3D Contrast Harmonic Echocardiography

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Abstract— **Fast acquisition and reconstruction is required for 3D-echocardiography to be applicable and accepted as a clinical tool. We developed a fast rotating phased array transducer for 3D-imaging of the heart with harmonic capabilities making it highly suitable for contrast imaging. In this study the feasibility of 3D harmonic contrast imaging was evaluated in-vitro and in-vivo. This goal is pursued because improved endocardial border delineation with the application of contrast agents should allow for less complex and faster quantification algorithms.**

A commercially available tissue mimicking flow phantom was used in combination with Optison micro bubbles. Backscatter power spectra from a tissue and contrast regions of interest were calculated from recorded radio frequency data. The spectra and the extracted contrast to tissue ratio from these spectra were used to optimize the excitation frequency, the pulse length and the receive filter settings for the transducer. Frequencies ranging from 1.6 to 2.5 MHz and pulse lengths of 1.5 and 2.5 cycles were explored.

An increase of 8 dB in the contrast to tissue ratio was found at the second harmonic compared to the fundamental frequency. This was found for an optimal transmit frequency of 1.74 MHz and an optimal pulse length of 2.5 cycles. For these optimal transmit settings the receive filter was configured with a center frequency of 3.6 MHz and a bandwidth of 1.3 MHz giving the maximum harmonic amplitude. Using the optimized settings, clinical harmonic contrast recordings were made.

The results presented in this paper show the feasibility of 3D contrast imaging and improved endocardial border delineation when used in combination with harmonic imaging.

Keywords: 3D, echocardiography, harmonic imaging, contrast agent, Optison

I. INTRODUCTION

Measurement of left ventricular (LV) volume and function is the most common clinical referral question in the echocardiography laboratory. A fast, practical and accurate method would facilitate access to this important diagnostic information. Currently, 2D-echo is employed to determine LV volumes with the use of geometric assumptions of its shape. 3D-echo allows for much more accurate calculation of LV parameters without the use of geometric assumptions. However, the analysis time of 3D-datasets is a limitation. Improved endocardial border delineation with the application of contrast agents should allow for less complex and faster tracing algorithms for LV volume analysis.

We developed a fast rotating phased array transducer for 3D-imaging of the heart with harmonic capabilities making it highly suitable for contrast imaging. In this study the feasibility of 3D contrast harmonic imaging (CHI) was evaluated in-vitro and in-vivo.

In-vitro measurements were used to optimize the transmit and receive settings for 3D-CHI. Determination of the optimal transmit settings was based on the highest contrast to tissue ratio calculated from radio frequency (RF-)data. Transmission frequencies ranging from 1.6 to 2.5 MHz and pulse lengths of 1.5 and 2.5 cycles were explored. The receive settings were optimized in terms of center frequency and bandwidth of the receive filter. As contrast agent Optison was used.

Ultimately 3D-CHI was used for clinical evaluation with patients recordings.

II. METHOD

A. Fast rotating ultrasound transducer

The fast rotating ultrasound (FRU-)transducer consists of three major parts: a DC motor that drives the array, a slip-ring device with 82 contacts, establishing signal transfer to and from the rotating array, and a linear phased array [1].

The DC motor drives the array at a rotation speed ranging from 240 to 480 rpm and is connected to an external control system with a manual setting for the rotation speed. A 4D-dataset (three spatial dimensions and time) can be acquired in a short time (e.g. 1 second), resulting in a sparse sampling of the time-volume space. Longer acquisitions yield a much denser sampling. The typical acquisition time is approximately 10 seconds, which has proven to be convenient for clinical application.

The array of the transducer, custom made by Delft Instruments (Delft, The Netherlands), contains 64 elements with a pitch of 0.21 mm and is tapered into an octagonal shape, approximating a circle with a radius of 7 mm. It has a fractional bandwidth of 86 % with a center frequency of 3.2 MHz. The fixed focus of the acoustic lens in the elevation direction was set at 60 mm.

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The transducer is connected to a General Electric / VingMed (Horten, Norway) Vivid 5 system. For this study the third prototype of the transducer is used which is shown in figure 1.

Fig. 1: *Third prototype of the fast rotating ultrasound transducer.*

Improvements of this third prototype can be found in the wider bandwidth, allowing improved harmonic imaging, and the more ergonomic design of the transducer.

