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Photoacoustic Characterization of Cortical and Cancellous Bone in The Vertebrae

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Abstract— **To date, spinal problems are not rare, and relevant therapies are always required. Although the combination of photoacoustic imaging (PAI) and spinal fusion surgery, a widely applied operation for spinal cures, is unprecedented, we assume that such combination might improve the accuracy and safety of the surgery. This paper aims to testify that PAI is effective in monitoring and navigating during spinal fusion surgery. Specifically, we examined the optical absorption spectrum of bones to determine the optimal laser wavelength as 532nm. Afterwards, we measured the photoacoustic signals of this bone samples, discovering that the signals of two kinds of samples, cortical bone and cancellous bone, differ considerably in frequency domain. It demonstrated the feasibility that PAI is effective enough to distinguish different bone tissues during the spinal fusion surgery.**

I. Introduction

Nowadays, spinal diseases like scoliosis and fracture are common clinical issues, most of which originate from physical accidents or genetic inheritance [1]. Once the spine is hurt, the specific vertebrae may not function properly, bearing the potential of more severe injury. Therefore, orthopedic surgeries play an important role in avoiding disability and providing health to many patients. One of the most commonly conducted therapy is spinal fusion surgery [2, 3], with more than 400000 cases performed annually in the United States [4]. Spinal fusion fuses two or more vertebrae together with screws for recovery, which is also widely applied in degenerative diseases and tumors. This surgery should be operated with high accuracy due to the delicate structure of backbones [5]. The screws should go through the pedicle without damaging other tissue. According to the anatomical structure of the spine shown in Fig. 1, the size of pediculus is only of several millimeters, leaving the operation with quite small room for error. Besides, the dense nerves and blood vessels surrounding the vertebrae play an irreplaceable role in the movement and perception of human body, damage of which could result in paralysis or disability of senses [4, 6-8]. Therefore, precise prognosis and monitoring of the surgery is of great importance.

Photoacoustic imaging (PAI) is an emerging medical imaging modality that seems to have the potential to solve the above-mentioned problem [9]. Based on photoacoustic (PA) effect, the target tissue would emit ultrasound waves once it was exposed to pulsed laser beams. Then, the ultrasound transducer receives the signals for subsequent image reconstruction and analysis [10]. It is quite safe for clinical application, since it is free of ionizing radiation and poisoning contrast agent. There are several types of PAI according to the difference in excitation source and reconstruction method [11]. Photoacoustic tomography (PAT) is one of them, which has developed quickly in recent years [12]. As a hybrid imaging method, PAT possesses both high spatial resolution and molecular contrast, combining the merits of optical imaging and ultrasound imaging [10]. Another worth noting category is photoacoustic microscopy (PAM). While PAT is always applied in imaging large organs, PAM has more advantages in the case of cells and subcellular fractions at superficial of the tissue [13]. It can provide anatomical and molecular information on micrometer scale *in vivo*. Therefore, PAM usually functions well in invasive surgical operations, where the imaging tissue is at superficial with sub-millimeter depth.

During the spinal fusion surgery, the screw needs to go through cortical bone on the surface and reach cancellous bone deeper inside [14]. The direction and depth of the screw must be monitored in real time to guarantee safety. On one hand, the distance between cortical and cancellous bones should be avoided of being too close in case that the drill may break the vertebra. On the other hand, the advance path of the drill should avoid the plentiful blood vessels and nerves surrounding the vertebrae, damage of which would bring irreversible consequence to the body. Therefore, during the development of medical operation, minimally invasive surgery has become popular, since it always leads to less severe operative wound and nerve injury [15-17]. However, it still suffers from the non-negligible disadvantage of insufficient view, hence requiring efficient guidance and monitoring during the operation, especially for tissues as delicate as the vertebrae [18]. We thought PAI could be a potential candidate for operative guidance here since it performs well in differentiating different tissues and can be miniaturized to fit into invasive operation devices. We conducted several experiments to testify our idea in this work. We ground our sample bone into powder for the test of absorption spectrum, so that we could decide the most appropriate wavelength of the laser used to trigger PA signals. Afterwards, we collected and analyzed the PA signals of bones samples, aiming to confirm that PAI can effectively distinguish between cortical and cancellous bones.

