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● *Original Contribution*

FAST VOLUMETRIC IMAGING USING A MATRIX TRANSESOPHAGEAL ECHOCARDIOGRAPHY PROBE WITH PARTITIONED TRANSMIT−RECEIVE ARRAY

Deep Bera,* Franc van den Adel,† Nikola Radeljic-Jakic,† Boris Lippe,† Mehdi Soozande,* Michiel A.P. Pertijs,‡ Martin D. Verweij,*,‡ Pieter Kruizinga,* Verya Daeichin,‡ Hendrik J. Vos,*,‡ Antonius F.W. van der Steen,*,‡ Johan G. Bosch,* and Nico de Jong*,‡

* Department of Biomedical Engineering, Thoraxcenter, Erasmus MC, Rotterdam, The Netherlands; † Oldelft Ultrasound, Delft, The Netherlands; and ‡ Delft University of Technology, Delft, The Netherlands

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Abstract—We describe a 3-D multiline parallel beamforming scheme for real-time volumetric ultrasound imaging using a prototype matrix transesophageal echocardiography probe with diagonally diced elements and separated transmit and receive arrays. The elements in the smaller rectangular transmit array are directly wired to the ultrasound system. The elements of the larger square receive aperture are grouped in 4×4-element sub-arrays by micro-beamforming in an application-specific integrated circuit. We propose a beamforming sequence with 85 transmit−receive events that exhibits good performance for a volume sector of $60^\circ \times 60^\circ$. The beamforming is validated using Field II simulations, phantom measurements and *in vivo* imaging. The proposed parallel beamforming achieves volume rates up to 59 Hz and produces good-quality images by angle-weighted combination of overlapping sub-volumes. Point spread function, contrast ratio and contrast-to-noise ratio in the phantom experiment closely match those of the simulation. *In vivo* 3-D imaging at 22-Hz volume rate in a healthy adult pig clearly visualized the cardiac structures, including valve motion. (E-mail: n.dejong@erasmusmc.nl) © 2018 Published by Elsevier Inc. on behalf of World Federation for Ultrasound in Medicine and Biology.

Key Words: **Transesophageal echocardiography, Matrix transducer, Sub-array beamforming, Parallel beamforming, Volumetric ultrasound imaging.**

INTRODUCTION

Echocardiography is an indispensable diagnostic modality used to assess the anatomy and function of the heart. In general, two types of echocardiography are routinely performed in the clinic: transthoracic echocardiography (TTE) and transesophageal echocardiography (TEE). In TTE, an ultrasound transducer is placed on the chest, and the imaging is performed through an acoustic window between the ribs. The ultrasound images produced by TTE may suffer from poor image quality because of the limited acoustic window and attenuation, aberration, shadowing and reflections caused by the skin, fat and ribs. In TEE, a transducer is mounted on the tip of a gastroscopic tube and inserted *via* the mouth into the patient's esophagus to image the heart. Therefore, unlike TTE images, TEE images are not deteriorated by the skin, fat or ribs. Moreover, as the esophagus is located only millimeters away from the heart, the received ultrasound signals in TEE are less attenuated than those in TTE. TEE, therefore, has superior image quality compared with TTE, especially for cardiac structures such as the aorta, pulmonary artery, valves, atria, atrial septum, atrial appendages and even coronary arteries.

At present, TEE is routinely performed for several heart conditions. It is most commonly used to evaluate valvular disease, prosthetic heart valve dysfunction, cardiac sources of embolism, aortic dissections or aneurysms and endocarditis (Khandheria et al. 1994). In addition, TEE is performed both to verify the pre-operative diagnosis and to monitor the progress in many cardiac surgical procedures such as congenital heart disease corrections and valve repair (Cheitlin et al. 2003).

Several studies have found that real-time 3-D imaging is preferred over 2-D imaging in most cardiac diagnostics (Kapoor et al. 2016; Montealegre-Gallegos et al.

Address correspondence to: Nico de Jong PO Box 2040, 3000 CA Rotterdam, The Netherlands. E-mail: n.dejong@erasmusmc.nl

2014) because of its superior visualization of 3-D structures in the heart. Unlike 2-D imaging where the acquisitions are performed only at fixed imaging planes corresponding to standard views, in 3-D TEE all the important information is captured in a single data set. In a comprehensive study, an acquired volume can be rotated and cropped at any desired plane to view different cardiac structures. Moreover, compared with 2-D TEE, 3-D TEE provides more consistent measurements of clinically relevant parameters such as volumes of the left ventricle (LV) and the right ventricle (RV), ejection fraction and cardiac output (Montealegre-Gallegos et al. 2014). Furthermore, 3-D TEE allows better morphologic and dynamic evaluation of 3-D cardiac structures such as the tricuspid valve, the aortic valve and the mitral valve. Consequently, 3-D TEE has become an essential diagnostic modality for a comprehensive examination of cardiac anatomy and function, as well as for guiding and monitoring operative and catheter-based interventions (Frank et al. 2014; Sugeng et al. 2008).

