Original Article

Detection of Early Stages Dental Caries Using Photoacoustic Signals: The Simulation Study

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Abstract

Purpose: Dental caries is known as one of the most common oral diseases in the world. Tooth decay progresses slowly, and the symptoms are not regularly visible until it reaches an irreversible phase and needs to be removed with extensive restoration treatment. If the lesions could be diagnosed at an initial stage, the progress of dental diseases would be stopped through preventive treatments. Conventional methods for caries detection are visual examinations and X-Ray imaging methods that have significant limitations such as poor sensitivity and specificity at the earliest stages of the disease due to the small size of the lesions.

Materials and Methods: Photoacoustic imaging as a non-invasive hybrid imaging modality combines the high spatial resolution of ultrasound with the rich optical contrasts of optical imaging, and it is much safer than the ionizing radiation like X-ray imaging. In this study, the simulation of the light propagation and energy deposition in the tooth was done using Monte Carlo to form the initial pressure for acoustic simulations which is done by the K-Wave toolbox. The simulations were implemented by a tooth model which is including enamel, dentin, pulp, and gum layers.

Results: Simulation results revealed that early tooth lesions could be detected by a broad beam light source better than the pencil beam light source in photoacoustic imaging. Also, as our simulation results proved, the amount of energy deposition for the bigger lesions is significantly higher than the smaller lesions using the broad beam light source.

Conclusion: Photoacoustic imaging as a promising imaging modality which is non-contact, non- invasive and non-ionizing imaging modality could detect early-stage tooth caries and provide quantitative information for white spot lesion evaluation.

1. Introduction

Dental caries is known as one of the most common oral diseases in the world [1]. Dental caries progresses slowly, and the symptoms are not often visible until it reaches an irreversible phase and needs to be removed with extensive restoration treatment [2]. If the lesions could be diagnosed at an initial stage, the progress of dental diseases would be stopped through preventive treatment, such as diet modification, plaque control, appropriate usage of fluoride for early caries and occlusal adjustment, adhesive crown restoration for a cracked tooth. The ability to detect the developing lesions accurately at a very early stage in a dental practice and to quantify the size of the lesions will provide the practitioner with an effective means of determining caries status and of

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monitoring the effectiveness of professional treatments for reversing and controlling the caries process [3]. Both at the patient level and the community level, early detection measures can have a positive impact by ensuring that preventive treatment is delivered to those who need it. Thus continued research to develop accurate methods for the early detection of dental caries has a remarkable potential for enhancing dental health and merits priority considerations.

Caries results from demineralization of the hard tissues of the teeth (enamel and dentin) which is caused by bacterial fermentation of accumulated sugar the tooth surface [4]. Under normal oral hygienic conditions, the hard tissues of the teeth undergo a constant cycle of demineralization and re-mineralization. However, if the environmental pH of the tooth drops below 5.5, the balance of the cycle is disrupted, and demineralization proceeds faster than re-mineralization. Improper oral hygiene combined with bacterial fermentation of food debris produces waste products that increase the acidity of the environment, which further accelerates the demineralization process [4]. The dental lesion will incur localized dissolution and destruction of calcified hard tissues, and further cause oral pain, tooth loss through pulp and periapical tissue inflammation [5]. Previous studies show that caries lesion can be restored if it is treated before it becomes irreversible [6].

When the surface of the lesion is disrupted, the lesion is known as a cavity. The process accelerates, eventually producing an infection that can extend to the pulp chamber (which contains nerves and blood vessels) causing inflammation and pain. At this point, the tooth would either be extracted, or a filling put in place caries lesion is detected at a sufficiently early stage, treatment regimes such as increased brushing and flossing or fluoride treatments, can be prescribed, which restore the tooth back in to the normal mineralization cycle and thereby halt and possibly reverse disease progression.

Visual and radiographic examinations are the most widely used methods for dental disease diagnosis. However, they are inefficient in assessing the hard tissue lesion at an initial stage. Visual examination as a subjective method has a low reproducibility in detecting early enamel lesions due to the dependency of the knowledge and clinical experience of the examiner.

