A METHOD FOR REAL-TIME THREE-DIMENSIONAL VECTOR VELOCITY IMAGING

J. A. JENSEN* and S. I. NIKOLOV, Center for Fast Ultrasound Imaging, Orsted*DTU, Technical University of Denmark.
Corresponding e-mail: jaj@oersted.dtu.dk

Current high-end three-dimensional systems can acquire 15 to 20 B-mode volumes per second, and this can be used for visualizing the dynamic anatomy of the heart. It is, however, not possible to acquire real time flow information. Eight to sixteen emissions in the same direction should be made for reliable flow estimation, and this would for cardiac imaging lower the volume rate to an unacceptable 2 to 3 volumes per second.

This paper presents an approach for doing real-time three-dimensional vector flow imaging. Synthetic aperture data acquisition is used, and this data is beamformed along the flow direction to yield signals usable for flow estimation. The signals are cross-correlated to determine the shift in position and thereby velocity. The data can be beamformed after reception in any direction and any vectorial velocity can be found. More than 60 independent velocity volumes can be made per second with this approach.

A 3 MHz 2D matrix transducer consisting of 64 x 64 elements with \( \lambda/2 \) pitch is used. The emissions are done using 16 x 16 = 256 elements at a time, and the received signals from the same elements are sampled. A defocused field is emitted and a circular Hamming apodization is applied on the transmitting elements. A total of 16 emissions is made to cover the full aperture and acquire data from all 4096 elements. Access to the individual elements is done through 16-to-1 multiplexing, so that only a 256 channel transmitting and receiving system is needed.

The method has been investigated using Field II. Parabolic flow in a 10 mm radius vessel inclined at 60 degrees to the acoustical axis of the transducer was simulated using 50,000 point scatterers. The vessel’s peak velocity was 0.3 m/s, the pulse repetition frequency 7.7 kHz and 800 emissions were simulated. Eight groups of 16 emissions were used for forming beams for the velocity estimation, and 6 independent cross-sectional flow images in the azimuth-axial direction were formed. The standard deviation of the estimates was 0.0098 m/s over the whole vessel cross-section, which is 3.3 % relative to the peak velocity. The bias was 0.023 m/s (7.5 %). False peaks were found mainly at the edges of the vessel due to the echo-canceling, and the probability of false detection was 2.2 %.

This work was supported by grant 9700883, 9700563 and 26-01-0178 from the Danish Science Foundation and by B-K Medical A/S, Denmark.
EXPERIMENTAL INVESTIGATION OF TRANSVERSE FLOW ESTIMATION USING TRANSVERSE OSCILLATION

J. UDESEN*1,2 and J. A. JENSEN1, 1Technical University of Denmark, Kgs. Lyngby, Denmark, 2B-K Medical A/S, Herlev, Denmark.
Corresponding e-mail: ju@oersted.dtu.dk

Conventional ultrasound scanners can only display the blood velocity component parallel to the ultrasound beam. Introducing a laterally oscillating field gives signals from which the transverse velocity component can be estimated using 2:1 parallel receive beamformers. To yield the performance of the approach, this paper present simulated and experimental results, obtained at a blood velocity angle transverse to the ultrasound beam.

The Field II program is used to simulate a setup with a 128 element linear array transducer emitting a 5 MHz pulse with 8 oscillations using an fprf of 4.5 kHz and introducing a lateral oscillation period of 0.8 mm transverse to the ultrasound beam. At a depth of 25 mm a virtual blood vessel of radius 2.4 mm is situated perpendicular to the ultrasound beam. The velocity profile of the blood is parabolic, and the speed of the blood in the center of the vessel is 0.5 m/s. An fourth order autocorrelation algorithm is used for velocity estimation for 100 trials, each containing of 32 RF lines. The velocity can be estimated with a mean relative bias of 1.6 % and a mean relative standard deviation of 7.0 % over the entire vessel length.

With the experimental RASMUS ultrasound scanner the simulations are reproduced in a experimental flow phantom using a B-K 8804 transducer and vessel characteristic as in the simulations. The flow is generated with the Compuflow1000 programmable flow pump giving a parabolic velocity profile of the blood mimicking fluid in the flow phantom. The profile is estimated for 100 trials each containing of 32 RF lines. The relative mean bias over the entire blood vessel is found to be 0.6 % and the relative mean standard deviation is found to be 20.4 %.

With the Compuflow1000 programmable flow pump the flow of the human carotid is reproduced in a flow phantom, using the same transducer setup and vessel characteristic as in the simulations. It is found that the characteristics of the carotis flow can be estimated and the clinical implications of these results are discussed.

