Laser Illumination Modality of Photoacoustic Imaging Technique for Prostate Cancer

Dong-qing Peng1,2, Yuan-yuan Peng1, Jian Guo1 and Hui Li1*

1.Key Laboratory of Optoelectronic Science and Technology for Medicine (Ministry of Education of China), College of Photonic and Electronic Engineering, Fujian Normal University, Fuzhou, Fujian, 350007

2.School of Science, Jimei University, Xiamen, Fujian, 361021

Corresponding author’s e-mail:hli@fjnu.edu.cn

Abstract. Photoacoustic imaging (PAI) has recently emerged as a promising imaging technique for prostate cancer detection, such as laser illumination modality. Knowledge of absorbed light distribution in prostate tissue was essential since the distribution characteristic of absorbed light energy would influence the imaging depth and range of PAI. In order to make a comparison of different laser illumination modality of photoacoustic imaging technique for prostate cancer, optical model of human prostate was established and combined with Monte Carlo simulation method to calculate the light absorption distribution in the prostate tissue. Characteristic of light absorption distribution of transurethral and trans-rectal illumination case, and of tumor at different location was compared with each other. The relevant conclusions would be significant for optimizing the light illumination in a PAI system for prostate cancer detection.

1. Introduction

In recent years, prostate cancer has been a serious health concern around the world, especially in the United States[1-4]. As a new biomedical imaging modality for various biomedical applications which combined contrast capability of optical imaging with the resolution of ultrasound imaging, Photoacoustic imaging (PAI) has recently emerged as a promising imaging technique for imaging prostate lesions [5-14]. But there was still a lot of challenge in the PAI for prostate cancer detection[13]. Some critical issues were required to be considered, such as a light delivery to the prostate with a sufficient penetrating depth and a minimal invasiveness. Nowadays, trans-urethral and trans-rectal light illumination had both been used as light irradiation model in the past PAI studies[11,14]. As we known, the temporal amplitude and profile of photoacoustic signals were spatial mappings of the absorbed optical energy. Therefore, knowledge of absorbed light distribution in prostate tissue was essential since that the distribution characteristic of absorbed light energy would influence the imaging depth and range of PAI.

According to the structural characteristic of prostate tissue, in this paper, 3D optical model of human prostate was established to calculate the light absorption distribution in the prostate tissue at transurethral and trans-rectal illumination modality. Following, a three-tumors-embedded prostate optical model with trans-urethral laser illumination was also employed. Characteristic of light absorption distribution of transurethral and trans-rectal case was compared with each other. Comparison even be made between the light absorption of the three tumors. The relevant conclusions would be significant for optimizing the light illumination in a PAI system for prostate cancer detection.
2. Model and Method

A 3D triangular meshes prostate optical model was established based on human prostate morphology through programming, as shown in Fig.1(a) by trans-rectal and (b) trans-urethral laser illumination. The prostate phantom’s transverse diameter at x-axis, y-axis and the height were 2.0cm, 3.8cm, 3.18cm, respectively. In order to meet to the actual surrounding situation, here, a cube tissue with the diameter at x-axis, y-axis and the height 3cm, 5cm, 5cm, respectively, was used to surrounding around the prostate model. Then, an isotropic cylindrical diffusing light with diameter of 0.6mm, and effective light length 16mm, the center of light source was \( (x=0, y=0, z=15) \) mm, was employed in the transurethral light irradiation, and the center of light source for trans-rectal light illumination was \( (x=10, y=0, z=15) \) mm.

Fig.1 3D prostate model. (a) by trans-rectal light illumination; (b) by trans-urethral laser illumination

In this section, the optical model was combined with Monte Carlo method [15-16] to investigate light energy absorption distribution in prostate tissue by different laser illumination. Its simulation process can be found in reference [16]. The wavelength of these two light sources was both set to 732nm, and the total energy of incident light was 1J. The recorded range of light distribution in this simulation was always keep as: x-axis \((-15,15)\) mm; y-axis \((-25,25)\) mm; z-axis \((-10,40)\) mm; and the record step was set to 0.3mm, 0.5mm and 0.5mm, respectively. And the total incident photon number was 500,000. A Cartesian coordinates was used for the simulation. According to optical properties of human prostate from foreign groups [17], main optical properties, i.e. absorption coefficient \( \mu_a \), reduced scattering coefficient \( \mu_s' \) and refractive index \( n \) at 732nm wavelength for prostate optical model and surrounding cube tissue were specified as Table 1.

