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In vitro comparative study of vibro-acoustography versus pulse-echo ultrasound in imaging permanent prostate brachytherapy seeds

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ABSTRACT

Background: Permanent prostate brachytherapy (PPB) is a common treatment for early stage prostate cancer. While the modern approach using trans-rectal ultrasound guidance has demonstrated excellent outcome, the efficacy of PPB depends on achieving complete radiation dose coverage of the prostate by obtaining a proper radiation source (seed) distribution. Currently, brachytherapy seed placement is guided by trans-rectal ultrasound imaging and fluoroscopy. A significant percentage of seeds are not detected by trans-rectal ultrasound because certain seed orientations are invisible making accurate intra-operative feedback of radiation dosimetry very difficult, if not impossible. Therefore, intra-operative correction of suboptimal seed distributions cannot easily be done with current methods. Vibro-acoustography (VA) is an imaging modality that is capable of imaging solids at any orientation, and the resulting images are speckle free.
Objective and methods: The purpose of this study is to compare the capabilities of VA and pulse-echo ultrasound in imaging PPB seeds at various angles and show the sensitivity of detection to seed orientation. In the VA experiment, two intersecting ultrasound beams driven at f_1 = 3.00 MHz and f_2 = 3.020 MHz respectively were focused on the seeds attached to a latex membrane while the amplitude of the acoustic emission produced at the difference frequency 20 kHz was detected by a low frequency hydrophone.
Results: Finite element simulations and results of experiments conducted under well-controlled conditions in a water tank on a series of seeds indicate that the seeds can be detected at any orientation with VA, whereas pulse-echo ultrasound is very sensitive to the seed orientation.
Conclusion: It is concluded that vibro-acoustography is superior to pulse-echo ultrasound for detection of PPB seeds.

1. Introduction

Transperineal interstitial permanent prostate brachytherapy (TIPPB) provides an improved alternative for minimally invasive treatment of early stage prostate cancer [1]. Prostate cancer alone accounts for about 29% of incident cancer cases in men in the US [2], while it is estimated that 16% of these patients underwent treatment with this modality. Published guidelines by the American Brachytherapy Society (ABS) [3] elucidate the need for methods of real-time determination of seed location that would permit real-time intra-operative radiation dosimetry. Although progress is being made in this area [4], no means are widely available at present which allow accurate intra-operative radiation dosimetry, but clinicians often use a combination of intra-operative trans-rectal ultrasound (TRUS) [5] and fluoroscopy [6] to aid in imaging seed placement and for qualitative assessment of the seed distribution. In current prostate brachytherapy, seed location is typically verified using computed tomography (CT) which enables determination of the three-dimensional distribution of seed locations with respect to the prostate and adjacent structures. However, post-implant CT scanning leads to potential inaccuracies because the prostate is not necessarily in the identical position as during the seed implantation process. In addition, the prostate boundary is poorly shown in CT and dosimetric evaluation is not uniformly reproducible [7–9].

Over 100 seeds containing radiation sources (I-125 or Pa-103) are implanted by needles through the perineum in and around the prostate. The brachytherapy capsules are hollow titanium cylindrical shells with a diameter of 0.8 mm, a length of 4.5 mm, and a wall thickness of 0.05 mm. The end of the cylindrical shells are usually hemispherical. Seeds based on I-125 most often contain a loose silver wire impregnated with iodine. During implantation, a metallic frame is used for precise parallel alignment and

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positioning of the ultrasound transducer and the implantation needles with respect to each other. The seeds are implanted with their axis oriented along the patient's body axis. However, accurate seed location is hampered by deformation and swelling of the prostate caused by inserting the needles. As a result, the seeds frequently become oriented in a non-parallel manner with respect to one another and the trans-rectal ultrasound (TRUS) probe. It is therefore difficult to visualize the seeds once released from the needle because ultrasound beams are reflected specularly and backscattered wave motion cannot reach the ultrasound probe unless the incidence happens to be normal [10].

An improvement in the seeds ability to scatter ultrasound back towards the imaging transducer at a wider angular range is obtained by using the EchoSeed™ (Amersham Health, Inc., Arlington Heights, IL) which have a corrugated surface. However, reduction in the backscatter signal from these seeds still occurs as the incident angles increases away from normal incidence [10]. In addition to that, speckles caused by the multiple interference of ultrasound energy from randomly distributed scatterers within tissue degrade the contrast resolution in ultrasound images and thereby makes it hard to detect small targets such as seeds when implanted in the prostate. Limitations with TRUS justify the development of a new imaging modality suitable for seed detection. Ideally, such a method would be (a) insensitive to seed orientation, (b) speckle free and (c) applicable to the intra-operative setting.