Radiographic examination is highly accurate for cavitated proximal lesions but is poorly sensitive for non-cavitated lesions, such as white spot caries and cracks, which commonly appear at the early stage of the dental lesion [7, 8]. Current methods for detecting dental caries are employing the dental explorer and X-ray radiography which are subjective and not quantitative, and therefore they are unreliable at the early (reversible) stages of lesion formation. Additionally, X-ray radiography carries radiation risks, and dental-explorer techniques are invasive.

Photoacoustic Tomography (PAT) [9] is a hybrid non-invasive imaging modality which is combining the rich optical contrast with high ultrasonic resolution in turbid tissue. By extracting different imaging parameters from the photoacoustic signals, the PAT can effectively reflect the biochemical information [9-13], biomechanical properties [14-16], microstructural characteristics [17-24], blood velocity [25, 26], temperature distribution [27, 28], and so on. Besides, the non-ionizing laser used in PAT is much safer than the ionizing radiation, e.g., X-ray which is used as the radiographic method for the dental examination in clinics. Generally, rich contrasts and biosecurity make PAT have the natural advantages in mapping the physiological structure and function of biological tissue, such as breast cancer detecting, brain imaging, vessel diseases monitoring, and dental imaging.

The motivation behind this work is using a non-contact, non- invasive and non-ionizing technique to detect early-stage caries and to provide quantitative information for white spot lesion evaluation. In the present feasibility study, we simulated the utility of the photoacoustic imaging modality as a non-invasive and non-ionizing technique to indicate the teeth structure and identify the early tooth caries.

2. Materials and Methods

In photoacoustic imaging, when nanosecond pulsed light illuminates the tooth, light propagates through the tooth and as a result of the optical absorption in the absorber tissues, the temperature is increased, and due to thermal expansion, wideband ultrasound waves are generated and these waves could be detected by ultrasound transducers.

In this study, an acoustically heterogeneous mathematical tooth phantom has been developed to detect early dental lesions by photoacoustic signals. The designed 3D tooth model contains enamel, dentin, pulp, and gum [29]. In Figure.1 the cross-section of this model was shown. The voxel size of this model is 0.1×0.1×0.1 mm^3.

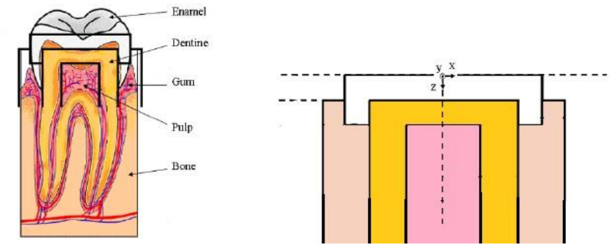

Figure 1. Left: tooth structure. Right: Tooth structure for Monte Carlo model [29]

Monte Carlo simulation has been used to solve physical problems, and it is a suitable approach for optical simulation and prediction of initial pressure of acoustic wave caused by the laser pulses.

To simulate the optical part of tooth photoacoustic imaging the optical properties of tooth component have been studied by pieces of literature and are selected as the Table. 1 for the wavelength of 633 nm [29-31]. It is notable that commonly used wavelengths for dental imaging in previous studies are 633 and 533 nm and in this simulation study 633 nm wavelength was selected.

Table 1. Tooth optical properties

λ=633 nm	μ_s	μ_a	**g**
Lesion	120	1.5	0.85
Enamel	15	0.4	0.7
Dentine	260	3	0.9
Pulp	100	0.35	0.97
Gum	150	0.3	0.9

Where μa is absorption coefficient, μs is a scattering coefficient, and g is anisotropy of scattering.

The output of Monte Carlo simulation; absorbed optical energy in tissue, was converted to the acoustic pressure wave and considered as the input of the acoustic simulation part. The K-wave as a powerful Matlab toolbox was used for the acoustic simulation and reconstruction of photoacoustic images. The adjusted parameters in the acoustic simulation part are element kerf zero and element width 0.1 mm. Also, the probe frequency of 7.5 MHz and bandwidth 50% was used.

