Ultrasound in Med. & Biol., Vol. 36, No. 1, pp. 86–94, 2010

0301-5629/10/$–see front matter

ELSEVIER

doi:10.1016/j.ultrasmedbio.2009.08.004

● *Original Contribution*

TIME REVERSAL ACOUSTIC FOCUSING WITH A CATHETER BALLOON

YEGOR D. SINELNIKOV,* ALEXANDER M. SUTIN,† ANDREY Y. VEDERNIKOV,‡ and ARMEN P. SARVAZYAN†

*ProRhythm, Inc., Ronkonkoma, NY, USA; †Artann Laboratories, West Trenton, NJ, USA; and ‡Siemens Healthcare Sector, Moscow, Russia

(*Received* 1 *December* 2008; *revised* 22 *June* 2009; *in final form* 5 *August* 2009)

Abstract—The ability to deliver configurable myocardial lesions was noted as a critical factor to the success of atrial fibrillation (AF) treatment. This article considers the implementation of time reversal acoustics (TRA) principles for ultrasound focusing using an AF cardiac catheter developed for pulmonary vein isolation. Experiments conducted with a single transmitting channel demonstrated that a catheter balloon could be used as an acoustic reverberator to enable focusing and steering of ultrasound short pulses in the TRA mode. The spatial effectiveness of the TRA focusing was improved using a catheter balloon of irregular, asymmetric shape and using a binary mode of ultrasound radiation. The experiments demonstrated the ability of steering the focal point over several millimeters without degradation of the focusing quality. An ability of the TRA mode to produce suitable therapeutic application focusing of long continuous ultrasonic signals was characterized in a theoretical model. (E-mail: yegorasha@yahoo.com) © 2010 World Federation for Ultrasound in Medicine & Biology.

Key Words: **High-intensity focused ultrasound, Time reversal acoustics, Catheter, Atrial fibrillation.**

INTRODUCTION

Ultrasonic energy focusing is used in many medical therapeutic applications. Conventional means for acoustic focusing such as concave transducers, mirrors, lenses, and phased arrays work well in homogeneous media, but it is challenging to apply them in inhomogeneous media. For phased arrays, there are various methods of phase correction for focusing through media inhomogeneities. Some of these methods are based on the theoretical evaluation of sound propagation in a medium. Other methods require application of a hydrophone for signal-phase tuning (Clement et al. 2000; Sun and Hynynen 1999) and phase-conjugation (Derode et al. 2002). These methods provide focusing of harmonic signals produced by multi-element arrays. An alternative approach to ultrasound focusing is using the time reversal acoustics (TRA) principles (Fink 1997). It has been shown that TRA ultrasound focusing systems are capable of delivering and steering ultrasound to a chosen location in a heterogeneous medium (Montaldo et al. 2004a). Numerous reflections from boundaries and internal structures, otherwise disturbing conventional geometrical focusing, improve focusing in the TRA system. The excellent focusing ability of TRA has been used in various biomedical applications such as focusing through the skull and ribs (Fink 1997; Fink et al. 2003), where a multi-element array was used.

Effective TRA focusing can be constructed using just one or very few transducers attached to an acoustic reverberator, where numerous reflections from the reverberator walls form a multi-element virtual phased array (Montaldo et al. 2004b; Anderson et al. 2008). TRA focusing systems, composed of several transducers attached to an acoustic reverberator, were also used in several nonmedical applications such as nondestructive testing of materials (Sutin and Johnson 2005) and land mine detection (Sutin et al. 2006). The TRA focusing systems described in the literature are based on the use of solid and liquid reverberators (Fink 2008; Sinelnikov et al. 2006; Sutin and Sarvazyan 2003; Fillinger et al. 2007; Quieffin et al. 2004), with one or several transmitters glued to reverberator facets. A single transmitter is capable of focusing a broad frequency band signal with time reversal, whereas it is not possible to focus a long monochromatic signal with single-channel time reversal (Derode et al. 2002). The narrow band signals typically require the construction of a time reversal mirror that consists of a large number of elements and time reversal channels (Fink 2008; Tanter et al. 2007).

Address correspondence to: Yegor Sinelnikov, ProRhythm Inc., 105 Comac Street, Ronkonkoma, NY 11779. E-mail: yegorasha@yahoo.com

This paper presents the results of an experimental investigation of TRA focusing of short pulses using a catheter balloon as the reverberator. Complimentary theoretical modeling is used to compare the performance of short and long signals TRA focusing and recommends a therapeutic catheter design. The main goal of this work is to test the feasibility and quality of TRA focusing using a developed high-intensity focused ultrasound (HIFU) catheter balloon with a single ultrasound transducer. Measuring focal spot dimensions and focal spot steering using the time reversal principle is amongst the main objectives.