B. Hydrophone measurements

To calibrate the pressure output of the FRU-transducer hydrophone measurements were performed. Recordings were taken at the focal point of the transducer (at approximately 5 cm) for all transmit frequency and pulse length variations used in the in-vitro experiments. From these recordings the peak negative pressure as function of the excitation voltage was extracted.

In addition, long pulses (10 cycles) were used to access the transmit sensitivity of the transducer. Again hydrophone measurements were taken at the focal point of the transducer. Frequencies ranging from 1.5 to 5 MHz and an excitation voltage of 5 V were used. The stationary amplitude of the propagated signal was extracted from the recordings and used for a sensitivity plot.

C. Contrast to tissue ratio measurements

The contrast to tissue ratio (CTR) was defined as the ratio of the scattered power by the contrast to that of the tissue. A commercially available tissue mimicking flow phantom (ATS Laboratories Inc., Model 524, Bridgeport, Connecticut, USA) was used to measure the CTR at different frequencies ranging from 1.6 to 2.5 MHz. This was facilitated by the availability of the RF-data from the scanner.

The voltage-pressure curves obtained from the hydrophone measurements were derated with the attenuation of the phantom (0.5 dB/MHz·cm). Using the derated voltage-pressure curves the derated peak negative pressure was controlled throughout the experiments.

The transmitted pulse contained 2.5 cycles and RF-data was recorded at a frame rate of half a frame per second. Optison (Amersham Health, Princeton, New Jersey, USA) was used at a dilution of 1 over 2000 in Isoton II (Beckman Coulter, Fullerton, California, USA) and was flowing at a constant rate of 90ml/min. through the phantom from which the 8 mm channel was used. Two-way frequency spectra were calculated from two regions of interest (ROI), one in the tissue and the other in the flow area, at equal depth (approximately 5 cm). The transmit frequency resulting in the highest CTR was selected as the optimal transmit frequency.

A similar procedure was used to determine the optimal pulse length at the optimal transmit frequency. Pulse lengths of 1.5 and 2.5 cycles were investigated. For reasons of resolution preservation larger pulse lengths than 2.5 cycles were not used.

Ultimately the receive filter of the echo system was set according to the obtained CTR results.

D. Clinical evaluation

3D contrast harmonic and tissue harmonic recordings were obtained from several patients with various cardiac pathologies. 3D-acquisition was performed during a 10 second breath-hold, at a frame rate of 100 frames per second and a rotational speed of 6 Hz.

After reconstruction of the recorded echo data, quantification was performed with 4D LV Analysis software from TomTec (Munich, Germany) featuring a semi-automated border detection algorithm [2].

III. RESULTS

Figure 2 shows the transmit sensitivity of the FRU-transducer obtained with the hydrophone measurements.

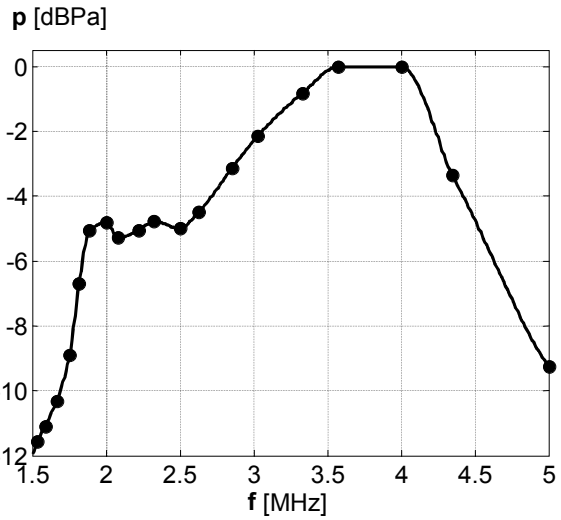

Fig. 2: *Transmit sensitivity plot of the FRU-transducer.*

The sensitivity plot yielded a fractional bandwidth of 86% (-6dB) with a center frequency of 3.2 MHz. With the help of figure 2 transmit frequencies ranging from 1.6 to 2.5 MHz were selected for the in-vitro experiments.

From figure 2 it can be seen that gaining sensitivity by increasing the transmit frequency will result in a decrease of receive sensitivity for the harmonic backscatter signal and visa versa. This is one of the effects in play when optimizing the transmit frequency.

