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A computer-based simulator for intravascular photoacoustic images

Sun Zheng*, Yuan Yuan, Han Duoduo

Department of Electronic and Communication Engineering, North China Electric Power University, Baoding 071003, Hebei, China

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ABSTRACT

Intravascular photoacoustic (IVPA) is a newly developed catheter-based imaging technique for the diagnosis of arterial atherosclerosis. A framework of simulating IVPA transversal images from a cross-sectional vessel model with given optical and acoustic parameters was presented. The light illumination and transportation in multi-layered wall and atherosclerotic plaque tissues were modeled through Monte Carlo (MC) simulation. The generation and transmission of photoacoustic (PA) waves in the acoustically homogeneous medium were modeled through the PA wave equation, which is solved explicitly with a finite difference time domain (FDTD) algorithm in polar coordinates. Finally, a series of cross-sectional gray-scale images displaying the distribution of the deposited optical energy were reconstructed from the time-dependent acoustic pressure series with a time-reversal based algorithm. Experimental results demonstrate a good correlation between the simulated IVPA images and the optical absorption distribution profiles. The simulator provides a powerful tool for generating IVPA image data sets, which are used to improve the imaging catheter and to test the performance of image post-processing algorithms.

1. Introduction

1.1. Backgrounds

Intravascular photoacoustic (IVPA) tomography is a newly emerged hybrid interventional imaging modality. It combines the advantages of ultrasonic and optical imaging for the diagnosis of coronary atherosclerotic diseases. With IVPA, the morphology and the function of the vessel wall and advanced atheroma are detected and measured in a minimally invasive manner within living individuals [1–3].

An imaging catheter integrating multimode fiber, optical reflection elements and miniature ultrasonic transducer is directly inserted into the target vascular lumen and pushed to the distal end. Then, it is drawn back slowly, during which a tiny probe mounted on the catheter tip emits nanosecond laser pulses in the near-infrared (NIR) ranges illuminating the surrounding tissues through the blood. Partial light energy is absorbed by the tissue absorbers and then is converted into the heat energy leading to a local thermo-elastic expansion of the tissues, which in turn causes a related rise in the local pressure. The increase in pressure subsequently becomes a propagating ultrasonic wave, i.e. photoacoustic (PA) waves, because of the elastic nature of the tissues [4]. The PA waves propagate through the tissues to the surface and are finally collected by an ultrasonic detector [5]. Gray-scale or pseudo-color coded images displaying the spatial distribution of the initial acoustic pressure or the optical deposition on each vascular cross-section are formed from the measured PA pressure time series through the inversion of the acoustic waves. The algorithms usually used to reconstruct IVPA images include filtered back-projection (FBP), time-reversal (TR) and algebraic reconstruction techniques (ART) [6,7], *etc.* Further, the spatial distribution of the optical absorption coefficient and scattering coefficient of the tissues can also be recovered from the initial acoustic pressure distribution obtaining the chemical characterization of the vessel wall components [4,8].

1.2. Progress of IVPA technique

Till now, *in vivo* and *ex vivo* IVPA imaging have been proved with the animal model of atherosclerosis [9,10]. Some important progresses have been achieved in the last decade, including thermal IVPA (*t*IVPA) [11], spectroscopic IVPA (*s*IVPA) [12,13], molecular IVPA (*m*IVPA) [14–16], and combined IVPA/IVUS imaging [1,17,18], *etc.* As an experimental technique, IVPA is currently being developed and undergoing continuous further refinement [3]. The current researches mainly focus on the improvement in the imaging catheter including miniaturization and integration of the catheter and increase of the repetition frequency of the laser pulses. According to the operation pattern, current IVPA imaging catheters are classified into rotated and unrotated catheters [19]. A rotated catheter is equipped with a single-element none-focused ultrasonic (NFU) transducer with circular scanning [20–22]. With the catheter, the real-time imaging is difficult to be

* Correspondence to: P.O. Box 21, North China Electric Power University, Baoding 071003, China.
E-mail address: sunzheng_tju@163.com (S. Zheng).

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achieved although the frequency of the imaging system can reach 60 MHz. Moreover, the catheter needs to revolve around its axis driven by a motor to collect the PA signals generated by the surrounding tissues. It may lead to a high mechanical failure rate and the possible motion artifacts in the reconstructed images. An un-rotated catheter is equipped with a circular array of ultrasonic transducers to acquire the acoustic waves generated by the surrounding tissues simultaneously. The catheter does not need to rotate in the lumen [18,23], thus the motion artifacts caused by the catheter rotation are avoided. With such a catheter, the time cost to collect PA signals is highly decreased in contrast to a rotated catheter, which in turn reduces the risk of the blood clotting in the clinical applications. The frame rate of an image sequence is consistent with the repetition frequency of the laser pulses to achieve the nearly real-time imaging. The main concern focuses on the miniaturization of the catheter in that the diameter of an IVPA catheter is usually required to be no more than 1 mm.

In a word, many problems of the real-time clinical applications still need to be solved although the past achievements have shown the powerful ability of IVPA in imaging atherosclerotic plaques.