This work was supported by grant 9700883, 9700563 and 26-01-0178 from the Danish Science Foundation, the Ministry of Science, Technology and Development, and by B-K Medical A/S, Denmark.
Arterial mechanics is typically investigated by separately studying the dynamic behavior of vessel walls and blood flow during the heart cycle. While blood flow investigations are now of routine clinical use, only a few ultrasound (US) instruments are dedicated to the accurate estimation of parameters like arterial distension, which is known to be reduced with the advanced atherosclerotic disease, as well as with aging and major risk factors for cardiovascular disease. This paper describes the application of an integrated ultrasound system to the real-time detection of both the flow velocity profile and the wall movements in human elastic arteries. The system basically consists of a PC add-on board including a high-speed DSP that independently processes the echo-signals generated from the walls as well as from red blood cells. Wall velocity is detected through the auto-correlation algorithm, while the blood velocity profile is detected through the complete spectral analysis of all echo-signals produced inside the vessel. The system was preliminarily tested in the common carotid arteries of a small population of patients. In each case, blood flow behavior was first checked by detecting the arterial velocity profile. The transducer position most appropriate for vessel wall interrogation was then rapidly found by observing both the velocity profile (which must look symmetrical around zero on the Doppler frequency axis) and the displacements of anterior and posterior walls, which are automatically tracked by the system. The diameter distension was measured over a minimum of 5 beats in each of 15 subjects (5 normal volunteers and 10 patients with major risk factors for atherosclerosis, age 25-76). The average distension turned out to be in the range 0.27-0.66 mm, with a typical standard deviation within measurement epochs of 30 µm. The relative distension ranged from 3.8% to 13.4%. These results were comparable to those provided by the commercial WallTrack© System II (PieMedical, The Netherlands). In conclusion, the system developed is accurate enough for assessment of arterial distension, and thanks to its real-time capability of detecting also the flow velocity profile, represents a promising means for an integrated investigation of arterial mechanics.

This work was supported by the Italian Ministry of Education, University and Research (MIUR 40%).
TWO-DIMENSIONAL SPECTRUM ESTIMATION FOR FLOW WITH MULTIPLE VELOCITIES USING MAXIMUM ENTROPY

A. YAO*, Y. ZHENG†, and J. GREENLEAF‡, §Saint Cloud State University, St. Cloud, MN, †Mayo Foundation, Rochester, MN.
Corresponding e-mail: ayao@stcloudstate.edu

Background: We have demonstrated that multiple velocities within one flow sample volume can be estimated by Two-Dimensional (2D) spectrum analysis. However, the resolution of the 2D spectrum analysis is limited in medical Doppler ultrasound applications because of the limited number of transmitted pulses. Maximum Entropy Method (MEM) can provide high resolution estimation with limited length of one-dimensional data. But due to the nonlinearity of 2D modeling, a 2D MEM is not developed yet. We have developed a new method to estimate 2D spectrum using one-dimensional (1D) MEM. Approach: The 1D MEM is applied to estimate a covariance matrix that corresponds to a sum of power spectrum density functions of positive and negative velocities. The positive and negative Doppler frequencies are separated before the method is applied. Once the covariance matrix is obtained, the power spectrum can be estimated by the hybrid method that provides high-resolution 2D spectrum estimation. The hybrid method is a high resolution 2D spectrum analysis method with a given covariance matrix. Methods: Experiment data are obtained with a flow phantom AST525. The RF data of 13.66 cm/s and 25.85 cm/s are added to simulate multiple velocities in one sample volume. The transmitting frequency is 3.5 MHz. The pulse repetition frequency is 5 kHz. The sampling frequency is 20 MHz. The 2D RF data have a size of 11×11 samples. Simulation is conducted to verify the accuracy of the method. Results: The simulation shows that the minimum separation distance is 0.080 in normalized frequency by our method with a size of 11×11 samples. It is 0.120 and 0.131 by the Hybrid method and 2D FFT, respectively. Our method improves the resolution by 33% and 39% comparing with the other two methods. Two flow velocities are successfully separated and estimated by our method. The estimated velocities are 13.63 cm/s and 25.40 cm/s. Conclusion: Our method provides excellent estimation for multiple velocities and is superior to other 2D spectrum estimation methods when data length is limited.

