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Real-time high-resolution ultrasound imaging method using adaptive beamforming technique applied to swine liver in vitro

適応型信号処理を用いたリアルタイム高分解能超音波イメージング法の豚肝臓への適用

Hirofumi Taki[1], Takuya Sakamoto[1], Kousuke Taki[2], Makoto Yamakawa[3], Tsuyoshi Shiina[4], Motoi Kudo[2] and Toru Sato[1] ([1] Grad. School of Informatics, Kyoto Univ.; [2]Dep. Anatomy, Shiga Univ. Medical Science; [3]Advanced Biomedical Engineering Research Unit, Kyoto Univ.; [4]Grad. School of Medicine, Kyoto Univ.)

瀧宏文 [1]，阪本卓也 [1]，瀧公介 [2]，山川誠 [3]，椎名毅 [4]，工藤基 [2]，佐藤亨 [1] ([1] 京大 情; [2] 滋賀医大 解剖; [3] 京大 先端医工, [4] 京大 医)

1. Introduction

Ultrasound guided surgery became a common procedure that provides ultrasound images to minimize interoperative invasion [1][2]. Because the surgery guided by low-quality ultrasound images reduces its accuracy and safety, the real-time high-resolution ultrasound imager has been awaited in ultrasound guided surgery.

We have reported a high-range-resolution ultrasound imaging method for vascular ultrasound based on frequency domain interferometry (FDI) with the Capon method [3]-[5]. The method depicted high-resolution images of swine arteries in homogenious medium; however, the previous works lack the invesitigation of the tissue aberration effect on the perfomance of the method. Ultrasound guided surgery is used in liver tumor resection, and we thus apply the FDI imaging method to a swine liver, and investigate the performance of the method in the improvement of the safety in ultrasound guided surgery.

2. Materials and Methods

The imaging method used in this study is based on frequency domain interferometry (FDI) with the Capon method. Our method is employed for optical coherence tomography to acquire high-resolution images of human retina using ophthalmic devices and those of arteries using optical imaging catheters.

We apply the FDI imaging method to each individual scan line of the RF data after the delay-and-sum process. The imaging method suppresses the contribution of interferences subject to a constant response at the desired depth. This problem is expressed as

$$\min_{\mathbf{W}} P(r) = \mathbf{W}^{\mathrm{T}*}\mathbf{R}_{\mathrm{HA}}\mathbf{W} \quad \text{subject to } \mathbf{C}^{\mathrm{T}*}\mathbf{W} = 1, \tag{1}$$

$$\mathbf{C} = \left[e^{jk_1 r} \quad e^{jk_2 r} \quad \cdots \quad e^{jk_N r} \right]^{\mathrm{T}}, \tag{2}$$

where $r/2$ is the desired depth, $\mathbf{W}$ is a weighting vector to improve the range resolution of the FDI imaging method, $\mathbf{R}_{\mathrm{HA}}$ is a covariance matrix among frequency components after whitening and frequency averaging, and k_l is the l-th wavenumber of the frequency components used by the FDI imaging method [3]. The solution to equation (1) is given by

$$P_{\mathrm{CAP}}(r) = \frac{1}{\mathbf{C}^{\mathrm{T}*}(\mathbf{R}_{\mathrm{HA}} + \eta\mathbf{E})^{-1}\mathbf{C}}, \tag{3}$$

where $\eta\mathbf{E}$ is a diagonal loading used to avoid instability in calculation of the inverse matrix. Equation (3) indicates that a single calculation of the inverse matrix $\mathbf{R}_{\mathrm{HA}}^{-1}$ is needed to estimate the intensity profile in each scan line, resulting the low computational load of the FDI imaging method.

In ultrasound guided surgery, inhomogeneity of surrounding tissue should cause the deterioration in the performance of the FDI imaging method. In this study, we prepared a fresh swine liver to investigate the performance of the FDI imaging method in depicting vessels accompanied by surrounding tissue. Experiment was conducted using a Hitachi EUB-8500 US device with a 7.5 MHz linear array. We applied the method to the RF data of the in-vitro swine tissue.

3. Results

Figures 1 and 2 show the ultrasound images of a swine hepatic vein in vitro acquired using the B-mode imaging method and the FDI imaging method, respectively. Because the conventional B-mode imaging method has the range resolution of one-half the pulse length, the image extent of the vessel wall interface in the range direction was

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E-mail address: htaki@i.kyoto-u.ac.jp

about 0.3 mm. In contrast, The FDI imaging method depicted a clear hepatic vein interfaces without the appearance of false peaks in the liver parenchyma, as shown in Fig. 2.

We quantitatively investigated the imaging performance of the FDI imaging method using the blurred extent of the hepatic venous wall, where the blurred extent was calculated by the average of the half-power width in 15 scan lines. The average blurred extent of the hepatic venous wall interface is 0.122 mm in the image acquired by the FDI imaging method. In contrast, that in the conventional B-mode image is 0.204 mm. This result indicates that the performance difference of the two methods is statistically significant using student's t-test ($P < 0.001$), showing the high performance of the FDI imaging method in depicting vessels accompanied by surrounding tissue.

4. Conclusion

The FDI imaging method with the Capon method depicted a high-range-resolution image of a hepatic vein in a swine liver. This result indicates that the FDI imaging method has high potential to achieve high-resolution ultrasound images when there is tissue aberration induced by a normal liver. We believe that the FDI imaging method is suitable to provide high-resolution ultrasound images for the interoperative guidance and it has the potential to bring the large progress in the ultrasound guided surgery.

Acknowledgment

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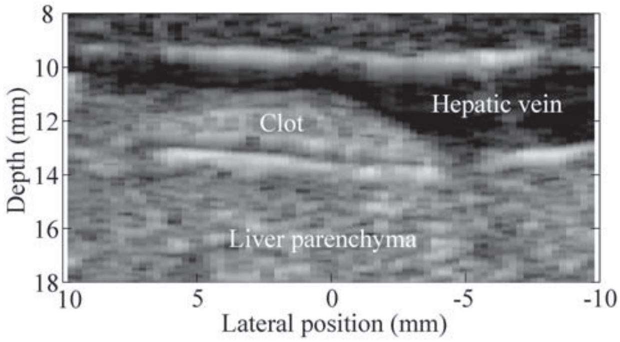

Fig. 1 Ultrasound images of a swine hepatic vein acquired using the conventional B-mode imaging method.

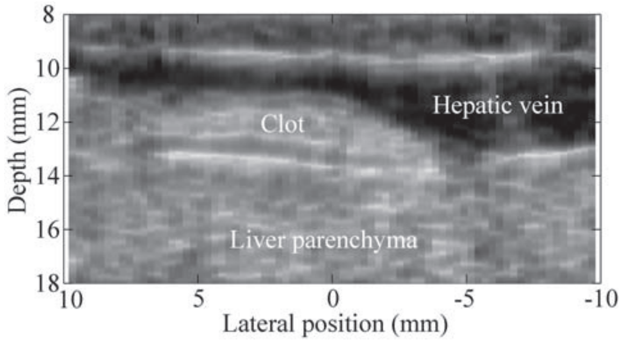

Fig. 2 Ultrasound images of a swine hepatic vein acquired using the FDI imaging method.