1.3. Related work of IVPA simulation

The content of an IVPA image depends on the configuration and component of the vessel wall and plaque tissues. Besides, the image quality is affected by the calibration parameters of the imaging device and the image reconstruction algorithms. A large amount of image data is needed to improve the imaging catheter, optimize the image reconstruction and post-processing algorithms (e.g., image segmentation and artifacts removal), and training clinical physicians, *etc*. However, IVPA devices have not been widely used for clinic, thereby enough case databases have not been available. Computerized modeling and simulation of IVPA images may be an efficient and feasible solution. It includes forward simulation of PA signals generated by the imaged tissues, propagation of the acoustic waves in the tissue and inverse image reconstruction.

The light migration in the PA imaging is currently modeled by radiative transfer equation (RTE), Monte Carlo (MC) simulation or diffusion approximation (DA). With RTE, the propagation of a photon in a turbid media is accurately described, particularly in a non-diffusive region. However, the wide application of RTE in practical imaging systems has been limited due to the high complexity of solving it [24]. DA, a first-order phase approximation of RTE, is the most popular PA forward model so far because its solution is relatively simpler in contrast to RTE. MC is usually used to depict the light transmission in a weakly absorbing and high scattering media. Besides, in [25], an equation depicting the relationship between the light fluence rate and the pressure field was deduced. But, the causal effect of the physical effects including the light absorption and PA effect was ignored. In [26], the light propagation in the multi-layered skin tissues was simulated with COMSOL Multiphysics software based on the finite element (FE) analysis. In [27], the generation of PA signals by a film was simulated, whereas the light propagation was not considered. In summary, above simulation models do not include all physical effects occurred in the PA imaging. Later, an FE numerical model integrating multi-physical fields was proposed in [28]. It consists of four parts: DA and Helmholtz equation depicting the energy transmission from the laser source to the imaged target, biological thermal equation describing the light energy deposition and the subsequent temperature variation of the target, acoustic pressure model depicting the generation of the ultrasonic waves caused by a thermo-elastic expansion, and acoustic wave equation describing the transmission of the ultrasonic waves in the media. When combined with a boundary condition, this model can be applied to model the typical biological PA imaging.

The IVPA inverse problem includes acoustic inversion and optical inversion [29]. In this study, we only focus on acoustic inversion to reconstruct the cross-sectional distribution map of the deposited optical energy or the initial acoustic pressure from the pressure time series collected by the ultrasonic detector. The IVPA scanning aperture is enclosed in a closed lumen, thus exact image reconstruction formulas do not exist [30]. However, the feasibility of applying the conventional image reconstruction algorithms, such as FBP, TR and ART, *etc*., to reconstruct IVPA images has been demonstrated [30–32].

Till now, the related research on the complete computer-based simulation of IVPA images including forward simulation of the generation and propagation of the PA waves in the tissues and inverse image reconstruction is relatively absent. Limited literatures can be retrieved. Fortunately, we can refer to the methods of simulating intravascular ultrasound (IVUS) images [33,34] by recognizing the similarity between the imaging mechanism of IVUS and IVPA. Current methods of simulating IVUS gray-scale images can be classified into three categories.

(1) Polar image-formation model (PIFM) [33].

The principle of PIFM is similar to that of the actual image generation. The transmission of the ultrasonic echo in the media is simulated in polar coordinates. Images in Cartesian coordinates are obtained through the coordinate transformation and interpolation. For example, in [35], a real-time simulator of IVUS images was designed with a hybrid method based on Beer-Lambert algorithm achieving a frame rate of 20 fps.

(2) Differential backscattering cross-section (DBC).

A simulation model is constructed according to the discrete distribution and backscattering cross-section of scatters. For example, an IVUS modeling scheme based on DBC and polar coordinate system was presented in [36].

(3) Histopathology-based simulation.

Computer-simulated images and radiofrequency (RF) signals are obtained from histology image counterparts [37,38]. Poor operation in practice hinders the application of this kind of methods.

1.4. Objectives of the work

In our previous work [31], an image reconstruction method based on TR for an endoscopic PA imaging catheter equipped with a single-element NFU transducer with circular scanning was reported. Only the solution of acoustic inversion from the collected PA pressure series was addressed. In this work, a computer-based simulator of IVPA images is designed based on PIFM. The formulation of images including laser illumination and transportation in the multi-layered vessel wall tissues, generation and propagation of the PA waves and reconstruction of the 2-D distribution map of the initial acoustic pressures are modeled and numerically simulated. Both a single transversal gray-scale image and sequential images for coronary arteries at a location during a cardiac cycle are achieved.

This work is organized as follows. In Section 2 the proposed method is described in detail. In Section 3, the results of our method are presented, which are then compared to the optical absorption profiles. Related discussions are given in Section 4. The work is ended with a conclusion in Section 5.

2. Method

In this section, the detailed procedures for simulating a series of transversal IVPA gray-scale images are described based on a brief introduction to the IVPA imaging algorithm and image features.

2.1. IVPA imaging algorithm

IVPA imaging essentially includes forward and inverse problem. As shown in Fig. 1, the forward problem is related to the process from the tissue absorbers to the measured PA pressure series. It focuses on the solution of the deposited energy density, furthermore, the generation of the PA waves from the known optical parameters of the imaged tissue.