Two evaluations are investigated in this study based on the map of the absorption energy using the Monte Carlo and reconstructed photoacoustic pressures using the K-wave toolbox. The first evaluation is related to the type of input light source and compare the absorption energy profile and reconstructed photoacoustic pressure between a broad beam and a narrow beam light source for the same amount of input energy and the same lesion sizes. The second evaluation is related to the effect of the different size of a lesion, by considering the same type of light source and input energy. In each test, 6,000,000 photons were launched in the incident point, and both run duration was 60 minutes.

3. Results

3.1. Comparison of Light Sources: Broad Beam VS. Narrow (Pencil) Beam

Broad collimated beam has the same size (diameter) as the enamel in our tooth model. Pencil beam is collimated, and the size of the beam is extremely narrow (1 voxel in this case). In general, the pencil beam has more concentrated energy to the target region. In Figure 2., the effect of different light sources on the amount of energy deposition was shown. As we have shown in Figure 2(a), tooth model simulated by considering two types of light sources: a broad and a pencil beam.

Figure 2-b shows the energy deposition in the simulated tooth model for the broad beam (right) and the pencil beam (left) and Figure 2-c shows the reconstructed pressure of the tooth model for two types of light sources, namely, broad and pencil beams. As we have shown in Figure 2-b, the energy deposition was more concentrated in the central part of a tooth for the pencil and the broad beam as we expected. The central part of the tooth contains dentine part, and the attenuation coefficient of dentin is higher than the other parts of the tooth.

However, the mean of absorbed energy by the lesion is 5.101 W/m^2 using the broad beam source and the mean of absorbed energy by lesion considering the pencil beam is 1.2790 W/m^2. Also, the mean of pressure made by pencil beam source is 0.1552 Pascal and the mean of pressure made by broad beam source is 0.0116 Pa

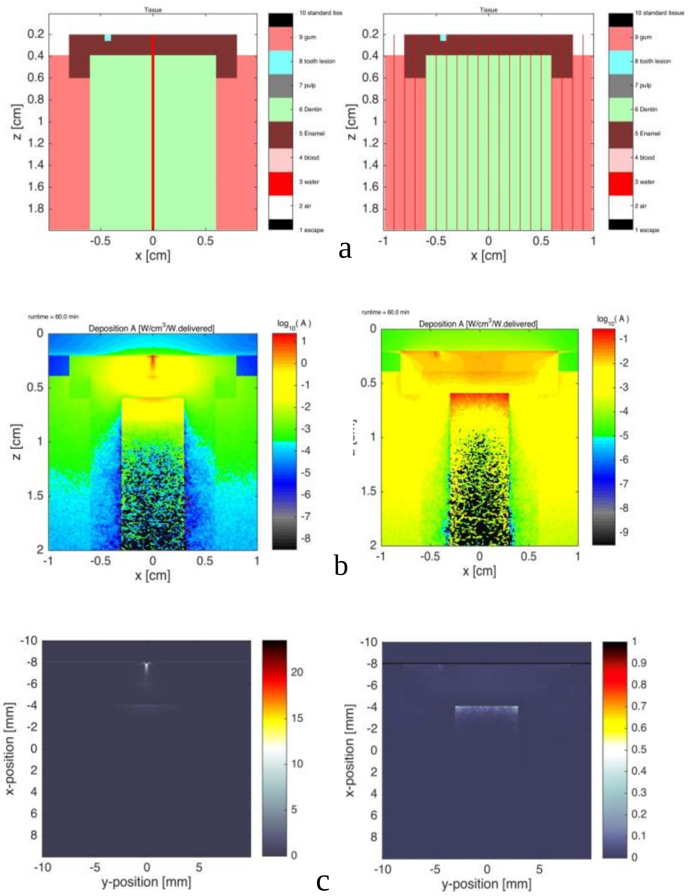

Figure 2. Comparison between broad beam and narrow beam: a. Simulated tooth model; b. Energy deposition map; c. reconstructed photoacoustic pressure

3.2. Comparison of Different Lesion Size

The Monte Carlo simulation was run for different size of lesions considering the broad beam light source. The tooth models with different size of the lesion by the use of Monte Carlo simulation were shown in Figure 3-a. There are 19×19×19 voxels with target cells (lesion) in the left phantom and 4×4×4 voxels with target cells in the right phantom. Each lesion voxel size is 0.1×0.1×0.1 in mm.