The purpose of the present study is to examine seed imaging as a function of seed orientation using an innovative ultrasound-based imaging method known as vibro-acoustography (VA) [11–13], which is based on the dynamic radiation force of ultrasound [14]. In this method, two intersecting ultrasound beams driven at slightly different frequencies are focused on or inside the object to be imaged, producing a localized tapping radiation force oscillating at the difference frequency of the incident ultrasound beams. Radiation force causes vibration at the arbitrary low-frequency and produces an acoustic emission field which is detected by a hydrophone. The image is formed by displaying the amplitude of the acoustic field at a position corresponding to the excitation point on the object. Unlike the conventional ultrasound pulse-echo imaging method, VA does not rely on the reflection of ultrasound; hence, it is not critically sensitive to object orientation. VA is particularly sensitive to tissue stiffness which makes it reliable in detecting solid inclusions such as seeds. Because VA images are based on the low- frequency sound emitted from the object, the resulting images have high contrast resolution. Finally, VA can be conducted intra-operatively, in a manner similar to conventional ultrasound imaging systems. It is notable that VA satisfies all the required criteria of an ideal imaging tool for detection of brachytherapy seeds.

In the medical field, VA has been successfully used for imaging small particles such as calcium deposits on heart valve leaflets [15], microcalcifications in breast tissue [16–19], calcifications in arteries [11,20], excised human cancerous liver tissue [21], and standard brachytherapy seeds in gel phantoms [22].

The goal of this paper is to compare the capabilities of VA and Pulse-echo ultrasound in imaging PPB seeds. For this purpose, we image a set of PPB seeds at various orientations by two methods: pulse-echo ultrasound (PE-U) and VA. Three seed types, namely OncoSeed™ (standard), EchoSeed™ (echogenic), and RAPID Strand™ (RS) are used. Particularly, it is shown here how the angle of incidence affects the VA technique's sensitivity in detecting the seeds. These experiments are conducted in a water tank under well-controlled conditions. Then a comparison between VA and PE-U (in a C-scan format) results is performed in order to assess the advantages and disadvantages of each method. These results may be useful for evaluation of VA-based real-time intraoperative dosimetry strategies and for the design of VA probes specifically for brachytherapy applications.

2. Method and materials

2.1. Vibro-acoustography (VA)

In previous publications, VA was presented as a technique based on the modulated radiation pressure (MRP) of ultrasound waves [11,12]. Two intersecting ultrasound beams slightly shifted in frequency and focused at the same point in space produce a dynamic radiation force (or stress in 3D) on or inside an object. Subsequent acoustic emission field is produced in the surrounding medium due to object harmonic vibrations at the difference frequency of the ultrasound beams. However the equations describing the acoustic emission based on the MRP approach do not include the "parametric" interaction [23,24] of the primary incident beams. In a nonlinear medium, the simultaneous propagation and mixing of two primary waves give rise to nonlinearly induced waves at sum and difference frequencies. These secondary waves are generated by the "parametric interaction" since they depend on the nonlinearity parameter $\beta = (1 + \frac{B}{2A})$, where *B/A* determines the nonlinear property of an acoustically driven medium. The objective of this paper is not to discuss the contribution of the "parametric" interaction with the MRP phenomenon, a topic that will be discussed in a forthcoming article [25]. In this work, we assume the generation of low-frequency waves (acoustic emission) is dominated by the MRP mechanism, which is consistent with the results presented herein.

2.2. Sensitivity to seed orientation of B-mode ultrasound versus VA

2.2.1. Sensitivity study on a single seed

To verify experimentally the sensitivity to seed orientation of the PE-U, an initial test was performed in which a dummy standard seed (OncoSeed, Amersham model 6711) was glued on a stretched latex rubber membrane of 50 μm thickness. The seed attached to the membrane were suspended in a water tank and filled with degassed water in an anechoic room used for making precise ultrasound measurements. The seed attached to the membrane were placed at the focus of an ultrasound transducer driven by a Panametrics 5050PR ultrasonic pulser/receiver (Panametrics, Waltham, MA) at 3 MHz. The transducer has a diameter dimension of 45 mm and focal length of 70 mm. The backscatter signal was full-wave rectified and low-pass filtered at 3 MHz before digitization with 12 bits of resolution at 10 MHz. The seed attached to the membrane were rotated with a precision optical rotation stage. At

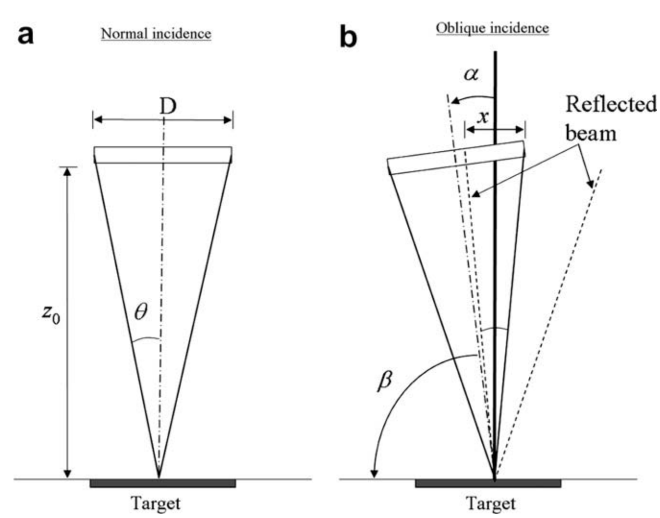

Fig. 1. Normal and oblique incidence in PE-U.