Stone Tracking with Time-Reversal Techniques

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Abstract: The objective is to focus an ultrasonic beam in real time on a stone during lithotripsy. We propose to study the conception of a piezoelectric shock wave generator in which the focal zone is moved electronically to track the stone (1). For this purpose, we use the autofocusing property of time reversal mirrors (TRM) to track in real time a gall bladder or kidney stone embedded in its surrounding medium. We show that TRM allows us to obtain a sharp focusing on one bright point of the stone. The time of flight profile is then determined and used in a minimization method to calculate the spatial coordinates of the stone. Finally a high power beam could be steered on the coordinates of the stone.

Shock-wave generators are now currently used for the treatment of renal stones. One of the problem to overcome in the field of lithotripsy is related to stone motion due to breathing. Indeed, the lateral dimension of the shock wave in current lithotripsy devices is less than 5 mm and the amplitude of the stone displacement can reach up to 20 mm from the initial position. Hence, many shock waves miss the stone and submit neighboring tissues to unnecessary shocks that may cause local bleeding.

Different approaches have been investigated to overcome these limitations. Most of them are based on a trigger of the high power pulses when the stone goes through the focus of the shock wave generator. These approaches may reduce the number of shots needed to disintegrate the stone but increase considerably the time of treatment.

A time-reversal piezoelectric generator has been developed to electronically move the focus and track the stone during a lithotripsy treatment. Time-reversal experiments are performed with bidimensional transducer arrays working at a central frequency of 360 kHz, especially designed for lithotripsy. They are made of 121 prefocused piezo-composite transducer elements arranged on a spherical cup of 190 mm radius of curvature, Fig. 1. To illustrate the efficiency of the time-reversal approach, different focusing experiments will be presented where iterative time-reversal mode is used. The goal is to locate and focus on a given reflecting target among others, as for example, a stone in its surrounding: others stones and organ walls. Moreover, the stone is not a point like reflector but has dimensions up to ten times the wavelength. In the basic procedure that has been developed, the region of interest is first insonified by the transducer array. The reflected field is sensed on the whole array, time-reversed and retransmitted. As the process is iterated, the ultrasonic beam selects the target with the highest reflectivity. If the target is spatially extended (like a stone of dimension greater than the wavelength), the process converges on one spot, whose dimensions depend only on geometry of the time-reversal mirror and the wavelength. In order to explain the convergence of the focusing on a small portion of an extended target, we modeled the stone echo as resulting from a continuous set of target points of different scattering strengths. The first backscattered wavefront results from the interference pattern of the wavelets scattered by each elementary surface element of the stone. One of these surface elements yields a significant echo only if the wavelets scattered in its region interfere constructively on the surface of the transducer array. Such a bright point is located on a surface element for which the acoustic path is extremum (stationary phase theorem). For complicated stone structure we may observed different bright spots. Again, iteration of the time-reversal process allows to select the brightest one.

High amplification during the last iteration could be used to produce a shock wave for stone destruction. However, two problems limit this technique. For human applications, it is necessary to use very short high power signals (bipolar and unipolar pulses) to prevent damages caused in the organs by cavitation gas bubbles, while the time reversal process lengthens the pulses duration at each iteration. Besides, a complete time-reversal electronic is expensive and the number of time-reversal channels must be limited. To solve these problems, another procedure has been developed. In the first step, only a subgroup of the array is used in a time-reversed mode. This step is conducted with low power ultrasound in order to remain in linear acoustics and as seen previously, after some iterations, a low power ultrasonic beam, generated by the array subgroup, is focused on the stone. In the second step, a time of flight profile on the subgroup is deduced from the last set of received signals. In the third step, this time of flight profile is interpolated to the whole array. The final step consists in the generation, by the whole array, of very short high power signals with the correct delays.
In the second step, the time of flight between the bright point selected by the iterative time-reversal process and each transducer is determined. A classical mean to determine the arrival time of echoes from a point-like reflector is to use cross-correlation between signals from neighboring transducer elements. However, for a complex target like a stone, the spatial coherence of the backscattered wave can be very limited. Indeed, as seen in the previous experiment, specular echoes from an extended target may result from the interference of wavelets coming from several bright points and thus be very different from one element to the other. Moreover depending on the transducer element, one or two replicas of the specular echo can be observed. These replica come from either a reflection on the back side of the stone or the radiation of a creeping wave. The accuracy with which these arrival times can be estimated is then limited by the degree of correlation between received signals. The iterative time-reversal process is a spatial filter which selects the brightest surface element and hence, improve the level of coherence across the array. Nevertheless, the calculation of the relative times of flight between signals using the cross-correlation technique is time consuming and time-reversal process provides a very simple way to obtain these times of arrival. Indeed, the time-reversal process achieves an analogical correlation of the interelement impulse-response and so, the offsets of the peak in the signals measured after a time-reversal operation gives a much faster determination of the arrival times.

Finally in the third step, this set of experimental time delays is fitted to a model, that depends on the unknown spatial coordinates, x,y,z, of the bright point. The medium of propagation is assumed to be homogeneous (distortions due to refraction in tissues are very weak at 360 kHz). The estimated coordinates are used to steer a very short beam on the stone. The focusing obtained on the one hand with the iterative time-reversal process and on the other hand with time shifted pulses (according to the estimated coordinates) were compared. We observed that both acoustic beams focus at the same location and that this method improves spatial filtering: The main lobe is sharper and secondary lobe, corresponding to other stone or bright point, have been eliminated. Moreover, the time delay profile can be now interpolated to the 121 transducers, which allows the generation of the high power ultrasonic beam from the whole array. Another advantage of this optimization method is to provide controls on the process. First, the area of track can be limited and the shock wave triggered only if the estimated location of the stone is in the region defined by the physician. Secondly, the fit quality provides a way to assess whether the iterated echoes come from a single bright point.

A prototype especially designed for TRM experiments in the field of lithotripsy has been developed. It is able to calculate the coordinates of one bright point of the target in less than 40 ms and in a region of 60 mm along the axis and 40 mm laterally. Many in-vitro experiments with kidney or gall bladder stones have shown the efficiency of the method. In vivo-experiments have been performed, yielding very encouraging results.

REFERENCES