Mechanical Damage from a Growing Gas Bubble in the Spinal Cord *Ex-Vivo*

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ABSTRACT

- Spinal Cord Decompression Sickness (SC-DCS) is caused by the growth of inert gas bubbles in the spinal cord.
- We investigate the question how the growing bubble causes damage to the surrounding tissue.
- We create decompression gas bubbles in *ex-vivo* bovine spinal cords and then look at the response of the surrounding tissue to further bubble expansion using high-resolution magnetic resonance imaging (MRI).
- We find that the expanding gas bubble deforms the surrounding tissue irreversibly and not just elastically, likely by tearing it locally.
- We also note that the incidence of bubble formation in the *ex-vivo* tissue is low despite a very aggressive dive profile. This may indicate that vascular circulation is important for bubble nucleation.
- Our results suggest that SC-DCS can be viewed as a form of traumatic spinal cord injury, and that treatment strategies should focus not only on the elimination of the bubble, but also on treatment of the trauma caused by it.

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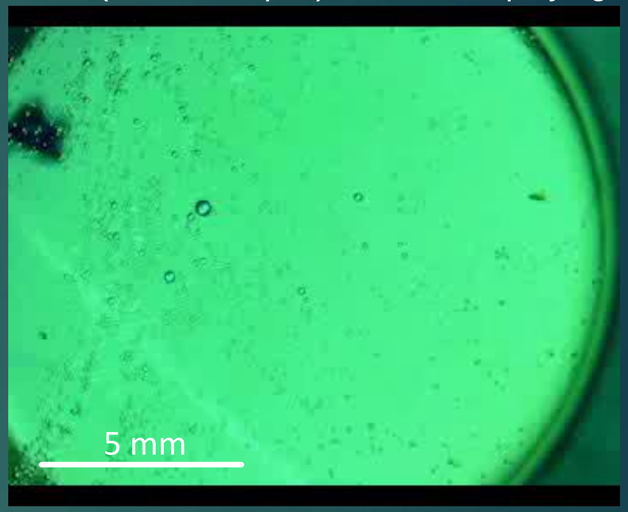
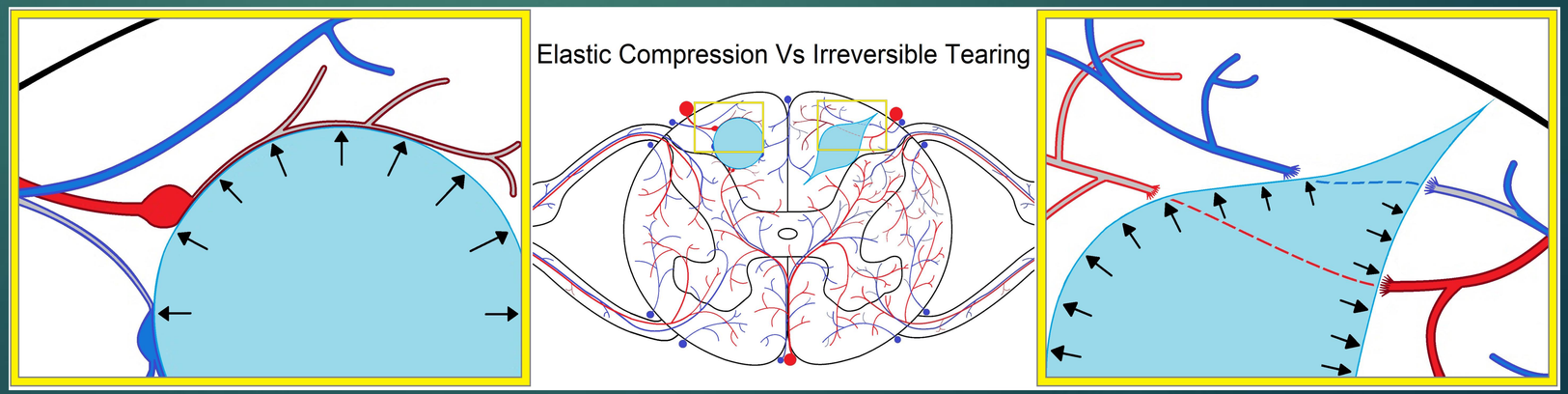
INTRODUCTION

- It is often assumed that the bubble deforms the surrounding tissue elastically, and tissue damage stems from ischemia as surrounding blood vessels are pinched off.
- In agarose phantom tissues, we have seen that growing decompression bubbles do not grow elastically like a balloon, but rupture the surrounding medium (see video on the right).
- Our question: Does a decompression bubble damage the spinal cord in a similar fashion, i.e. by tearing it, and not just elastically deforming it?

Bubble growth in an agarose phantom
Video (60x time lapse) - click if not playing