To calculate the CTR for different frequencies the RF-data from the contrast and tissue ROI were selected as shown in figure 3a. The backscattered frequency spectra from the two ROI were calculated of which an example is shown in figure 3b. Subtraction of the two spectra yielded the CTR as function of frequency (see figure 3c, solid line). The highest CTR was found close to the second harmonic of the transmitted frequency. To reduce influence of noise a 1 MHz moving window average of the CTR curve was calculated before maximum CTR levels were extracted (see figure 3c, dashed line).

From figure 3c it can be seen that the CTR of the second harmonic is 8 dB higher than at the fundamental frequency. An excitation frequency of 1.74 MHz was found to give the highest harmonic CTR (see figure 3d).

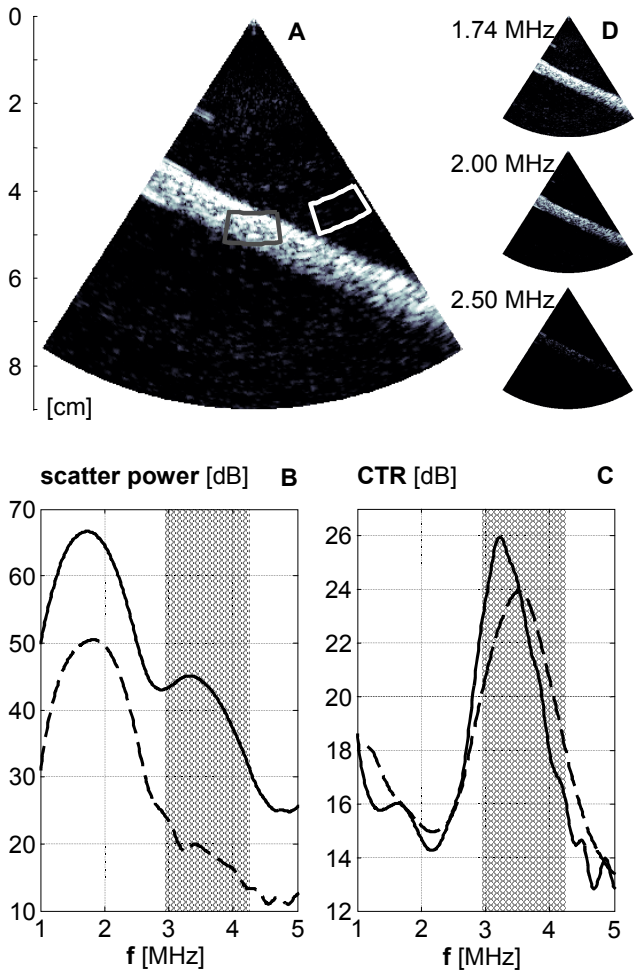

Fig. 3: *B-mode image from the tissue-mimicking phantom with contrast in the flow area showing the regions of interest used for the power spectra calculations (panel A). Power spectra from the tissue (dashed line) and contrast (solid line) region (panel B) and their difference (panel C, solid line) defined as the CTR. A 1 MHz window average of the CTR curve (panel C, dashed line) was used before maximum CTR levels were extracted. Contrast harmonic B-mode images at different transmit frequencies are shown in panel D revealing the optimal excitation frequency at 1.74 MHz. The receive filter settings for the optimal excitation frequency is indicated with a shaded area in panel B and C.*

Pulse length variations at the optimal excitation frequency of 1.74 MHz were evaluated from 50 kPa to 400 kPa derated peak negative pressure. From figure 4 it can be seen that at low pressures there is no significant difference between the CTR levels of 1.5 and 2.5 cycles pulse lengths. At moderate and high pressures, however, there is an intrinsic CTR increase of approximately 2 dB for a pulse length of 2.5 cycles.

For the optimal transmit settings the receive filter was configured with a center frequency of 3.6 MHz and a bandwidth of 1.3 MHz giving the maximum harmonic amplitude (see figure 3b and c).

