is almost 15 years old and includes waves between 100 GHz to 100 THz. The first imaging

device based on terahertz imaging was introduced by Hu and Nuss [9].

3.2 Recently, a new imaging technique has been developed based on pulses of THz radiation generated and detected using photoconductive or electro optical effects with visible pulses (fs-ps) from Ti: Sapphire lasers. This technique commonly referred to as T-Ray Imaging or THz Pulse Imaging (TPI) holds enormous promise for a wide variety of applications. One area of potentially great significance is the application of TPI to medical imaging, as the potential ability of TPI to distinguish between certain types of healthy and abnormal soft tissue. Its penetration depth for various tissue types, as well as its ability to distinguish between different tissue types, has dictated the utility of THz in medical investigations. The ultimate goal of TPI is to provide high quality images that contain diagnostic information not readily available with other techniques. TPI provides such information for certain medical applications where it might have distinct advantages over X-Ray, MRI, and ultrasound because of a) its possible diagnostic capabilities arising from the spectral information available at each pixel in the image, and also due to b) the multiplicity of contrast mechanisms available in TPI.

3.3 The main targets of TPI medical imaging are epithelial diseases that several advanced imaging modalities are also competing to diagnose. Basal cell carcinoma (BCC) is most common form of skin cancer that arises in the deepest layer of epidermis and is diagnosed by biopsy & the most effective treatment is Mohs Micrographic Surgery (MMS). In this surgical treatment samples of skin are cut out. This process is repeated until no cancer is found in the skin sample. TPI is a promising technique to assess the size and depth of invading tumor prior surgery. The ability to assess the direction of sub-clinical spread and define the histological subtype of the tumour pre-operatively, may simplify MMS to a single layer excision, saving time, money and patient discomfort. The study of BCC using terahertz pulse imaging (TPI) has helped identify its potential as a pre-operative tool for MMS [14].

3.3 Terahertz frequencies have great potential in medical imaging because they are strongly absorbed by large biological molecules & by water [2]. A technique such as terahertz tomography is of great interest in a wide range of applications. While the strong water absorption precludes the use of terahertz radiation in most biomedical research areas, those which are particularly concerned with surface (e.g., dermatological, corneal, etc.) issues may find the unique properties of these sub-millimeter waves to be of interest [3]. In particular, it may be possible to obtain quantitative and highly sensitive measurements of burn

depth using terahertz tomography. The noncontact measurement of burn depths and severities using photonics is a topic of considerable interest. In 2-D THz imaging images are taken using transmission & reflection geometry. These wavelengths offer potential for medical application because they are non-ionizing as an alternate to x-ray.

4. IMAGE- GUIDED CLINICAL APPLICATION IN THERAPY

4.1 For the past decades ultrasound has been an imaging modality with multiple applications. Ongoing developments improved diagnostic possibility remarkably whereas ultrasound also became of interest as a therapeutic tool in interventional cardiology e.g. for intravascular sonotherapy of coronary arteries and non-invasively for induction of thrombolysis.

4.2 US diagnostic imaging with contrast agents uses acoustic pressure higher than 0.05 mechanical index, and the harmonic imaging modality, which improves signal-noise ratio by transmitting a fundamental frequency and receiving multiples of this frequency [6]. This creates an acoustic impedance mismatch between body tissue and fluids containing microbubbles and makes them useful in diagnostic ultrasound imaging. Microbubbles are small gas-filled microspheres that have specific acoustic properties that make them useful as a contrast agent in ultrasound imaging. . Enhancement of thrombolysis by ultrasound is a promising technique and microbubbles are an interesting option in treatment of cardiovascular disease; however, the bio-effects of low-frequency ultrasound with high power and the safety of these techniques in humans need further investigation [7].

4.3 Using computer-generated 3-D images from dozens of CT scans, intensity modulated radiation therapy, or IMRT, maps the tumor precisely, bombards it with high-intensity radiation. At the same time, IMRT radiation skirts organs and other healthy tissue, thereby shielding them from radiation exposure.

