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2aBA9. Ultrasonic atomization: A mechanism of tissue fractionation
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High intensity focused ultrasound (HIFU) can be used to atomize liquid by creating a fountain on the surface exposed to air. The mechanism of atomization can be most accurately described by the cavitation-wave hypothesis wherein a combination of capillary waves excited on the liquid surface with cavitation beneath the surface produces a fine spray. Here, we show experimentally that a free tissue surface can also be atomized resulting in erosion of tissue from the surface. A 2-MHz spherically focused transducer operating at linearly predicted in situ intensities up to 14,000 W/cm$^2$ was focused at ex vivo bovine and porcine livers and in vivo porcine liver tissue surfaces without the capsule. The end result for both in vivo and ex vivo tissues was erosion from the surface. In bovine liver at the maximum intensity, the erosion volume reached 25.7±10.9 mm$^3$ using 300 10-ms pulses repeated at 1 Hz. Jet velocities for all tissues tested here were on the order of 10 m/s. Besides providing a mechanism for how HIFU can mechanically disrupt tissue, atomization may also explain how tissue is fractionated in boiling histotripsy.
INTRODUCTION

High intensity focused ultrasound (HIFU) has been used since 1927 to atomize liquids (Wood and Loomis, 1927). While the precise mechanism of atomization is unknown, the capillary-wave hypothesis most accurately describes what is observed when a liquid is atomized (Rozenberg, 1973). The hypothesis states that a combination of capillary waves parametrically excited on the liquid surface in conjunction with the collapse of cavitation bubbles beneath the liquid surface results in atomization or the ejection of fine particles from the surface. We recently showed that tissue can be atomized and that the result of atomization was erosion from the tissue surface (Simon, 2012). Here we compare the differences in atomization between ex vivo and in vivo tissues.

METHODS

A 2.165-MHz spherically focused transducer operating at linearly predicted in situ intensities up to 14,000 W/cm² (55 MPa peak positive and -12 MPa peak negative) was focused at the surface between bovine or porcine liver without the liver capsule and air as shown in fig. 1.a. Ex vivo tissues were placed in a custom-designed container, with the water level positioned just below the tissue surface to provide adequate coupling. In vivo porcine liver samples were exposed as shown in fig. 1.b, with the abdomen of the animal opened and the liver accessed. The transducer was coupled to the liver using a water-filled cone and Tegaderm™ membrane. For both experimental arrangements, the tissue thickness at the exposure location was 1-1.5 cm. The Photron APX-RS high speed camera (monochrome, San Diego, CA, USA) was used to visualize atomization at 10,000 fps, with a resolution of approximately 40 µm/pixel. Depending on the set-up constraints, experiments were either backlit (ex vivo) or back and side-lit (in vivo) with a Photogenic Powerlight 2500 DR (Bartlett, IL, USA).

RESULTS

Fig. 2 shows a sequence of images that detail atomization of ex vivo porcine liver. From the figure, it is apparent that atomization begins as a fine spray very quickly after the ultrasound wave arrives at the surface. The initial atomization spray is followed by the formation of a mound at 0.5 ms, with a slight cessation of atomization. As the mound develops, atomization becomes more dramatic, as seen in the last two frames of fig. 2. The velocity of the ejected fragments is on the order of 10 m/s, with the size of the ejected fragments ranging from tens to hundreds of microns in diameter. If the 10-ms pulses are strung together, the end result is a hole in tissue. While the erosion volume has not been carefully studied in porcine liver, in bovine liver at the maximum intensity, the erosion volume reached 25.7 ± 10.9 mm³ after 300 10-ms pulses repeated at 1 Hz (Simon, 2012).
Fig. 3 shows a sequence of high speed images (with the same time stamps as in fig. 2) taken in *in vivo* porcine liver at the maximum *in situ* intensity of 14,000 W/cm². In fig. 3, we see that atomization begins very quickly and becomes more dramatic with time. In addition, the spray looks liquid, most likely due to the presence of surface blood that appears when the liver capsule is cut. As compared to the *ex vivo* case where an obvious mound forms in tissue and enhances atomization, *in vivo* atomization becomes very dramatic with little to no mound forming over the duration of the pulse. The end result of *in vivo* atomization is surface erosion (not shown).

**DISCUSSION AND CONCLUSIONS**

In this paper, we showed that atomization occurs similarly between *in vivo* and *ex vivo* porcine livers. In fact, preliminary evidence suggests that the blood present in *in vivo* tissues enhances atomization and tissue erosion. Atomization may also explain how HIFU can mechanically disrupt tissue in techniques such as boiling histotripsy, where the boiling bubble is the tissue-vapor interface. Showing that atomization is successful *in vivo* is a step towards establishing atomization as a potential mechanism for boiling histotripsy, which is essential as it transitions into clinical applications.

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**REFERENCES**