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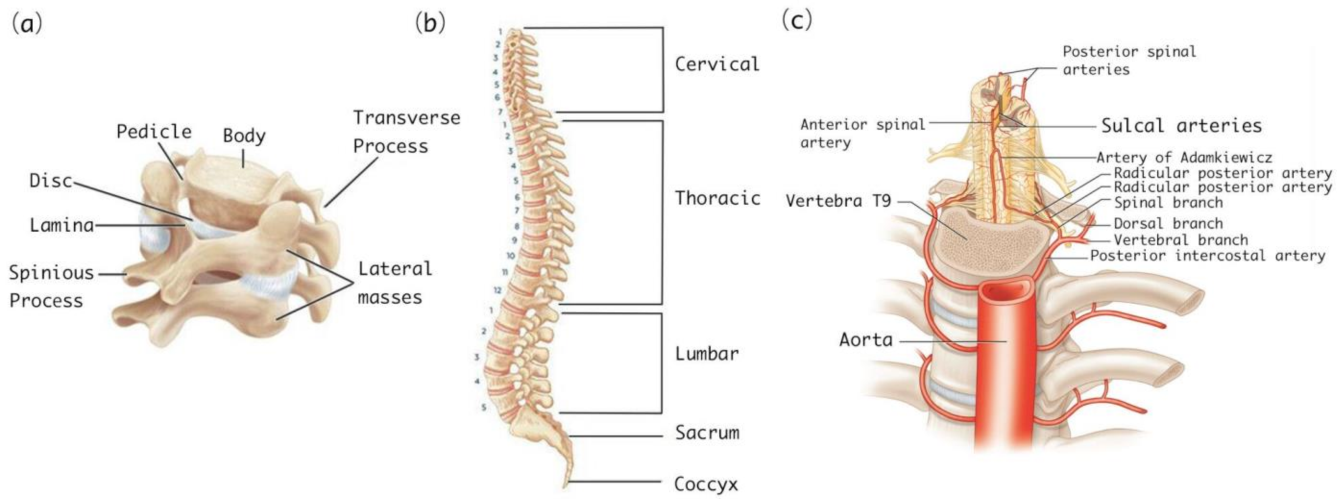

Figure 1. The atlas of human spine anatomy. (a) The anatomical map of vertebrae. (b) The profile of backbone. (c) The surrounding nerves and connective tissue.

II. Methods and Results

A. Absorption spectrum of cancellous bone

Structurally, bones are composed of periosteum, sclerotin and marrow. Being the outermost layer, periosteum is full of nerves and blood vessels, which are important for sensing and regeneration of bones. Our focus goes to the interlayer, sclerotin, when the fusion surgery is concerned. The sclerotin can be divided into cortical and cancellous parts according to their density and position [14]. Cortical bone is always rigid and compact, spreading over the surface of bones, while cancellous bone is spongier with poor anti-pressure ability. As discussed in introduction part, it is of great importance to efficiently distinguish cortical bone from cancellous bone in real time, otherwise there remains the risk of causing bruise or even more dangerous damages.

To start with, we need to set the system up and determine the detailed parameters of devices, the most important of which is the wavelength of the excitation laser source. It is well known that absorption spectrum refers to the spectrum generated by absorption of photons from lower energy levels to higher energy levels, which is usually applied in distinguishing matters according to their characteristic absorption peak. While in our experiment, we expect the sample would absorb the laser energy with possibly maximum efficiency, so that it would produce the PA signals with sufficient intensity for detection. Therefore, we tested the optical absorption characteristics of the targets. Experiment for cancellous bone is set as an example. The vertebrae of a sheep were chosen as experimental subjects, whose cancellous bone was carefully separated from cortical ones, and was ground for easier measurement of absorption spectrum. Around 2 grams of the sample was ready for the test. The test equipment is UV spectrophotometer (UV-2600, Shimadzu (Shanghai) Global Laboratory Consumables Co., Ltd) with a wavelength coverage of 340 nm-960 nm. From the result in Fig. 2, it is clear that there are three characteristic peaks. The highest peak is at the wavelength of 413 nm, while the other two being at 541 nm and 576 nm, respectively. Obviously, the sample performs best in light absorption at the wavelength of 413 nm. However, at this wavelength, the laser beam would bear great energy, which means the potential of being unsafe to the operator. As for wavelength of 576 nm, the absorption here is similar to that at 541 nm. Considering that it would cost much less since we already have the laser equipment of 532 nm, which is a standard output wavelength of high-power pulsed laser. More importantly, the absorption at this wavelength is high enough for imaging, so we chose 532 nm as the wavelength of the pulse laser source for excitation.