For 3-D TEE in adults, there are a number of commercially available matrix array TEE probes: X7-2t from Philips Ultrasound, Bothell, Washington, USA (Salgo 2007); V5 M TEE from Siemens Healthineers GmbH, Erlangen, Germany (Siemens Healthineers 2012); and 6 VT-D from General Electric Healthcare, Amersham, United Kingdom (GE Healthcare 2013). These matrix TEE probes are capable of real-time acquisition and live 3-D display. The Philips X7-2t probe has an active aperture of 10×10 mm^2 with 2500 elements of frequency range 2−7 MHz (Salgo 2007). The V5 M TEE probe has an aperture size of 14.5×11.5 mm^2 (operating frequency: 3−7 MHz). The 6 VT-D TEE probe has an effective aperture size of 14.3×12.7 mm^2, and its operating frequency range is 3−8 MHz. These probes comprise complicated interconnect circuitry to support integrated transmit and receive elements. In these probes, the transmit beamforming is limited by the capabilities of the on-chip high-voltage pulsers. Additionally, with these probes, volume imaging at a high volume rate is achievable only with limited viewing angle and compromised image resolution. To produce volumes of larger viewing angle with high resolution, we employed volume stitching using electrocardiography, which reduces the achievable volume rate and may introduce image artifacts with irregular heartbeats. Hence, a 3-D TEE probe avoiding these challenges would certainly be very helpful for high-frame-rate volumetric imaging.

As an alternative to the commercially available 3-D TEE probes, Oldelft Ultrasound (Delft, Netherlands) has recently developed a prototype matrix probe for 3-D TEE that facilitates full-volume imaging with good resolution at a sufficient frame rate (>20 Hz) for visualizing the motion of the 3-D structures of the heart. To reduce the complexity and power dissipation of the application-specific integrated circuit (ASIC) design, the prototype matrix probe is divided into separate transmit and receive arrays based on a split-array architecture (Blaak et al. 2011; Yu 2012). This split-array concept offers several advantages. The transmit elements are directly wired out to an external ultrasound system, thereby enabling the use of a compact low-voltage (1.8 V) 180-nm CMOS process for the ASIC, which is only connected to the receive elements. Moreover, the absence of in-probe transmit electronics reduces power dissipation and provides full flexibility in defining the transmit pulse shapes; on-chip high voltage pulsers for transmission mostly provide only very simple pulse shapes. Additionally, for non-fundamental imaging techniques such as (sub)harmonic imaging, in the split-array architecture the transmit and receive arrays could be optimized separately; however, this was not realized in this prototype. To reduce the receive channel count, micro-beamforming (or sub-array beamforming) is performed by applying small analogue delays before summing the received RF signals from the individual elements of each sub-array. These micro-beamformed RF receive signals are then transferred to the external ultrasound system (Blaak et al. 2011). The prototype transducer comprises a small rectangular transmit array at the distal end of the gastroscopic tube and a larger square receive array proximal to the transmit array (Fig. 1). The PZT material is diced at an angle of 45° to the azimuth and elevation plane, which produces elements and sub-arrays rotated diagonally. This diagonal dicing reduces the overlap between transmit sidelobes and grating lobes and receive grating lobes for the separated transmitter−receiver layout, as was found in this study.

The specific transmitter−receiver layout will affect the image characteristics in several ways. First, the misalignment between the transmit and receive beams produced by the separated transmit and receive arrays will cause slightly tilted speckles and point spread functions (PSFs). Second, the combination of rectangular transmit aperture and square receive aperture will produce asymmetric PSFs (narrower in azimuth direction than in elevation direction). Finally, the diagonal dicing will produce transmit and receive grating lobes that are most prominent in the diagonal directions. Because of these effects, the appearance of the volume image might change based on the orientation of the probe with respect to the imaging object. For any 3-D beamforming technique using the prototype probe, these effects on the image characteristics are expected, as they are caused by the intrinsic properties of the prototype. In this article, we examine these effects and discuss the implications.