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Considerations on ultrasonic array-element-pitch and interpolation beamforming in displacement vectoral Doppler observations

Chikayoshi Sumi[†1]
([1]Dept Info Commun Sci, Sophia Univ.)

1. Introduction

We have been developing real-time medical vectoral Doppler measurement/imaging methods. For instance, we had developed the multidimensional autocorrelation method[1)] and the multidimensional cross-spectral phase gradient method.[2)] The method features are specifically compared in ref. 1, for instance. The common advantage of these vectoral Doppler methods over conventional 1-dimensional (1D) Doppler methods is that they do not require the ultrasonic beam to be directed in the direction of displacement of the object to be observed, and displacement in any direction, including the direction of intersection with the ultrasonic beam, can be observed simply by pointing the ultrasonic probe at the object to be observed. It is expected to simplify the measurement technique and shorten the imaging time, and it is also expected to broaden the scope of the observation target. Recently, we have also applied this technique to the fields of orthopedics/sports medicine and reported the observation of limb motion (muscle stretching and contraction).[3)] Both methods can realize observations that take into account the direction of the ultrasonic beam generated at the observation location,[4)] and they can also realize extremely accurate observations that enable the observation of the strain (rate) tensor.[5)] The latter is more robust to noise than the former and is suitable for observation of not only carotid arteries but also deep organs including the heart and various tumors, while the former requires much less computation and is faster.

To improve the accuracy of lateral displacement relative to the depth direction, the beam crossing method[1)] and the spectral frequency division method[6)] have been developed as lateral modulation methods, but the current ultrasound probe has a wide lateral bandwidth, and the former beamforming requires the generation of multiple intersecting beams, whereas the latter can be simply performed in normal diagnostic imaging scanning. In this paper, we report the results of a phantom experiment evaluating the effect of probe array pitch and interpolated beamforming on the accuracy of lateral displacement observation with the latter spectral frequency division method. The performance of the former beamforming is reported elsewhere. Next, the confirmed proper beamforming parameter was used for observing human tibia and knee dynamics with the vectoral Doppler Imaging.

E-mail: [†*]c-sumi@sophia.ac.jp

2. Methods

2.1 Fundamental study on phantom

Fundamental synthetic aperture echo data were acquired with the ultrasound system (Japan Probe Co, Ltd, Kanagawa, JP), and the custom-made 1D-linear-array-type probe (Ueda Japan Radio Co., Ltd.). The fundamental pitch of elements was 0.1 mm and the nominal frequency was 7.5 MHz, of which 128 elements were used. The sampling frequency was set to 50 MHz. The probe was excited by electric one wave. The target was our made agar-graphite phantom (3 and 4%), which was immersed in a water tank and was compressed in the lateral direction relative to the axial direction of probe set at the upper surface of the phantom. The beams were made in the axial direction with various element and beamformed pitches:

(i) Element pitch, 0.10 mm, with beam pitches, (1) 0.10 and (2) 0.05 mm;
(ii) Element pitch, 0.10 mm, generated by adding acquired, laterally adjacent echo signals sequentially, i.e., with beam pitches, (1) 0.10 and (ii) 0.05 mm;
(iii) Element pitch, 0.2 mm, generated by adding acquired, laterally adjacent echo signals once, with beam pitches, (1) 0.20, (2) 0.10 and (3)0.05 mm;
(iv) Element pitch, 0.2 mm, generated by thinning out echo line signals while skipping one line, with beam pitches, (1) 0.20, 0.10 and 0.05 mm;
(v) Element pitch, 0.05 mm (mechanically, lateral sliding with 0.05 mm), with beam pitches, 0.05 mm.

Instead of the interpolated beamforming, the normally beamformed echo data were also interpolated in a frequency domain.

For the vectoral measurement, the 2-dimensional (2D) autocorrelation and/or cross-spectral phase gradient methods were performed.