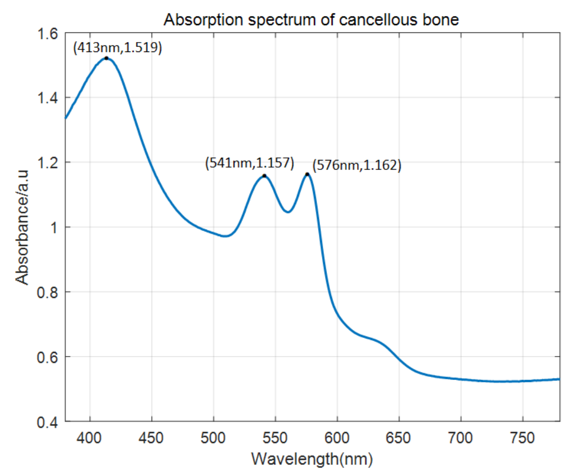

Figure 2. The absorption spectrum of cancellous bone

B. Acquisition and analysis of PA signals

As discussed above, the pulsed laser with the wavelength of 532 nm was chosen to be the most appropriate excitation source. To testify whether PAI can efficiently distinguish cortical bones from cancellous ones, we need to collect the PA signals of these two kinds of bone components for comparison. As shown in Fig. 3, we set up a photoacoustic sensing system with a laser device of 532 nm wavelength and other necessary optical elements. The combination of two convex lens aims to produce laser beam with great collimation. The pinhole functions to filter noise waves and purify the light, so that the beam is of better focus after the special filtering. After reflection by a plane mirror, the laser beam goes through an aspherical lens instead of a common convex lens for better phase configuration. The bone sample was completely submerged in water for signal coupling. Once the sample was exposed to the focused laser beam, the excited PA signals were collected by the ultrasound transducer, which is also immersed in water. The detected PA signals go through the amplifier and demonstrated by the oscilloscope. We possessed the data with MATLAB, including both time-domain and frequency-domain demonstration after Fourier transformation. The results are shown in Fig. 4.

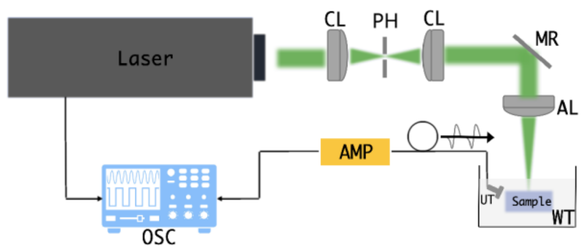

Figure 3. The photoacoustic imaging system. (CL: convex lens, PH: pinhole, MR: mirror, AL: aspherical lens, WT: water, UT: ultrasound transducer, AMP: amplifier, OSC: oscilloscope)

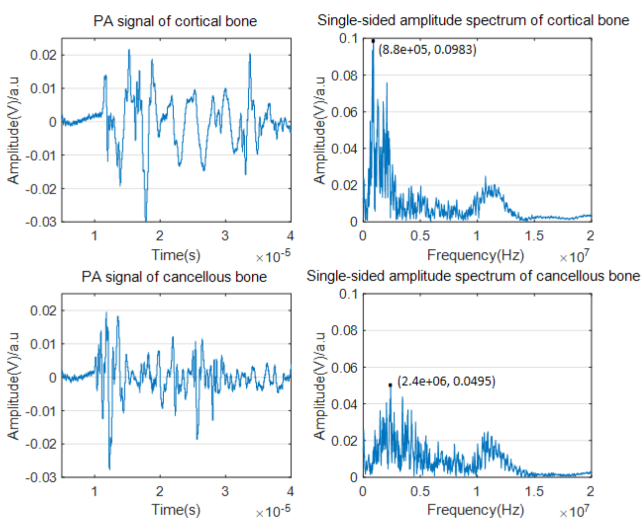

Figure 4. The PA signals and the corresponding Fourier transfomation results. The left column being the graphes showing the original PA signals of cortical and cancellous bones, the right column being the frequency domain demonstration respectively.

III. Discussion

We may conclude from the amplitude graphs in Fig. 4 that signals of cancellous bone are more compact, while cortical bone produces sparse signals. This conclusion is also vividly reflected in the frequency domain, where cortical bone signals mostly take up the low-frequency range and the peak signal lies at the frequency of 0.88 MHz. Comparatively speaking, cancellous bone signals reach its peak at 2.4 MHz with lower amplitude. The difference mainly results from the microstructure of these two types of bones. For cortical bones, the bone mineral density is relatively high and the porous feature is less obvious than cancellous bones. Therefore, the PA signals of cortical bone have higher amplitude but lower frequency, while for cancellous bone is the other way round. To conclude, the difference between cortical bone and cancellous bone can be greatly distinguished by PAI. In other words, applying PAI in spinal fusion surgery for guidance and monitoring is feasible in principle.

It requires more explanation for the choice of laser wavelength. Photoacoustic imaging experiments usually adopt the lasers of medium wavelength out of safety concern, especially for in vivo experiments, where there are strict rules towards the maximum laser energy on the experimental sample (American National Standards Institute safety standard being 30mJ/cm^2)[19]. Therefore, we did not adopt the laser with the wavelength of 413nm, despite the high absorption there. The absorption at 532nm is only slightly less than that at 541nm, so it is safer and more economical to image at this wavelength, at no sacrifice of signal quality.

Another worth noting point is that we ground our sample for the test of absorption spectrum. This is because that spectrophotometers usually functions better when the sample is in fluid state, so it is more reasonable to test for powder specimens than solid ones. However, the process of griding has unavoidably transformed the appearance of our sample, and it remains a question whether its absorption spectrum truly reflects the optical characteristics of the non-broken bones as in real surgery. We should further conduct experiments to confirm that idea.

IV. Conclusion

To conclude, our intention to testify whether PAI is a good candidate for the guidance in endoscopic operations like spinal fusion surgery is successfully conducted. Judging from the PA signals of samples in both time domain and frequency domain, photoacoustic technology performs well in distinguishing different components of bones, which means the opportunity of it been successfully applied in spinal fusion quite a great one. Based on this discovery, we shall promote further research in mechanical and circuit part for the construction of the whole operative system, and it would undoubtedly enhance the safety and accuracy of existed systems.

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