![Table 1 Optical parameters of the simulation model](image)

| Tissue            | \( \mu_a \) (mm\(^{-1}\)) | \( \mu_s' \) (mm\(^{-1}\)) | \( n \) |
|-------------------|-----------------------------|-----------------------------|-------|
| Prostate          | 0.03                        | 0.19                        | 1.43  |
| Surrounding tissue| 0.01                        | 1.0                         | 1.41  |

3. Simulation and Results

Using model as shown in Fig.1(a) and (b), the light absorption distribution patterns in the tissue model by trans-rectal light illumination and trans-urethral laser illumination were obtained, which was demonstrated in Fig.3.(a) and (b).

Comparison results between Fig.3(a) and Fig.3(b) showed that there was a full light absorption within the prostate tissue through trans-urethral laser illumination. It indicated that laser illumination from urethral would allow the prostate tissue to obtain a more efficient light absorption than trans-rectal light illumination, most of the light energy was absorbed within the prostate. In order to give a quantitative comparison of irradiance range of two kinds of light illumination model, contour line of the absorbed light energy was marked in the \( xz \)-plane where \( y = 0 \). Value of contour line \(-9.4\)J/cm\(^2\) was logarithm of absorbed energy, i.e. \( \log(A) \). It demonstrated furtherly that most the light absorption can be found in the whole volume of prostate for transurethral case. However, lots of the light absorption were happened outside the prostate, there was absorption only in the vicinity of prostate since of the attenuation of surrounding tissue. In the Fig.4, profile of relative absorbed light energy distribution along z direction and contour line of the relative light absorption energy in the \( xz \) plane were further drawn, (a) along z direction in the \( xz \)-plane where \( x = 1.5 \)mm, and (b) along x direction in the \( xz \)-plane where \( z = 15 \)mm. Two dash lines were used to show the boundary of model. From fig.4(a) and fig.(b), we could
find that the relative absorbed light energy along z direction or x direction at internal illumination case was almost larger than that of external illumination, with the except of vicinity of prostate. Note that absorption at two sides of light source was similar at trans-urethral laser illumination case, which was good for analysis of photoacoustic image. This hint there was a strong light energy absorption in the deep position for internal illumination model considering the transrectal photoacoustic signal detection model.

![Fig.3](image)

**Fig.3** Light absorption pattern and contour line of the absorbed light energy distribution in the xz-plane where y=0. Value of contour line -9.4 J/cm² was logarithm of absorbed energy. (a) by trans-rectal light illumination; (b) by trans-urethral laser illumination.

![Fig.4](image)

**Fig.4** Profile of relative absorbed light energy distribution in the xz-plane. (a) along z direction where x=-1.5 mm. (b) along x direction where z=15 mm.

Next, a three-tumors-embedded prostate optical model with trans-urethral laser illumination was also established, as shown in Fig.5(a). Diameters of the three tumors were all set to 2 mm. The center of three tumors was located at (2,0,19) mm, (-2,0,19) mm, and (2,0,12) mm, respectively. The center of light source was (x=0, y=0, z=15.9) mm. Considering tumor has a strong light absorption capacity, here, the absorption coefficient of tumor was set to be 10 times of the background prostate tissue. Main optical properties at 732 nm wavelength for prostate optical model were specified as the absorption coefficient of $\mu_{ap}=0.03$ mm⁻¹, scattering coefficient $\mu_s=0.19$ mm⁻¹, refractive index $n=1.43$. For tumor, the absorption coefficient of $\mu_{ac}=0.30$ mm⁻¹, scattering coefficient $\mu_s=0.135$ mm⁻¹, refractive index $n=1.40$.

The light absorption results for the tumours-embedded prostate model were shown in Fig.5(b) for xz-plane. It can be seen that light absorption was happened everywhere of the prostate tissue model. It was worth noting that there was a symmetrical light absorption property around the light source. Simulation results revealed that the light absorption of tumor1 and tumor3 irradiated by the cylindrical diffusing light was roughly alike as shown in Fig.6(a), which illustrates a better uniform lateral illumination range of cylindrical diffusing light source. These hinted that the cylindrical diffusing light would be suitable to the 3D scanning of PAI and was a proper light source for PAI.
Fig. 5 Embedded tumors optical model (a) and its light absorption distribution (b)

Meanwhile, it can be seen from Fig. 6(b) that the laser absorption energy in tumor-1 was similar to that of tumor-2 which was more far from the light source. Results demonstrated the light absorption of tumor at left side of the light source was the same to that of tumor at right side because of the symmetrical light emitting characteristic of cylindrical diffusing light through internal irradiation model via urethra. Therefore a further imaging depth could be obtained since a ultrasound transducer was located outside of prostate tissue.

