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CAN ACOUSTIC VORTICES FRAGMENT KIDNEY STONES?

Sergio Maldonado-Ortega[1*], Enrique González-Mateo[1], Alejandro Cebrecos[1], Cesar D. Vera-Donoso[2], Alicia Carrión[1], Francisco Camarena[1], Noé Jiménez[1]

[1] Instituto de Instrumentación para Imagen Molecular (i3M), Universitat Politècnica de València (UPV) –Consejo Superior de Investigaciones Científicas (CSIC), Camino de Vera S/N, 46022 València, Spain

[2] Department of Urology, La Fe University and Polytechnic Hospital and Health Research Institute, Hospital La Fe, 46026 Valencia, Spain

ABSTRACT

Burst wave lithotripsy (BWL) is an ultrasound-based technique used to fragment kidney stones. In this proof-of-concept, we test a novel approach based on acoustic vortices to improve the efficiency of stone fragmentation. Acoustic vortices are wavefronts containing phase dislocations which carry pseudo-orbital angular momentum. These beams can be synthesized and focused by spherical phased-arrays which also enable beam steering and control the topological charge of vortices. Experiments were conducted using real and artificial kidney stones in water using a 128-channel therapeutic ultrasound phased-array transducer with 1.1-MHz central frequency. Sinusoidal-pulsed bursts of 20 cycles at 200-Hz pulse repetition frequency were generated. A confocal 128-element imaging probe monitored stones, while a camera recorded the fragmentation. Conventional BWL and single-topological-charge vortices were compared using same rarefaction pressure and, additionally, same energy. Artificial stones (Bego-stone) and real stones (calcium-oxalate-monohydrate and brushite) were tested. We observe that fragmentation speed is enhanced in a factor of two using vortices in artificial and real stones. Furthermore, vortices are a kind of defocused beams. Therefore, the mechanical index using vortices is lower than using BWL, resulting in a potentially less injurious therapy for surrounding tissues. These results demonstrate that acoustic vortices can enhance fragmentation using low-amplitude focused ultrasound.

Keywords: Acoustic vortices, Burst Wave Lithotripsy, Kidney stones

1. INTRODUCTION

Nephrolithiasis, or kidney stone disease, is a common and recurrent pathology affecting approximately up to a 20% of the population in some regions [1, 2]. It is characterized by the formation of solid crystalline deposits in the renal system [3]. Currently, shock wave lithotripsy (SWL) [4] remains a first-line, non-invasive treatment for renal calculi. SWL is an ultrasound-based technique used to eliminate these calculi based on high-energy acoustic pulses to fragment stones into smaller particles. However, SWL is associated with several limitations, including incomplete stone fragmentation, healthy tissue injury, and reduced efficacy [5, 6].

In recent years, burst wave lithotripsy (BWL) has emerged as a promising alternative to SWL [7]. This ultrasound-based technique, designed to fragment kidney stones using high-intensity and short-duration ultrasound bursts with low pressure amplitudes, improves precision and potentially reduces tissue damage. Preclinical and early clinical studies suggest that BWL may offer enhanced fragmentation efficiency and better patient outcomes compared to SWL [8-10].

Acoustic vortices are wavefronts with phase dislocations that carry pseudo-orbital angular momentum [11-13]. These specialized beams can be synthesized and precisely focused

*__Corresponding author__: smalort@upv.es

using spherical phased-array transducers, which also allow beam steering and the control of vortex topological charge.

In this proof-of-concept study, we explore a novel approach to improve conventional BWL which leverages acoustic vortices to enhance fragmentation efficiency [14] as shown in Fig. 1.

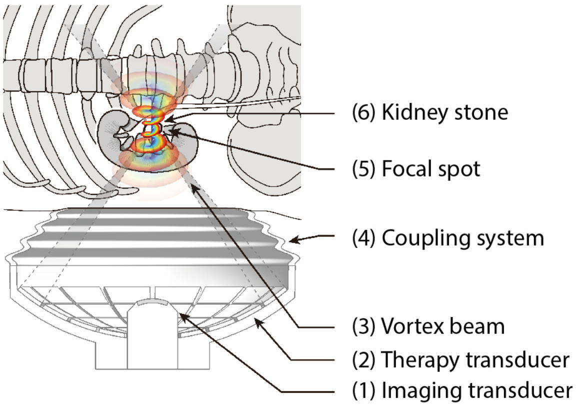

Figure 1. Schematic diagram of the proposed technique.