4.4 Image-guided surgery also known as computer-assisted surgery, surgical navigation, 3-D computer surgery is computer based procedure that uses 3-D imaging real time sensing in the planning, execution and follow-up of surgical procedures. Similarly robotic surgery requires imaging to diagnose and perform operation. Out of various imaging modalities CT & MRI images guide the robot to implement the navigation step [9].

5. MODERN APPLICATION IN MEDICAL IMAGING AND THERAPY

5.1 MRI accurately stage, and help surgeons plan sphincter-sparing surgery in patients with rectal cancer.

MRI has been increasingly accepted by radiologists, surgeons and patients to image the rectum because of its superior soft tissue contrast and multi-planar capability. Non-invasive magnetic resonance imaging (MRI) is a good diagnostic tool for the evaluation and staging of testicular cancer and may improve patient care [9].

5.2 Under the guidance of MRI or ultrasound, physicians can place radioactive "seeds" – about the size of grains of rice – inside the prostate where the seeds can deliver the radiation dose directly to the cancerous tissue [9]. Minimally invasive procedure, called brachytherapy, results in lower complication rates, including chronic side effects such as urinary incontinence and impotence. Medical imaging takes cancer-killing agents directly to the diseased tissue, even if it lies deep within the body. The results are improved treatment, fewer complications, and – in many cases – longer life.

5.3 Liver-cancer patients are living longer than they used to because of an image-guided therapy called chemoembolization [10]. Under the guidance of X-ray angiography, physicians insert a catheter through the patient's arteries to the liver and inject a high-dose of chemotherapy into the cancerous tissue. Next, the catheter releases an embolizing material that closes the blood vessels that feed the tumor. The result is the chemotherapy is trapped inside the tumor, and the tumor dies.

5.4 Only a few years ago, patients with suspected cancerous tumors had to undergo exploratory surgery-with long hospital stays and recuperation time. Today, the medical imaging, minimally-invasive procedures guided by fluoroscopy, CT, ultrasound, and MRI have virtually replaced open surgical biopsy for bone and other tumors [11]. Studies reported that image-guided percutaneous biopsy of bone tumors creates new efficiencies while fostering less invasive care [12]. Among them are shorter procedure time, fewer infections, fewer complications, and earlier wound healing.

5.5 Conventional invasive coronary angiography constitutes the clinical gold standard for detection of coronary artery stenoses [5]. However, the risk of potentially serious adverse effects and the associated costs have led to an intensive search for non-invasive alternative. It has been recently shown that multi-detector CT (MDCT) in combination with retrospective ECG gating permits visualization of the coronary artery lumen and detection of coronary artery stenoses. Although multi-detector CT (MDCT) with retrospectively ECG- gated image reconstruction has been shown to permit invasive visualization of coronary arteries [5].

5.6 The designing of the new medical contrast agents permit multiple imaging & therapy applications using a single agent. This provides concurrent contrast imaging for multiple modalities with complementary spatial, temporal & depth resolution for more accurate diagnosis. Nanoparticles-incorporated microbubbles act as multifunctional contrast agents for medical imaging and therapy [8].

5.7 In medical imaging and therapy, phantoms are important tools for verifying simulated data, planning radionuclide treatments, and demonstrating the quality of imaging instruments. Small-animal imaging is rapidly becoming an essential tool for preclinical development of new compounds for imaging and therapy [4]. Although imaging performance evaluations and regular quality control are both important, surprisingly, there are relatively a few appropriate phantoms available for such procedures. Imaging phantoms have played important role in evaluating the performance of larger systems. It is believed that micro-phantoms should be equally important accessories for all serious preclinical imaging research facilities that utilize these modalities. Recently developed high-resolution nuclear medicine imaging systems [e.g., micro single photon emission computed tomography (μ SPECT), micro positron emission tomography (μ PET)] require small phantoms with structures having dimensions of less than a millimeter [4]. Phantoms for nuclear medicine imaging also generally have fillable compartments, which are more challenging to make when the size is small. Several mouse-size phantoms are commercially available. However, many μ SPECT and μ PET systems have unique properties that may require custom-designed phantoms with small structures.

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