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● *Original Contribution*

EVALUATION OF LARGE-APERTURE IMAGING THROUGH THE *EX VIVO* HUMAN ABDOMINAL WALL

Nick Bottenus,* Will Long,* Matthew Morgan,* and Gregg Trahey*†

* Department of Biomedical Engineering, Duke University, Durham, North Carolina, USA; and † Department of Radiology, Duke University, Durham, North Carolina, USA

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Abstract—Current clinical abdominal imaging arrays are designed to maximize angular field of view rather than the extent of the coherent aperture. We illustrate, in *ex vivo* experiments, the use of a large effective aperture to perform high-resolution imaging, even in the presence of abdominal wall-induced acoustic clutter and aberration. Point and lesion phantom targets were imaged through a water path and through three excised cadaver abdominal walls to create different clinically relevant clutter effects with matched imaging targets. A 7.36-cm effective aperture was used to image the targets at a depth of 6.4 cm, and image quality metrics were measured over a range of aperture sizes using synthetic aperture techniques. In all three cases, although degradation compared with the control was observed, lateral resolution improved with increasing aperture size without loss of contrast. Spatial compounding of the large-aperture data drastically improved lesion detectability and produced contrast-to-noise ratio improvements of 83%–106% compared with the large coherent aperture. These studies indicate the need for the development of large arrays for high-resolution abdominal diagnostic imaging. (E-mail: nick.bottenus@duke.edu)   © 2017 World Federation for Ultrasound in Medicine & Biology. All rights reserved.

Key Words: **Large aperture, Low *f*-number, Swept aperture, High resolution, Synthetic aperture, Abdominal imaging, Image quality, Acoustic clutter.**

INTRODUCTION

The prevalence of obesity is a serious problem for ultrasound imaging. Nearly 35% of adults in the United States were considered obese as of 2012, a rate that has remained fairly constant over the past decade (Ogden et al. 2014). Obesity is tied to an increased rate of diabetes, the combination of which is a risk factor for a number of different cancers, heightening the need for screening tools in the obese population. For instance, obese patients with diabetes have a 2.5 times higher risk of hepatocellular carcinoma than the general population (Klysik et al. 2014). Typical screening for hepatocellular carcinoma using ultrasound relies on identifying subtle differences in hypoechoic or iso-echoic structures in the liver that are easily missed in the presence of acoustic clutter or poor resolution, especially in a cirrhotic liver (Irshad et al. 2012; Virmani et al. 2013).

Address correspondence to: Nick Bottenus, Department of Biomedical Engineering, Duke University, 1427 FCIEMAS, Box 90281, Durham, NC 27708, USA. E-mail: nick.bottenus@duke.edu

Transabdominal fetal imaging is particularly difficult in obese women because of the naturally added imaging depth (Tsai et al. 2015). Obesity is a risk factor for a number of both maternal and fetal complications that must be carefully monitored throughout pregnancy. Fetal cardiac imaging presents the largest challenge, with obesity nearly doubling the rate of suboptimal visualization, increasing from 18.7% to 37.3% for normal versus obese patients in diagnostic scans (Hendler et al. 2004). Typical first- and second-trimester scans for cardiac defects include identification of the four-chamber view, Doppler imaging of inflow and outflow and various measurements of valve and vessel sizes (Becker and Wegner 2006; DeVore and Medearis 1993). Skeletal features must be identified throughout development, including measurement of the head, limbs, bladder, stomach and umbilicus (Becker and Wegner 2006). The size of the nuchal translucency during the first trimester has been identified as a significant marker for abnormal development, requiring precise differentiation around the cutoff of 3.5 mm (Souka et al. 2001).

Despite advancements in transducer construction, pulse sequencing and signal processing, in difficult clinical situations there remain key impediments to diagnostic ultrasound imaging such as penetration, resolution and clutter. Fundamentally, a longer array made up of many individual elements would produce images with improved lateral resolution and penetration. Preliminary phantom and *in vivo* work suggests that increasing aperture size improves target detectability at least up to the extent of current commercial arrays (Bottenus et al. 2013). However, linear system theory is insufficient to predict the performance of such an array for *in vivo* imaging. Waves emitted from and received in different sections of the array experience unique realizations of the clutter-generating body wall. Reverberation clutter superimposes spatially incoherent noise on the received data (Pinton et al. 2014). Aberration distorts the point spread function (PSF), broadening the main lobe and increasing off-axis scattering (Moshfeghi and Waag 1988).