2. METHODS

Experiments were conducted to evaluate the feasibility of vortex-induced fragmentation using real and artificial kidney stones in a degassed-distilled water tank under controlled conditions. A 128-channel therapeutic ultrasound phased-array transducer, operating at a central frequency of 1.1 MHz, was used to deliver precise acoustic energy. The piezoelectric elements, arranged on a 150-mm diameter and 150-mm aperture bowl, generated sinusoidal pulsed bursts of 20 cycles at a 200-Hz pulse repetition frequency. Lower frequency and pulse repetition frequency are typically used in BWL experiments [15, 16].

A confocal 128-element ultrasound imaging probe enabled real-time monitoring of the stone and its progressive destruction, while a water-proof video camera recorded the fragmentation process enabling us to capture the fragmentation rates and patterns. The video of the experiment, once saved, was used for post-processing, in which the stone was segmented using a binary mask. This allowed us to determine the percentage of remaining stone.
The study compared conventional BWL with BWL enhanced by single-topological-charge acoustic vortices under identical rarefaction pressure conditions (8 MPa for both techniques) and at equal energy levels (8 MPa with vortex and 14 MPa with conventional BWL). Note that, since the focal spot volume is larger when using vortices, at similar energy values the mechanical index is reduced with vortices due to the lower applied pressure.

Artificial kidney stones were fabricated using cylindrical BegoStone [17, 18] samples of 2 mm radius and 10 mm height, with variations in the concrete-to-water ratio to replicate different mechanical properties of real kidney stones [19]. Concentrations of 3:1 and 5:1 were used in the experiments conducted with artificial stones. These two types of concentrations replicate Uric Acid and Calcium Oxalate Monohydrate (COM) real stones respectively. Experiments with real stones included the use of COM and Brushite samples, which were obtained from patients.

Both artificial and real stones were glued to a transparent film, ensuring they remained fixed to a non-rigid surface to enable the correct treatment without the displacement of the stone. This film was placed in 3D-printed structure designed to capture any fragments expelled from the surface of the stones.

3. RESULTS

We observed that acoustic vortices enhance fragmentation speed by a factor of two in artificial kidney stones and most real stones, with some exceptions. Fig. 2 illustrates the average fragmentation speed achieved across all experiments conducted with 3:1 artificial stones, which have similar properties to Uric Acid stones. The blue line represents experiments performed with acoustic vortices, while orange and gray lines correspond to experiments conducted without vortices. The orange line represents cases using the same rarefaction pressure as the vortex experiments. In contrast, gray line represents cases with the same energy levels as the vortex experiments, i.e., a much larger rarefaction pressure. Note that the fragmentation speed using conventional BWL is always slower, both for the same pressure and same energy levels, ensuring that the key factor leading to a more efficient fragmentation is the use of vortices.

In addition to the results presented in this work, similar experiments were conducted with 5:1 artificial stones, as well as with COM and Brushite real stones. Results obtained using real stones show a similar enhancement in fragmentation speed, with some exceptions that showed no enhancement. These may be attributed to variations in the size and shape of the treated stones, which can influence the fragmentation process. However, for all artificial stones, results remained consistent, doubling the fragmentation speed when using vortices.

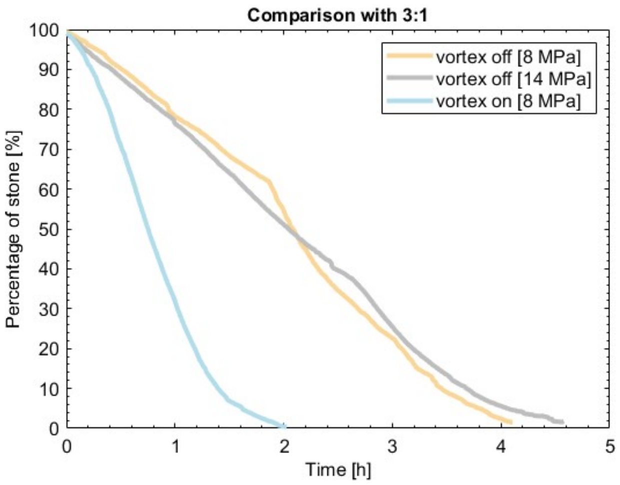

Figure 2. Evolution of the fragmentation as recorded by the video for the artificial stones of concentration 3:1.

4. CONCLUSION

The results indicate that acoustic vortices significantly enhance fragmentation speed, approximately doubling it in artificial kidney stones and in most real kidney stones. Additionally, due to the defocused nature of vortices, the mechanical index is reduced, suggesting potentially safer treatment for surrounding healthy tissue compared to conventional BWL. These findings demonstrate that acoustic vortices can effectively improve kidney stone fragmentation using low-amplitude focused ultrasound, offering a promising avenue for more efficient and less invasive lithotripsy techniques.

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