The HIFU catheter was developed to treat AF (Meininger et al. 2003; Wong et al. 2006) and was found effective in the creation of transmural thermal lesions (Okumara et al. 2008). The approach was based on the demonstrated effectiveness of the pulmonary vein (PV) electrical isolation, which markedly reduces the episodes of AF, common for cardiac arrhythmia (Haissaguerre et al. 1998). The use of HIFU for cardiac ablation (Zimmer et al. 1995; He et al. 1995; Hynynen et al. 1997) and its potential for clinical application (Lee et al. 2000; Engel et al. 2006) prompted the development of the HIFU catheter for AF ablation (Sinelnikov et al. 2009).

The HIFU catheter is inserted into a femoral vein and advanced into a left atrium through a trans-septal guiding sheath. First, the sheath is advanced through a vena cava into a right atrium and into the left atrium after transseptal puncture. Second, the HIFU catheter is inserted through the sheath, introduced into the left atrium. Then, the distal catheter balloon is inflated to a working size (Fig. 1). A physician then steers the catheter into position with the targeted PV and performs ablation. The catheter balloon serves as a parabolic reflector that forward focuses ultrasound into a ring of high intensity, which creates a circumferential lesion in PV ostia, with the diameter fully defined by the balloon geometry. Figure 1 illustrates an occlusion of the targeted left superior PV with the HIFU catheter: the interior of the PV is highlighted by an angiographic contrast. In this approach, the size of ostial lesion is fully defined by the geometry of the HIFU catheter balloon. If the PV orifice has a substantially different diameter than that of the balloon, the ablation procedure can be ineffective. An anterior-posterior diameter of the PV ostia varies between 9 and 27 mm according to a computed tomographic depiction study (Jongbloed et al. 2005). This warranted the development of a set of catheters with different size balloons, allowing physicians to make critical decisions about what size catheter to use for a particular PV. As a result, catheter exchanges became a common practice, lengthening the procedure and introducing additional risks to the patient (Reddy et al. 2008). On the basis of clinical experience, the clear and unmet need to develop a method to create circular lesions of different sizes using a single catheter emerged. Moreover, simultaneous isolation of ipsilateral PV and the ability to deliver linear lesions was noted as a critical factor to the success of AF treatment (Satomi et al. 2007). The existing HIFU catheter is unable to produce such accurate tailoring of the acoustic focus to target locations, whereas TRA focusing has the potential to create lesions of multiple size and shape without the need to replace catheters. The time reversal method also optimizes the ultrasound energy deposition at the focus, even if the medium is absorbing (Aubry et al. 2008). In this study, we present the evaluation of using the HIFU catheter balloon as an acoustic reverberator to focus ultrasound energy in TRA mode. As the balloon comes within close proximity of an atrial tissue, the focusing distance of 2 mm has been selected.

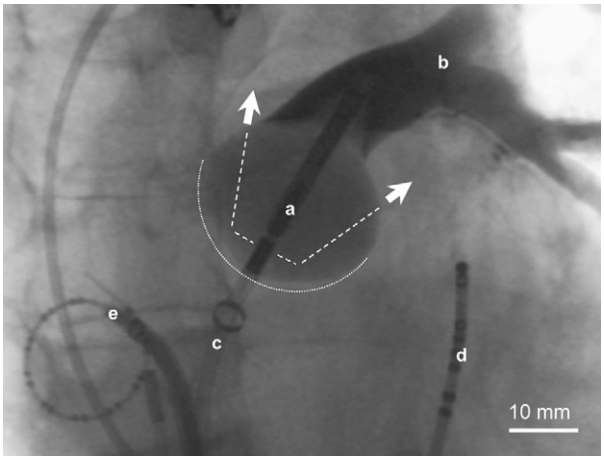

Fig. 1. The angiogram of the HIFU catheter balloon in the human heart. (a) The white dashed arrows outline the ultrasound path from cylindrical transducer inside a water-filled balloon and focused by a parabolic reflector interface (*dotted line*) into a PV atrial ostia (*large arrows*). (b) Left superior PV highlighted by angiographic contrast injection. (c) Transseptal delivery sheath. (d) Pacing catheter in coronary sinus vein. (e) Electrical mapping lasso catheter. Image is obtained following an institutional review board approved imaging protocol from the Medizinische Klinik Allgemeines Krankenhaus St. Georg in Hamburg, Germany.

METHODS

The original HIFU catheter balloon was designed to geometrically focus the ultrasound energy redirected by a proximal reflector. To create an acoustic reverberator necessary for accumulating acoustic energy in time and subsequently directing it to the target location using TRA principles, we added an additional distal reflector and a distal transducer as shown in Fig. 2. Two opposite reflectors enhanced reverberation of ultrasound inside the water balloon. A middle section of the water balloon was left transparent to ultrasound. The diameter of the balloon was 24 mm and ~10 mL of liquid was required to inflate it to a predefined shape. When inflated to the level of an operating pressure, the balloon repeated the