In each test, 6,000,000 photons were launched in the incident point; the energy deposition at the different size of lesions was shown in Figure 3-b (right and left).

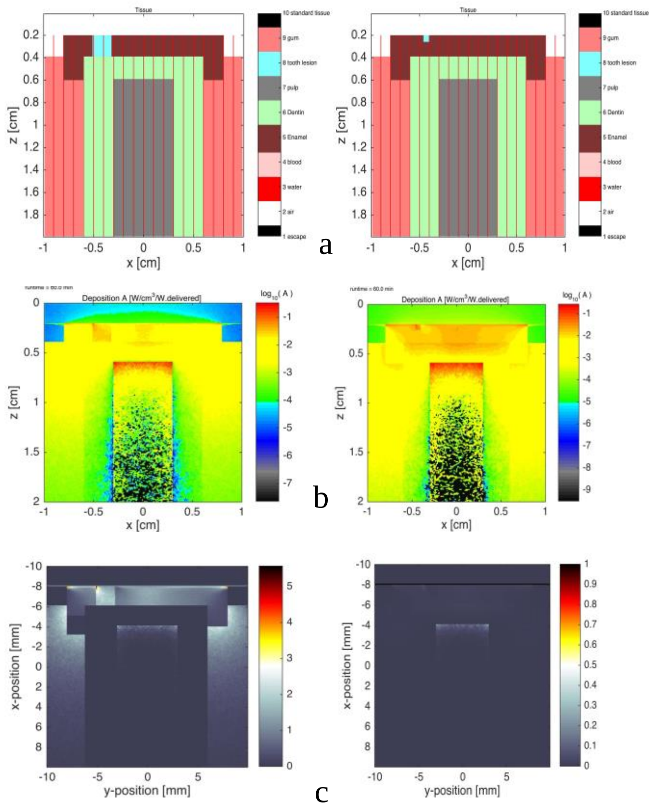

Figure 3. Comparison between two sizes of the lesion using broad beam light source: a. Simulated tooth model; b. Energy deposition map; c. reconstructed photoacoustic pressure

The mean of absorbed energy in the big lesion is 0.0508 W/m^2, and the mean of absorbed energy by the small lesion is 0.0267 W/m^2. Figure 3-c shows the result of reconstructed pressures of both simulated models using K-Wave. The mean of pressure made by a simulated model including the big lesion (19×19×19 voxels) is 0.2895 Pascal and the mean of pressure made by a simulated model including the small lesion (4×4×4 voxels) is 0.0116 Pa.

4. Discussion and Conclusion

Since the photoacoustic imaging is a non-invasive promising imaging modality to detect early tooth caries, in this study, we simulated the photoacoustic imaging for this purpose using the tooth simulated model.

This simulation study is performed in two parts optical and acoustic simulations using Monte Carlo and K-Wave toolbox, respectively. This study simulates a cubic shape object as a lesion, and the tissue around the object is considered as a uniform turbid medium. In this evaluation, the effect of two types of light sources when the lesion size was fixed and the effect of different lesion size when the light source was considered broad beam, were investigated.

The simulation results revealed that early lesions could be detected using a broad beam better than the pencil beam both in the energy deposition and reconstructed images.

In general, the pencil beam has more concentrated energy in the target region, but the early lesions are not detectable with the human eye to put the pencil beam in the right place.

Also, as our simulation results proved, the amount of energy deposition for the bigger lesions is significantly higher than the smaller lesions, considering the same broad beam light source.

Furthermore, experimental validation of our approach confirms that when the lesion size is increased, the reconstructed photoacoustic pressure is increased too. The criteria of best detection are the more energy and pressure deposits to the target region, and other region does not receive enough light energy to damage the tissue.

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