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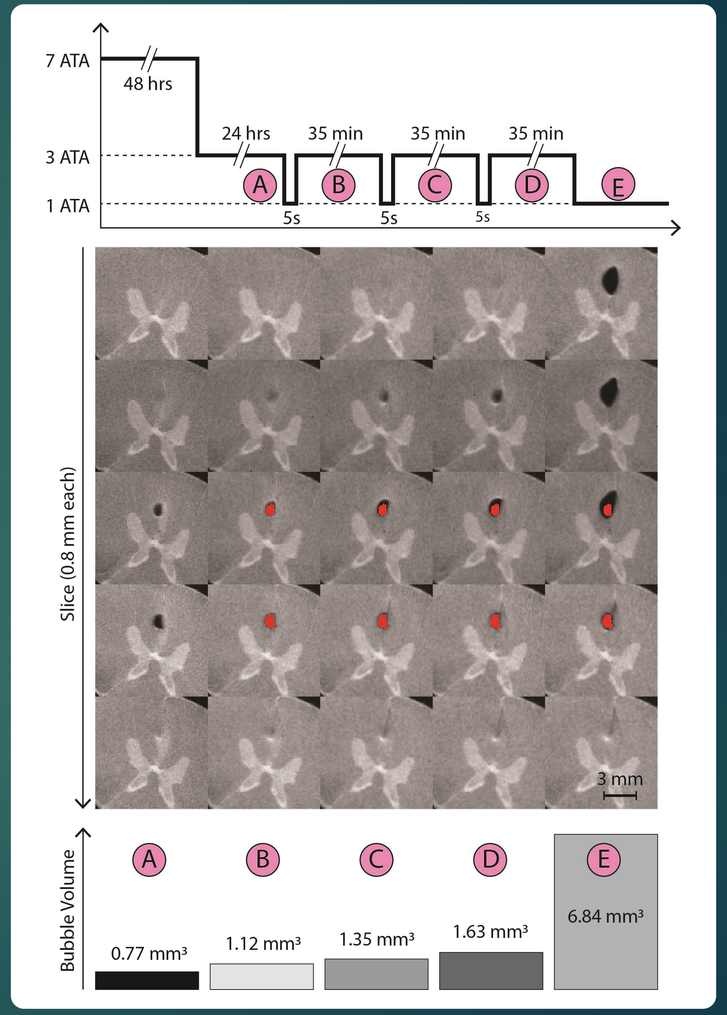
METHODS

- We create stable decompression bubbles in *ex-vivo* bovine spinal cords by compressing the tissue in 7ATA N_2 to saturation followed by rapid decompression to 3ATA. No further bubble growth or shrinkage is observed after 24 hours.
- The spinal cord is then imaged inside the MRI-compatible pressure chamber using a fast spin-echo (FSE) sequence. Images stacks are acquired in all three dimensions for volumetric analysis (A).
- The mechanical response of the tissue surrounding a bubble is then tested by rapidly decompressing the sample to 1ATA, and recompressing back to 3ATA in less than 5 seconds, followed by acquisition of another image. This cycle is repeated three times (B, C, D).
- Finally the sample is fully decompressed and another image stack is acquired (E).



Probing the mechanical response of the spinal cord through rapid pressure cycling

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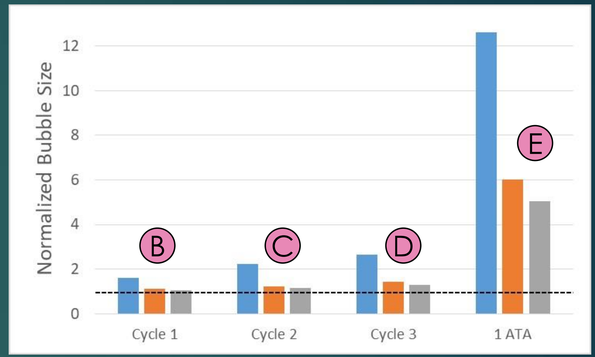
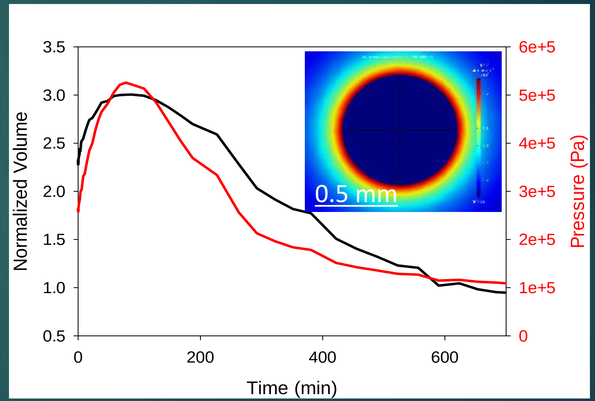
RESULTS

- Volumetric analysis of the MRI image stacks shows the bubbles grow with each rapid decompression / recompression cycle. They do not return to their original size, as elastic expansion would predict.
- The bubbles tend to grow the most along the axial direction.
- We observe a very low incidence of bubble formation (<10% of all samples) despite a rather aggressive dive profile. No bubbles were observed in the gray matter.
- Preliminary Finite Element (FE) simulations of bubble growth and resolution of a decompression bubble in an elastic medium show that the stress is narrowly concentrated around the bubble surface and high enough to potentially cause tearing.
- In this elastic model, the bubble shrinks because of the excess pressure exerted on it by the surrounding medium, dissolving within hours to a day. We do not observe this behavior in our experiments, suggesting that the excess pressure in the bubble negligible.

Growth of three different bubbles in response to pressure cycling





3D-FE simulation of the growth and resolution of a decompression bubble in an elastic medium. The inset shows the distribution of the stress in the medium surrounding the bubble at maximum size.

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CONCLUSIONS

- We have seen clear evidence for irreversible tissue deformation – most likely tearing – from expanding decompression gas bubbles in the spinal cord. We have ruled out a purely elastic, reversible expansion.
- We speculate that such traumatic injury to the spinal cord also happens in clinical cases of SC-DCS.
- The reduction of the internal pressure of the bubble from an expansion into the tear explains naturally why decompression bubbles do not dissolve on their own, unless the inert gas pressure in the tissue is further lowered by administering oxygen.
- Our pressure-cycling results suggest caution with repeat hyperbaric treatments for SC-DCS, as additional pressurization / depressurization cycles may potentially lead to a re-injury of the bubble-induced lesion.

ACKNOWLEDGMENTS

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