A sound option for the removal of kidney stones

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Ultrasound is well known for use in medical imaging and, at high intensities, as a therapeutic treatment. A perhaps less well known use is as a method of noninvasively trapping and manipulating particles in a fluid. In their paper in PNAS, Ghanem et al. (1) demonstrate how careful control of the acoustic field from a multitransducer ultrasonic array may be used to trap and move millimeter-sized particles in the bladder of live pigs. The motivation for the work is to use it as a method for the removal of small kidney stones with a noninvasive procedure.

The key component for the operation of the device is a 256-element circular focused ultrasonic array operating at 1.5 MHz. With independent control of the phase of the sound emitted from the elements in this array it is possible to produce complex and dynamically changing interference patterns in which small particles may be trapped and manipulated. A key innovation of the method is the production and application of acoustic vortex beams (2) that allow manipulation of particles from a single array and with sizes greater than the wavelength of the ultrasound used.

The ability to trap particles in the nodes of an acoustic standing wave is well known and can be traced back to the original work of Kundt in the 19th century. However, despite this early demonstration it took many decades and much work by highly respected scientists, including Lord Rayleigh (3) and Brillouin (4), before Gor'kov (5) and Bruus (6), following the work of King (7) and Yosioka and Kawasima (8), were able to develop a general theory for the trapping of spherical compressible spheres in an acoustic standing wave field.

Many simple devices using this principle have been developed for trapping and levitating small particles in both air and water (e.g., refs. 9–11). In these devices the field is usually produced by an ultrasonic emitter/reflector combination in a resonant system or with opposed ultrasonic transducers. In the latter case, provided the transducers are made nonreflective (with an antireflection quarter-wave coating or operating them precisely at resonance) the position of the nodes and hence the particles trapped in them can be moved by dynamically changing the phase difference between the two opposing transducers. The principle can be extended with orthogonal pairs of transducers to produce trapping in two dimensions and three dimensions. However, an important constraint for the Gor'kov theory, that is often seen as a limitation, is that the radius of the trapped particle, r, must be much less than the wavelength of the sound, λ. At 1.5 MHz in water $\lambda = 1$ mm so the limit for the particle size is a few hundred micrometers.

While simple and straightforward, the use of opposed transducers is impractical for medical applications. In contrast, a single, curved, multielement circular array can produce a standing wave field, with a focus determined by its curvature and without the need for a reflector or opposing transducer. However, although it may be used to produced focused ultrasound when the elements are driven in phase, it does not give rise to an acoustic field suitable for trapping or manipulating particles. Recently, Marzo et al. (12) have demonstrated how differently shaped traps (twin, bottle, and vortex) can be produced by multielement arrays by careful control of the relative phase of the ultrasound emitted by their individual elements. Furthermore, the limitation of $r << \lambda$ is lifted so that particles with $r > \lambda$ may be trapped and manipulated.

In their paper in PNAS, Ghanem et al. (1) have used this principle to generate vortex beams with their transducer array and they demonstrate the trapping and manipulation of millimeter-sized particles under ideal conditions and in vivo in live pigs. Vortex beams are generated by dividing the circular array into groups of transducers in separate segments that may each be driven with different phases. Helical wavefronts (vortices) are produced when neighboring segments are driven with a successive change in phase such that a total phase change of $2\pi M$ occurs for a circumferential circuit of the transducer (Fig. 1). Here M is an integer $\{\ldots, -2, -1, 0, 1, 2, \ldots\}$ defining the so-called topological charge for the emission. $M = 0$ corresponds to the case when all of the transducers are in phase and negative and positive values correspond to clockwise and anticlockwise rotation of the helical wavefront produced.

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Author contributions: A.C.B. wrote the paper.

The author declares no competing interest.

See companion article, "Noninvasive acoustic manipulation of objects in a living body," 10.1073/pnas.2001779117.