Fig. 6 Profile of absorbed light energy distribution through center of tumors (a) along z direction (b) along x direction

4. Conclusion
In a word, a numerical modeling was still an important and effective way of gaining a deeper understanding of the complex interactions of the laser-tissue interaction process. In this paper, a 3D optical model of human prostate was established and was combined with Monte Carlo simulation method to calculate the light absorption distribution in the prostate tissue. A three-tumors-embedded prostate optical model with trans-urethral laser illumination was also employed. Characteristic of light absorption distribution of transurethral and trans-rectal case was compared with each other. Results show there was a more efficient light absorption in the whole volume of prostate using transurethral light illumination, and there was a strong light energy absorption in the deep position for internal illumination. Comparison results also demonstrated the light absorption of tumor at two side of the light source was the same because of the symmetrical light emitting characteristic of cylindrical diffusing light through transurethra irradiation model. Therefore a further imaging depth could be obtained since a ultrasound transducer was located outside of prostate tissue. In contrast, there was absorption only in the vicinity of prostate boundary since of the attenuation of surrounding tissue, and light absorption was quite small at the other side of urethral. Therefore, only half of the volume of the prostate has the possibly of imaging. The relevant conclusions would be significant for optimizing the light illumination in a PAI system for prostate cancer detection, and be helpful to the choice and the placement of laser source in the system.

Acknowledgment
This work has been sponsored by Natural Science Foundation of China (No.61178089), Natural Science Foundation of China (No.81201124), Fujian provincial key program of science and technology (No.2011Y0019), Fujian provincial education science research project(JA15125). Natural Science Foundation of Fujian
Province(No.2014J01226). and supported by the Key Laboratory of OptoElectronic Science and Technology for Medicine of Ministry of Education, Fujian Provincial Key Laboratory for Photonics Technology, Fujian Normal University, China (Grant No. JYG1417)

References

[1] Siegel, R., Naishadham, D., Jemal, A. 2013 *CA-Cancer J. Clin.* **63** 11.
[2] Siegel, R., Ma, J. M., Zou, Z. H., Jemal, A. 2014 *CA-Cancer J. Clin.* **64** 9.
[3] Dogra, V. S., Chinni, B. K., Valluru, K. S., Joseph, J. V., Ghazi, A., Yao, J. L., Evans, K., Messing, E. M., Rao, N. A. 2013 *J. Clin. Imaging Sci.* **3** 41.
[4] Kuo, N., Kang, H. J., Song, D. Y., Kang, J. U., Bocter, E. M. 2012 *J. Biomed. Opt.* **17** 066005.
[5] Wang, X. D., Roberts, W. W., Carson, P. L., Wood, D. P., Fowlkes, J. B. 2010 *Biomed. Opt. Express.* **1** 1117.
[6] Yaseen, M. A., Ermilov, S. A., Brecht, H. P., Su, R., Conjusteau, A., Fronheiser, M., Bell, B. A., Motamedi, M., Oraevsky, A. A. 2010 *J. Biomed. Opt.* **15** 021310.
[7] Spirou, G. M., Vitkin, J. A., Wilson, B. C., Whelan, W. M., Henrichs, P. M., Mehta, K., Miller, T., Yee, A., Meador, J., Oraevsky, A. A. 2004 *Proc. SPIE* **5320** 44.
[8] Bauer, D. R., Olafsson, R., Montilla, L. G., Witte, R. S. 2011 *J. Biomed. Opt.* **16** 026012.
[9] Harrison, T., Zemp, R. J. 2011 *J. Biomed. Opt.* **16** 080502.
[10] Su, J. L., Bouchard, R. R., Karpouk, A. B., Hazle, J. D., Emelianov, S. Y. 2011 *Biomed. Opt. Express* **2** 2243.
[11] Bell, M. A. L., Kuo, N. P., Song, D. Y., Kang, J. U., Bocter, E. M. 2014 *J. Biomed. Opt.* **19** 126011.
[12] Xie, W. M., Li, L., Li, Z. F., Li, H. 2012 *Proc. SPIE* **8553** 85532V.
[13] El-Gohary, S. H., Metwally, M. K., Eom, S., Jeon, S. H., Byun, K. M., Kim, T. S. 2014 *Biomed. Eng. Lett.* **4** 250.
[14] Valluru, K., Chinni, B., Bhatt, S., Dogra, V., Rao, N., Akata, D. 2010 *IEEE International Conference on Imaging Systems and Techniques* Thessaloniki, Greece, July 1-2, 2010, p121.
[15] Ren, S., Chen, X., Wang, H., Qu, X., Wang, G., Liang, J., Tian, J. 2013 *Plos One* **8** 1.
[16] Li, H., Tian, J., Zhu, F., Cong, W., Wang, L. V., Hoffman, E. A., Wang, G. 2004 *Acad. Radio.l* **11** 1029.
[17] Zhu, T. C., Dimofte, A., Finlay, J. C., Stripp, D., Busch, T., Miles, J., Whittington, R., Malkowicz, S. B., Tochner, Z., Glatstein, E., Hahn, S. M. 2005 *Photochem photobiol.* **81** 96.