2.2 Observation of Human Tibia and Knee Dynamics

The vectoral observation has the potential to enable in situ observation of various musculoskeletal organs including muscles, joints, and tendons.[3)] In this paper, to observe foot directional expansion and contraction of human tibia and knee (slightly above the knee, adult male), the right ankle was placed on another chair in a sitting position and the ankle movements were performed with the right leg extended and the toe erected/turned down. The equipment used to acquire the echoes was a real-time medical equipment (SSD5500, Aloka, Japan) and the same linear probe was used with the effective beamforming parameters. In addition, another real-time equipment (AcousticX, CYBERDYNE Inc., Japan) was also used with the manufacture's original linear probe (nominal frequency, 7 MHz; frame rate, 15 Hz) similarly.

3 Results

3.1 Fundamental study

The setting (v) was the best in terms of the vectoral Doppler measurement. In real-time, for the probe, it was confirmed that (ii) should be performed rather than the setting (i) and in the human experiment, the parameter was used as the reference. Current probes have excellent diffraction characteristics and can cause aliasing in the lateral direction, making the processes (ii) and (v, but only when real-time nature is not required) important when performing lateral displacement observations.

Regarding the lateral broadbanding, the setting (v) was able to perform better than the beamforming interpolation and the simple interpolation. In other words, while fundamental experiments such as the present one are important, the aperture plane synthesis echo data frames can be checked by performing a multidimensional Fourier transform including the lateral direction in the first place. Actually, in refs. 4 and 6, the setting similar to (v) was performed for a 0.2-mm pitch linear probe.

Comparing the beamforming interpolation and the simple interpolation, the beamforming interpolation was more effective, although it required more processing time. The results are convincing due to the unique characteristics of echoes. For example, in (iii) and (iv), even if the number of data was reduced to make it seemingly sparser, the fine pitch returned in a good situation, clearly confirming that the echo signal contains a wealth of information. In the first place, the higher the data density in spatio-temporal terms, the better the accuracy of the observation can be stabilized and improved by statistical processing of the signal station. In addition to the fact, the beamforming interpolation was effective and was also performed in the human experiment. Actually, in ref. 5, the processing was effectively performed to increase the lateral frequency with theoretically coping with the aliasing. We have performed beamforming by pixel-wise delay-and-summation (DAS) and Fourier beamforming (other papers).[7]

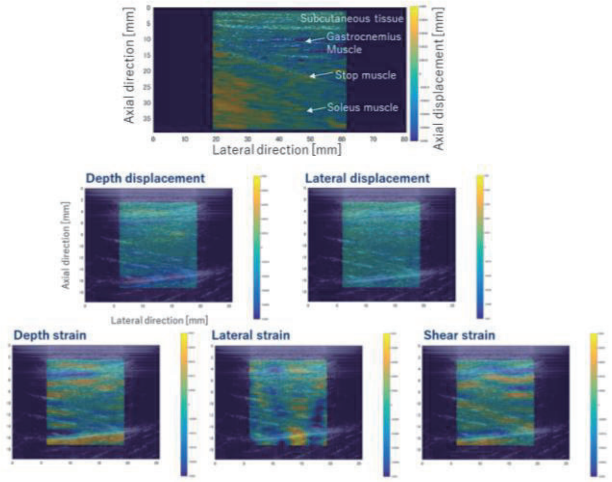

Fig. 1. Observed displacement vector and strain tensor on tibia.

3.2 Human in vivo tibia and knee

We obtained the movie results of the displacements and strains as shown in Fig. 1, as example for a tibia. The displacement confirmed that the gastrocnemius and soleus muscles move differently via the stop muscle. Large strains generated were confirmed between tendons and stop muscle. Interestingly, shear waves were also confirmed. In the knee, the intervening quadriceps tendon and anterior femoral adipose body were found to move differently (omitted). Thus, the displacement and strains were highly correlated with the tissue structures.

4. Conclusions

Particularly for the lateral displacement measurement, the proper setting of pitches of element and beam is significantly important. The human experiment results suggested the effectiveness of vectoral Doppler imaging on in situ musculoskeletal system observation. With adapting the observation configuration to respective systems to enable observation in as natural a position as possible, we will continue to observe various systems, for instance, including abdominal, back and arm muscles, etc. in addition to clinical diseases.

References

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