ULTRASONIC ATOMIZATION OF TISSUE: A MECHANISM FOR ULTRASOUND-BASED SURGERY

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INTRODUCTION

As the future of space flight involves longer missions, further from Earth, surgical intervention during flight may become a life-saving necessity due to a traumatic event or environmental factors. Focused ultrasound offers a non-invasive way to perform surgery and has been used to ablate or emulsify soft tissue tumors in the abdomen and sites of the brain and heart in addition to being used to treat benign prostatic hyperplasia, bone cancer, and more on Earth. My doctoral dissertation work explored ultrasonic atomization as a mechanism of mechanical tissue disruption in boiling histotripsy. Ultrasonic atomization is a phenomenon that occurs when an ultrasound wave in liquid encounters an air interface and ejects small liquid droplets into the air. Boiling histotripsy is a technique that was developed at the University of Washington that uses high intensity focused ultrasound (HIFU) to fractionate tissue into its submicron components. Boiling histotripsy works by rapidly heating tissue at the transducer focus to form a millimeter-diameter boiling bubble in a matter of milliseconds (figure 1, frames 1-3) which somehow fractionates the tissue into its submicron components; it is unclear how the millimeter-diameter bubble breaks the tissue into submicron components. We hypothesize that the boiling bubble is a large enough air or vapor interface to cause ultrasonic atomization of tissue within the boiling bubble which breaks the tissue into its submicron components.

METHODS

A 2-MHz HIFU transducer operating at a linear *in situ* intensity of 14,000 W/cm^2 (p_+ = 53 MPa, p_- = 12.7 MPa) was aligned with the surface of flat and curved (to approximate the 1-mm boiling bubble) air interfaces in *ex vivo* bovine liver and *ex vivo* and *in vivo* porcine livers. Exposures were 10-ms in duration and were filmed with a Photron high speed camera at speeds up to 20,000 frames per second with a resolution of 20 µm/pixel. Fountain jets were collected on a microscope slide and stained with Hematoxylin and Eosin (H&E) for histological analysis.

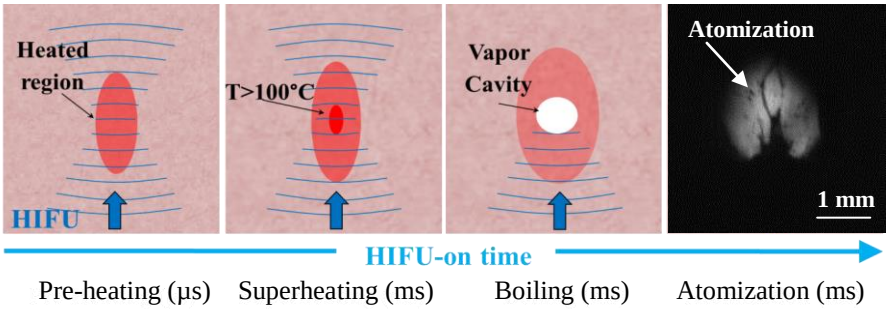

Figure 1: Frames 1-3 depict the proposed mechanism of atomization. Frame 4 shows a high speed video frame of atomization in a 1.5-mm diameter hole.

RESULTS

As shown in figure 1, frame 4, we observed tissue atomization with high speed photography, even when the air pocket was reduced down to 1-mm in diameter. The end result of atomization was a hole in tissue; in *ex vivo* bovine liver, the tissue erosion rate was approximately 0.15 ± 0.7 mm^3/10-ms pulse. When we analyzed the emitted jets histologically, we observed both intact and disrupted cells and nuclei. In addition, we found that *in vivo* atomization in porcine liver occurs very similarly to *ex vivo* atomization; the presence of blood appears to make atomization at least as efficient if not more efficient than the *ex vivo* case.

DISCUSSION/CONCLUSIONS

Ultrasonic atomization is the mechanism for tissue fractionation in boiling histotripsy. Even though the histological results differ from bulk boiling histotripsy in that the ejected droplets show whole cells in addition to disrupted cells, we have found that recirculating the fountain projectiles, as would happen in bulk histotripsy, further breaks up the tissue into its submicron components. Recognizing the potential of non-invasive ultrasonic surgery in space, we have been able to determine the mechanism of boiling histotripsy, which will aid its transfer to a clinical therapy. In the long term, boiling histotripsy could be used during space flight to non-invasively de-bulk tissue in a time-sensitive situation such as a urinary obstruction or a tumor that is causing pain. [Work supported by NIH DK43881, EB007643 and NSBRI through NASA NCC 9-58.