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Image Features in Medical Vibro-acoustography: In Vitro and in Vivo Results

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Abstract

Vibro-acoustography is an imaging method based on audio-frequency harmonic vibrations induced in the object by the radiation force of focused ultrasound. The purpose of this study is to investigate features of vibro-acoustography images and manifestation of various tissue structures and calcifications in such images. Our motivation for this study is to pave the way for further in vitro and in vivo applications of vibro-acoustography. Here, vibro-acoustography images of excised prostate and in vivo breast are presented and compared with images obtained with other modalities. Resulting vibro-acoustography images obtained with a 3 MHz ultrasound transducer and at a vibration frequency of 50–60 kHz show soft tissue structures, tissue borders, and microcalcifications with high contrast, high resolution, and no speckle. It is concluded that vibro-acoustography offers features that may be valuable for diagnostic purposes.

Keywords

Vibro-acoustography; radiation force; ultrasound; breast imaging; calcification

A. Introduction

Ultrasonography is one of the most common medical imaging modalities. However, there are some limitations to this method. Namely, ultrasound images suffer from a speckle artifact. As a result, small objects, such as microcalcifications are hard to detect with this method. Speckle also can reduce the sensitivity of the imaging system in detection of masses in tissue. For these and other reasons, investigators have been seeking alternative non-invasive imaging methods that can offer higher quality images as well as new information about tissue.

Vibro-acoustography is an imaging method based on the radiation force of ultrasound [1,2]. In this method, the image is formed from the acoustic response of the object to the oscillating radiation force of the amplitude modulated ultrasound. In vibro-acoustography, two intersecting continuous-wave ultrasound beams at slightly different frequencies of f_1 and f_2 =

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$f_1 + \Delta f$, where $\Delta f \ll f_1$, are used. The two ultrasound beams are focused, and they are aligned to intersect at their respective focal regions. At this intersection region, which is normally a small volume, the combined ultrasound field energy density is sinusoidally modulated at Δf , thus the field generates a highly localized oscillatory radiation force at the difference frequency when it interacts with the object. The harmonic force vibrates the object at Δf . The vibration results in a secondary acoustic field that propagates in the object. This acoustic field, which is at frequency Δf , is detected by an audio hydrophone. This signal is then filtered by a band pass filter centered at Δf to reject noise and any interfering signal. As the ultrasound beam is scanned across the object, the filtered hydrophone signal is recorded and its amplitude is mapped into an image.

To understand the interaction of two ultrasound fields at different frequencies and generation of a third acoustic field at the difference frequency, one needs to solve the nonlinear wave equation. The general theory of nonlinear wave propagation has been investigated extensively, for example see references [3] and [4]. A detailed theoretical and simulation study of wave propagation and interaction of two ultrasound beams, as it applies to vibro-acoustography, is presented in another paper in this issue [5]. Therefore, we do not elaborate on the theoretical details of wave propagation in this paper, instead refer the reader to [5].

A comparison of conventional B-mode ultrasound imaging and vibro-acoustography is illustrated in Figure 1. Ultrasound imaging is based on linear reflection or scattering of ultrasound. That is, the echo, which is used to construct the image, is at the frequency of the source ultrasound. In contrast, the secondary acoustic field that is used for making the vibro-acoustography image is at the difference frequency Δf , which is typically two order of magnitude smaller than the incident ultrasound frequency. This frequency conversion is the result of a nonlinear process that is central to vibro-acoustography methodology. The frequency conversion enriches the vibro-acoustography image with additional information not present in conventional ultrasound image.

A vibro-acoustography image contains two types of information: ultrasonic properties of the object, such as the scattering and power absorption characteristics, and the dynamic characteristics of the object at frequency Δf , which relates to tissue stiffness, boundary conditions, and coupling to the surrounding medium [6]. The former properties are those that are also present in conventional ultrasound imaging. The latter properties, which can be described in terms of object's mechanical parameters at Δf , are not available from conventional ultrasound. Another feature of vibro-acoustography relates to image speckle. Speckle is the snowy pattern seen in conventional ultrasound images. Speckle results from random interference of the scattered ultrasound field. Speckle reduces the contrast of ultrasound images and often limits detection of small structures, such as microcalcifications in tissue. Because vibro-acoustography uses the secondary acoustic field, this modality is practically speckle free, resulting in high contrast images that allow small structures to be visible. This feature makes vibro-acoustography particularly suitable for detection of breast microcalcifications.

Vibro-acoustography has been tested on various human tissues [6–14]. A comparative study of vibro-acoustography with other radiation force methods for tissue elasticity imaging is presented in [7]. The spatial resolution of vibro-acoustography is in the sub-millimeter range, making the technique suitable for high-resolution imaging [9,11].

In this paper, we present some experimental results and discuss some features of vibro-acoustography images and their potential applications.

B. Methods

We examine images of ex-vivo and in vivo human tissues acquired by three methods: x-ray, ultrasound, and vibro-acoustography. Ex-vivo tissue samples are fixed in formaldehyde before the experiments. Vibro-acoustography scans of tissue samples are conducted in a water tank. Ultrasound images of ex-vivo tissue samples are obtained by a clinical ultrasound scanner (GE Vivid 7).

