

● *Original Contribution***IMPACT OF PROPAGATING AND STANDING WAVES ON CAVITATION APPEARANCE**ALEXANDER M. KENIS, JAVIER GRINFELD, EYAL ZADICARIO, and SHUKI VITEK
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Abstract—Standing waves play a significant role in the appearance of cavitation phenomena. The goal of this study was to investigate the effect that the relation between standing and propagating waves in a focused field has on acoustic bubble cloud formation. Measurements of the cavitation signals were performed on five different configurations of a hemispheric phased array transducer (230 kHz) representing a wide range of relations between propagating and standing waves. The results show that configurations with a larger propagating component induce bubble clouds at lower pressures than configurations with a larger standing component. (E-mail: javiereg@insightec.com) © 2012 World Federation for Ultrasound in Medicine & Biology.

Key Words: Cavitation, Standing waves, Bubble clouds, Focused ultrasound.

INTRODUCTION

In the past years high-intensity focused ultrasound (HIFU) surgery has become a viable noninvasive therapeutic method. One of the most important and promising applications of this technology is in neurosurgery, in thermal ablation of brain tumors, functional neurosurgery (Martin et al. 2009), thrombolysis, (Daffertshofer et al. 2005; Hitchcock and Holland 2010) and disruption of the blood brain barrier (McDannold et al. 2008). The most addressed physical problems related to these treatments are the successful transmission of the ultrasound through the cranium (Hynynen et al. 1998; Sun et al. 1999; Clement et al. 2000; Gâteau et al. 2010) and different aspects of cavitation (Azuma et al. 2005; Hitchcock and Holland 2010). It is believed that reflection of ultrasound waves from the cranium causes the formation of standing waves, which in turn, contribute to the creation of bubbles and cavitation onset (Azuma et al. 2005). It is also regarded as one of the causes for intracranial bleeding under the combined influence of low frequency ultrasound and tissue plasminogen activator (tPA) (Daffertshofer et al. 2005; Baron et al. 2009).

Cavitation in standing waves has been widely researched in the past. The concentration of bubbles in the standing wave's antinodes can be explained by

Bjerknes forces that affect the bubbles in a stationary sound field (Crum 1975; Leighton et al. 1990). It is known to be affected by different parameters including frequency (Laufer and Thomas 1954), temperature, duty cycle, level of water degassing (Pickworth et al. 1988), pulse length (Pickworth et al. 1989), liquid's memory effects (Overton et al. 1984; Trevena 1984), etc.

Cavitation is known to aid in disruption of living cells (e.g., Kerr et al. 1989; Leighton 1994; Xu et al. 2005). It was found that cavitating bubble clouds cause more extensive damage than single cavitation events, within a volume of soft tissue (Xu et al. 2005). The cloud's appearance is a threshold phenomenon, which has been shown to be higher than the threshold for inertial cavitation (Willard 1953; Fowlkes et al. 1988). Previous studies have also shown the importance of high pressure waves, reflected from the initial cavitation bubbles, for the appearance of bubble clouds (Maxwell et al. 2009).

Though the appearance of standing waves is usually associated with reflection from the rigid or pressure release boundary, these waves are also present, to a varying degree, in focused ultrasonic fields. On the other hand, these fields also contain a significant portion of propagating waves. This article describes and analyzes a study of the impact that standing and propagating waves have on the cavitation phenomenon, specifically, the creation of macroscopic clouds, with the geometry and parameters that are applicable to HIFU brain treatments. The criterion "propagating wave ratio" is introduced to

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describe the ratio of propagating vs. standing wave components. Next, the experiment and the method of data processing are described. Further, the results of measurements in water and in an aqueous gel are presented, followed by a discussion of the results and conclusions.

The results show that waves with larger propagating components induce cavitating bubble clouds at lower pressures.