This work sought to evaluate, in a controlled, clinically relevant context, the role of increased aperture size in improving image quality in the presence of acoustic clutter. Pulse-echo imaging using a large synthetic aperture setup was performed through three excised cadavaric abdominal walls that represented a range of expected clutter levels. We observed improved lateral resolution and target detectability with increasing aperture size despite the effects of the abdominal wall. Although contrast and contrast-to-noise ratio remained fairly constant with aperture size, both metrics were improved by using spatial compounding to take advantage of the large available aperture extent. These studies may encourage the future development of large-aperture imaging systems for clinical abdominal imaging tasks.

METHODS

The feasibility of evaluating large-aperture imaging configurations with existing clinical hardware and the swept synthetic aperture method has been previously established (Bottenus et al. 2016; Zhang et al. 2016). The overall goal of the experimental setup was to provide matched target images for each of the abdominal wall samples to evaluate the impact of clutter at varying aperture sizes. The swept synthetic aperture method was used to produce as large an effective aperture as the available equipment allowed—a 6.4 cm sweep equivalent to a 7.36-cm aperture— and to synthetically create images from a range of aperture sizes.

System overview

An overview of the electronics in the experimental setup and their communications is given in Figure 1. The Siemens SC2000 ultrasound scanner (Siemens Healthcare, Mountain View, CA) was used with custom pulse sequences, described below, to acquire in-phase and quadrature (I/Q) ultrasound data at a sampling rate of 2.5 MHz. The transducer used was the Siemens 4Z1c volumetric (2-D) array, described in Table 1. Sub-apertures of 3×3 elements summed without phasing were used in receive to reduce the channel count. A 3-D mesh model of the transducer produced using the Faro ScanArm laser scanner (Faro, Lake Mary, FL, USA) was used to create a rigid custom attachment to the translation stage using Soft PLA plastic (MatterHackers, Foothill Ranch, CA, USA) with the Lulzbot Taz 5 3-D printer (Aleph Objects, Loveland, CO, USA).

The translation stage was run by the Newport XPS-Q8 motion controller (Newport, Irvine, CA, USA). The setup consisted of three Newport UTM100/ILS100 linear translation stages (5-μm on-axis accuracy and 1.5-μm unidirectional repeatability) mounted in orthogonal directions and one Newport URS50 rotation stage (0.03° accuracy and 0.002° unidirectional repeatability) mounted on the last translation stage axis to rotate in the x–z plane. The translation stages had a maximum travel distance of 10 cm in all directions. The transducer was mounted with the face

Table 1. Siemens 4Z1c transducer geometry, transmit and receive configurations

Property	Value
Geometry	2-D
Lateral pitch	0.4 mm
Lateral size	1.92 cm
Lateral channels	48 channels
Elevation pitch	0.4 mm
Elevation size	1.44 cm
Elevation channels	36 channels
Center frequency	2.5 MHz
Fractional bandwidth (approx.)	0.6
Sub-aperture size	3×3 channels
In-phase and quadrature sampling rate	2.5 MHz

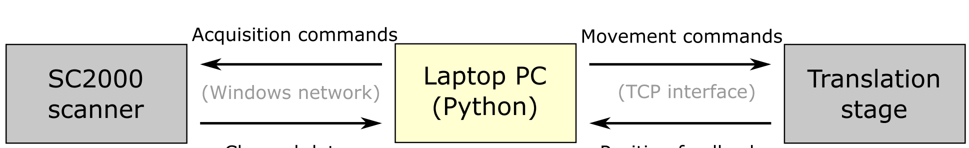

Fig. 1. Acquisition system diagram. The controlling PC (center) performed two-way communication with the translation stage and the Siemens SC2000 ultrasound scanner. Matrix channel data were stored for each transmission at each of the 207 translation stage positions.