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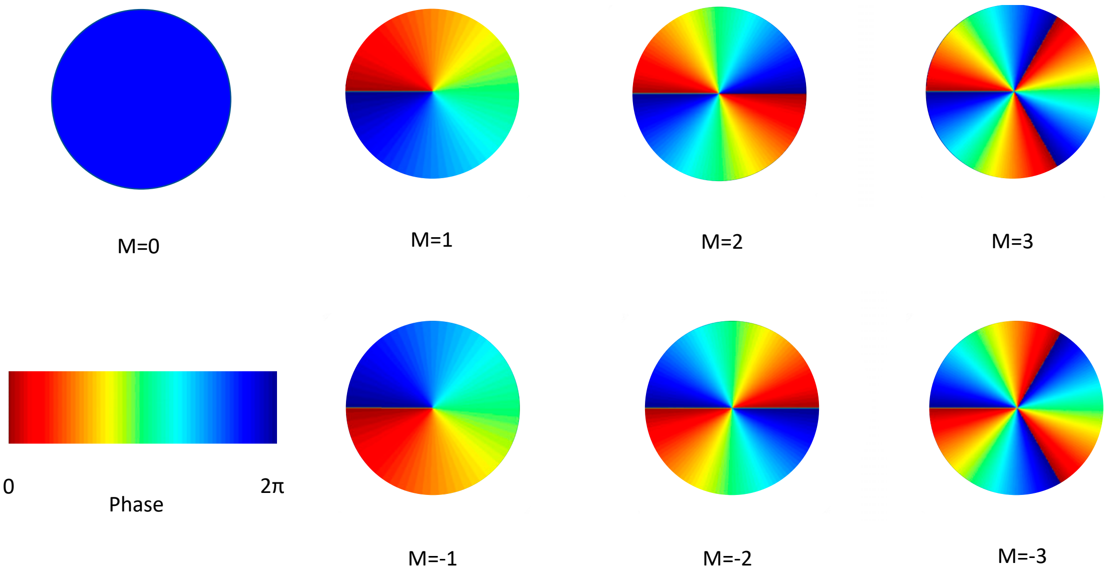

Fig. 1. **A representation of the topological charge for a segmented ultrasonic transducer. With M = 0 there is no phase difference in emission from the transducers. For integer M ≠ 0 there is a total phase change of 2πM when following a circumferential path around the transducer that gives rise to a helical wavefront. Positive and negative values of M give rise to clockwise or anticlockwise rotations of the helical wavefront. The phase discontinuity at the center of the array can be seen.**

When M ≠ 0 there is a phase discontinuity along the axis of the transducer so that there is always zero amplitude in the acoustic field along this line.

Although a complete theoretical understanding of the trapping in vortex beams is complex (12, 13) the net result is that ring-like traps are formed whose diameter increases as M increases. With this principle the ring traps can produce an upward force to balance the effect of gravity for a particle in the fluid. The ring also produces lateral inward forces so that the particle is consequently trapped at its center. A practical problem with vortex beam trapping is that the helical wavefront carries angular momentum that in turn will cause a particle in the trap to rotate. This can lead to instabilities and possible ejection of the particle from the trap. To avoid this problem, to obtain stable trapping the sign of M was rapidly switched so that the average angular momentum is zero over time.

To achieve movement of the particle in the fluid the position of the ring-like trap is electronically steered by additional dynamical changes in the phasing of the transducers. The vertical position of the particle can be controlled by changing the total power output of the array (that changes the net force balancing gravity), by changing M (the size of the ring in which the particle sits), or by superposing radial changes in phase over the transducer. The latter has the effect of changing the axial focusing position of the array. Lateral movement can be achieved by "striping" the phase over the transducer. Using a combination of these methods vertical and horizontal translations of 6 mm were achieved for a sphere with a 3-mm radius in a water tank. The extent of the movement was limited by the size, shape, and number of elements in the array.

The impressive result from this work is that successful particle manipulation was demonstrated in the much more acoustically complex environment of the bladder of a live pig, where acoustic contrast and reflections have the potential to disrupt and weaken the strength of the traps created. Furthermore, despite the relatively high power used, little evidence of tissue damage was observed following exposure. As such the method shows promise in, for example, the targeted removal of small kidney stones from the urinary tract.

Acoustic manipulation is emerging as a powerful technique for both medical and nonmedical applications. In many ways it is related to its optical analog of holographic tweezers (14), where fine control of phase in optical beams with spatial light modulators (SLMs) allows precise control and manipulation of submicron particles. Typically, SLMs have in excess of one-megapixel elements for tweezer applications. A framework of theoretical holographic acoustic elements that can be combined and used to define multiple trapping points and sample rotation from a multitransducer ultrasonic array in a similar way has already been developed (13). With the development of ultrasonic arrays with a larger number of phase-addressable transducers the technique demonstrated here could indeed lead to a revolutionary way for noninvasive removal of kidney stones.

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