The propagating wave ratio

In real life, pure propagating or pure standing waves rarely exist. In most cases, there are combinations in varying degrees of these types of waves. There are two widely accepted ways to describe the ratio between these wave types: the percentage of the standing wave (PSW) and the standing wave ratio (SWR) (Leighton 1994):

$$\text{PSW} = \frac{P_{\text{ant}} - P_{\text{nod}}}{P_{\text{ant}} + P_{\text{nod}}}, \quad (1)$$

$$\text{SWR} = \frac{P_{\text{ant}}}{P_{\text{nod}}}, \quad (2)$$

where P_{nod} and P_{ant} are the pressure in the node and the antinode of the standing wave, respectively. These parameters were introduced to describe standing waves created by reflection from boundaries. However, they have limited capability when describing focused fields.

In general, the relationship between the propagating and the standing parts of a wave can be characterized by the acoustic power flow density, which is described by the Poynting vector. The time averaged acoustic intensity (another term for Poynting vector) $\vec{P}$ for the acoustic wave is defined as (Williams 1999)

$$\vec{P} = \left\langle \text{Im} \left(\frac{p^* \vec{\nabla} p}{2\omega\rho} \right) \right\rangle, \quad (3)$$

where p is the acoustic pressure, $\vec{\nabla} p$ is the pressure gradient, ω is the cyclic frequency ($2\pi f$), ρ is the medium density; $\langle \rangle$ stands for the time average and $*$ for the complex conjugate. The absolute value of the Poynting vector of a standing wave is zero, since no energy flows in any preferred direction. For a purely propagating plane wave, which does not have any standing component, the eqn (3) becomes

$$P_{\text{plane}} = \frac{p^2}{2c\rho}, \quad (4)$$

where c is the sound velocity of the medium. The absolute value of the Poynting vector of any other wave would be somewhere between zero and P_{plane} .

It would be convenient to define the criterion of the propagating wave ratio (PWR), which is part of the total intensity taken by the propagating component, as

$$\text{PWR} = \frac{|\vec{P}|}{p^2/(2c\rho)} = \frac{|\text{Im}(\vec{\nabla} p)|}{kp}. \quad (5)$$

The last expression is obtained by dividing by p , so at the points with zero pressure, $\text{PWR} = 0$.

For a purely standing wave, the PWR parameter is zero, whereas for a purely propagating wave, such as plane or expanding spherical waves, the PWR parameter is one. In the natural focal point of an ideal hemispheric transducer, the exact result is $\text{PWR} = 1/2$, i.e., the total acoustic wave consists of 50% standing and 50% propagating components.

The behavior of the presented propagating and standing wave parameters was tested with respect to the focal point of a specific hemispheric transducer intended for brain treatments (ExAblate 4000, 230 kHz; InSightec Ltd, Haifa, Israel), shown in Figure 1. The transducer is a phased array with 980 elements that are located on flat tiles placed on a hemisphere with a radius of 150 mm. Each tile contains nine elements, sized 10.7×10.7 mm. The Cartesian coordinate system's axes are shown in the center of transducer. They are surrounded by a light parallelogram, which is a square drawn in perspective that assists in drawing. Figure 1b shows the spatial locations of the 980 active elements' centers and the transducer's axes. The symmetry axis is Z, which is also the main acoustical axis. The phase and amplitude of each element are individually controlled, with all elements transmitting at a frequency of 230 kHz.

For this study, five configurations of the hemispheric transducer were defined. The first configuration consists of the full transducer array of 980 elements. In the second and third configurations, the hemispheric transducer was divided into two equal parts: a "cap" (second configuration) and a "ring" (third configuration) as shown in Figure 2 below. Figure 2a shows the top view where the wave propagation axis is perpendicular to the figure's plane and Figure 2b shows the side view with the propagation axis directed downwards. The "cap" elements are marked by blue asterisks; the "ring" elements are shown as red dots. Each configuration has the same area of 490 elements. For the fourth and the fifth configurations, the transducer has been further divided into two equal parts, a quarter of the transducer, with 245 elements (Fig. 3). These last configurations allow further differentiation between the propagating and standing wave components. The "cap" configurations are expected to provide mainly the propagating component, whereas the "ring" configurations are expected to be primarily the source of the standing component. The propagating and standing wave parameters are expected to provide a clear differentiation between the configurations with the dominating propagating and standing components.

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