ULTRASONIC HIGH FREQUENCY BLOOD FLOW IMAGING OF SMALL ANIMAL TUMOR MODELS

P.-C. LI*, Y.-F. CHEN, and W.-J. GUAN, Department of Electrical Engineering, National Taiwan University.
Corresponding e-mail: paichi@cc.ee.ntu.edu.tw
Small animal models have been used extensively in genomics research and drug development. The mouse, in particular, offers the possibility to manipulate its genome and produce accurate models of many human disorders. Hence, the increasing number of studies performed on small animals has stimulated the development of new imaging tools. Among all the modalities, ultrasound plays an important role due to its cost-effectiveness, portability and ability to perform blood flow and real-time imaging. This role is also similar to its role in clinical diagnosis. In this paper, a 45 MHz ultrasonic small animal imaging system and its applications in blood flow measurements on mouse tumors are presented. The system had a lithium-niobate, single crystal transducer with a center frequency of 45 MHz and fractional bandwidth of 55%. The transducer’s diameter was 6 mm and it was geometrically focused at 12 mm. The imaging system also consisted of a 4-axis mechanical scan system, an 8-bit, 200 Msamples/sec waveform generator and an 8-bit, 500 Msamples/sec digitizer. Color Doppler, Power Doppler and PW Spectral Doppler were all available. Simulations and phantom experiments were performed in order to evaluate four different flow estimation techniques for color Doppler, including the 1D correlation technique, the 2D correlation technique, the wideband maximum likelihood estimation technique and the butterfly search technique. Generally, the butterfly search technique achieved the best tradeoff between computation complexity and imaging performance particularly when the signal-to-noise ratio was below 20dB. The system was also used to perform in vivo mouse imaging with a tumor cell line named WF-3. The WF-3 tumor cells were injected into the C57BL/6 mice subcutaneously and it was used as an ovarian cancer model. Vascularity of the tumor was successfully imaged when the diameter of the tumor was over 2 mm with flow velocities on the order of a few mm/s. The blood flow images were also correlated with histology after the mice were sacrificed. Good correlation between the blood flow image and the histology was demonstrated in that the lack of blood flow signals in the image for a tumor at a late development stage corresponded to necrosis at the center of the tumor shown in histology.

P2E-6

QUALITY CONTROL OF OFF-PUMP CORONARY HEART SURGERY USING ULTRASOUND COLOR FLOW IMAGING WITH ADAPTIVE CLUTTER REJECTION FILTERS

L. LOEVSTAKKEN*1, R. HAAVERSTAD2, S. BJAERUM3, S. SAMSTAD1, and H. TORP1, 1Norwegian University of Science and Technology (NTNU), 2St. Elisabeth Cardiac Centre, Trondheim, Norway, 3GE Vingmed, Horten, Norway. Corresponding e-mail: lasse.lovstakken@medisin.ntnu.no

Quality control of off-pump coronary heart surgery can be done efficiently using ultrasound color flow imaging. Because of excessive tissue movement due to the beating heart, new methods for clutter filtering should be applied to properly separate the signal originating from blood, from the clutter artefact signals. Data
obtained from pig experiments where coronary surgery had been performed, has
been used to compare the commonly used polynomial regression (PR) filter
with more advanced adaptive filtering techniques for clutter removal. More
specifically, three adaptive filtering techniques were used in the comparison. The
mean-frequency (MF) filter adapts to the tissue movement by down-mixing the
temporal signal with the mean Doppler frequency. The varying-frequency (VF)
filter adapts to the tissue movement by down-mixing the temporal signal with
the varying phase increments for each time sample. Both filters subsequently
apply a PR filter. The eigenvector regression (EV) filter spans the signal space
with an eigenvector basis, where the high-energy clutter signal can be extracted
by finding an appropriate basis for the clutter sub-space. The effectiveness
of the clutter filters was quantified by comparing the signal power before and
after filtering, from a region inside and outside a vessel. The procedure was
repeated for increasing filter basis size. Results showed that all three adaptive
filters outperformed the non-adaptive PR filter. A representative example from
a region with accelerated muscle movement and a filter basis size of two, yielded
a blood to clutter level of 11.2dB for the EV filter, 7.8dB for the VF filter, -
2.5dB for the MF filter, and -6.1dB for PR filter. As the filter basis size was
increased, the EV filter performance dropped to below that of all others in the
study. A reason for this may be that the basis vectors spanning the blood sub-
space is then included and removed by the filter. In conclusion, all three adaptive
filters ensured proper detection of blood, and a high reduction of clutter noise
artefacts. For a basis size of one to three the VF and EV filter were equally
the most effective. For a larger basis the VF filter prevailed. Also considering
computational demands, the VF filter should be the overall filter of choice.

The work presented was supported by the Medicine and Health program of the Norwegian
Research Council.

Session: P2F

ELASTICITY
Chair: M. Insana
University of California-Davis

P2F-1

HYSTERESIS PARAMETER IMAGING OF SOFT TISSUE
UNDER QUASI-STATIC DEFORMATION

N. NITTA*1, T. SHIINA1, and E. UENO2, 1Institute of Information Sciences
and Electronics, University of Tsukuba, Tsukuba, Japan, 2Institute of Clinical
Medicine, University of Tsukuba, Tsukuba, Japan.
Corresponding e-mail: nitta@milab.is.tsukuba.ac.jp

The strain image can be influenced by the amount and rate of deformation
because the nonlinear elastic and viscoelastic properties cannot be neglected.
For stable mechanical assessment independently of such conditions, these prop-
erties must be assessed. On the other hand, these properties are capable of