The in vivo experiments are conducted on human breast. The breast imaging system consists of a stereotactic mammography (x-ray) machine combined with a vibro-acoustography scanner. This system allows us to take matching x-ray and vibro-acoustography images of the same region of breast within a 5×5 cm window. The system uses a 3 MHz transducer, which provides sufficient penetration and suitable spatial resolution of 0.7 mm for our purpose. The difference frequency Δf is set at either 50 or 60 kHz, which is suitable for most experiments. The image contrast changes with Δf for a given object, as the dynamics of the object and the acoustic environment depend on frequency. The spatial increment for raster scanning is set at 0.2 mm. To acquire an image, the patient lies in prone position on the examination bed with a breast hanging down through a hole in the bed. The breast is slightly compressed between two panels. The x-ray detector is behind the breast and the audio hydrophone for vibro-acoustography is placed in contact with the side of the breast.

Three features of vibro-acoustography images will be discussed: speckle pattern, detection of calcifications in tissue, and definition of tissue borders. The x-ray and ultrasound images will provide helpful references in discussing vibro-acoustography image features.

C. Experimental Results

Figure 2 displays images of an excised human prostate. Panel (a) in this figure is the x-ray image, which shows the general view of the prostate. The bright spot at the center is a calcification. Tissue structures are not clearly visible in this image. Panel (b) displays the ultrasound image of the same sample. This image is overwhelmed with speckle, which makes it hard to distinguish tissue structures or the calcification. Panel (c) is the vibro-acoustography images of the prostate with the ultrasound focused at the depth of 10 mm from the top surface of the sample. The vibro-acoustography image shows detailed tissue structures as well as the calcification. Comparing the vibro-acoustography and ultrasound images, it is evident that vibro-acoustography provides speckle-free and clear images of tissue, which allows one to identify tissue structures and the small (< 1 mm) calcification.

Figure 3 displays images of another excised human prostate sample. Panel (a) displays the x-ray image of this sample, which indicates the presence of a cluster of microcalcifications on the right side and two larger calcifications at the center. Panel (b) shows the vibro-acoustography image of the prostate with the ultrasound beam focused at 10 mm depth from the top surface of the sample. The speckle-free vibro-acoustography image clearly shows the cluster of micro calcifications as well as the larger calcifications. Besides, the vibro-acoustography image displays a clear border between the prostate tissue and the prostatic fat around the sample.

Figure 4 displays in vivo images of a human breast. Panel (a) displays a clinical x-ray mammography of the entire breast. The dark regions indicate that this breast contains a significant amount of fat. Panel (b) displays the vibro-acoustography image of a region in the breast. In this case the ultrasound is focused at 15 mm from the skin. The vibro-acoustography image shows detailed structures of the breast with well-defined borders. The linear structures may include ducts, vessels, and Cooper's ligaments.

Figure 5 displays an in vivo image of a human breast. Panel (a) shows x-ray mammography with an obscured mass. Panel (b) displays vibro-acoustography image of this breast, which reveals the mass as a bright region with irregular border. Biopsy results indicated infiltrating ductal carcinoma, Nottingham grade I (of III).

D. Discussion and Conclusions

The imaging method described here is a noninvasive method that utilizes ultrasound energy, but the images are constructed from a low-frequency acoustic field. Unlike conventional ultrasound images, vibro-acoustography images are speckle-free, which increases image contrast and allows detection of mass lesions and small (sub-millimeter) details, such as microcalcifications. In addition, vibro-acoustography shows tissue borders with appreciable clarity as demonstrated in the breast images. Detection of small calcifications is an important issue, especially in breast, as they may be associated with some types of cancers. Detection of tissue borders can be important in sizing mass lesions. Also, it is important to be able to see tissue borders when conducting image guided procedures in prostate. Further investigation is needed to fully explore the potentials of vibro-acoustography for clinical imaging.

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Fig. 1. Comparison between ultrasound imaging and vibro-acoustography
a) Ultrasound imaging, b) vibro-acoustography.

Fig. 2.

a) X-ray image of an excised human prostate showing a single calcification. b) Ultrasound image of the prostate sample. This image presents an excessive amount of speckle and fails to reveal the calcification c) Vibro-acoustography scan of the same tissue focused at 15 mm depth inside the sample. This speckle-free image shows the calcification at the center of prostate.

Fig. 3.

a) X-ray image of an excised human prostate. b) Vibro-acoustography scan of the same prostate at 15mm depth. This image shows a cluster as well as a single calcification as confirmed by the x-ray. c) Ultrasound image of the prostate. The ultrasound image fails to reveal the calcifications.

Fig. 4. Breast images of a normal volunteer

(a) Clinical x-ray mammography of the entire breast, (b) vibro-acoustography focused at 2 cm depth from the skin at $\Delta f = 50$ kHz.

Fig. 5. Breast images of a volunteer

- a) X-ray mammography of the breast with an obscured mass in the region pointed by the arrow.
- b) Vibro-acoustography image focused at 15 mm depth at $\Delta f=60$ kHz. This image reveals the mass. The bright area in lower portion of the image (indicated by an oval) is the excess acoustic gel below the breast and should be ignored. (The acoustic gel is used to couple the breast to the vibro-acoustography system.)