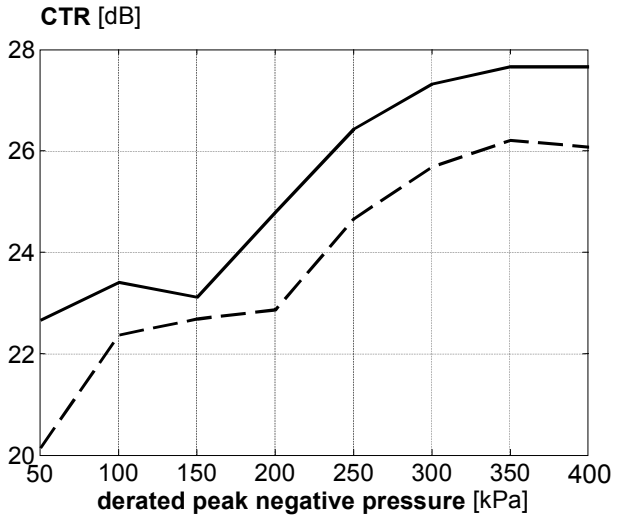

Fig. 4: *Harmonic CTR levels as function of the derated peak negative pressure for pulse lengths of 1.5 cycles (dashed line) and 2.5 cycles (solid line).*

Successful contrast harmonic patient recordings were obtained. Figure 5 shows an example from a 75 years old post-operative patient. LV-reconstructions from the end diastolic and end systolic volume (figure 5a and b) are shown along with the LV volume-time curves of the tissue harmonic and contrast harmonic recording of this particular patient. Although the time-volume curves only show small differences the tracing effort for the contrast harmonic recording was remarkably lower due to an improved delineation of the endocardial border.

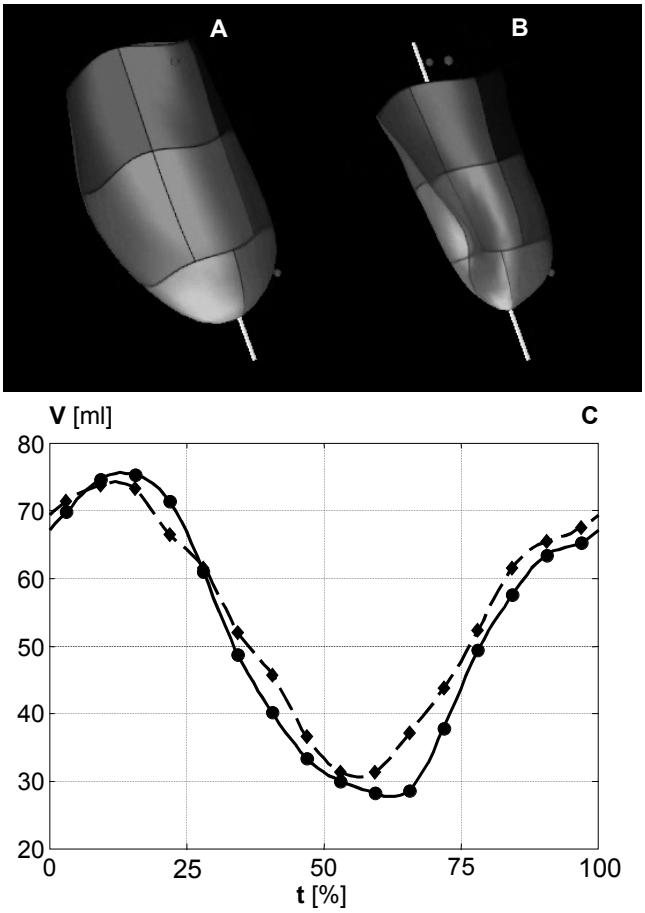

Fig. 5: *End diastolic (panel A) and end systolic (panel B) LV-reconstructions from a contrast harmonic patient recording. Panel C shows the time-volume curves obtained from the tissue harmonic recording (dashed line and diamonds) and the contrast harmonic recording (solid line and circles) of the same patient.*

In the preceding section accurate clinical volume measurements from harmonic contrast recordings of the FRU-transducer have been proven feasible. Currently, the only commercial 3D echo system for cardiac imaging with harmonic capabilities is the Sonos 7500 with its x4 xMATRIX transducer from Philips. However, no record has been found in the literature on its harmonic contrast imaging performance yet.

IV. CONLUSIONS

The results presented in this paper show the feasibility of 3D harmonic contrast imaging and improved border delineation when used in combination with harmonic imaging. Further investigations are required in a larger patient population to determine the improvement with 3D-CHI compared to other techniques like MRI. By then it can be investigated whether the improved delineation of the endocardial border from harmonic contrast recordings is beneficial for (semi-)automated border tracing algorithms.

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