Laser-induced shock wave expanded nanobubbles in spherical geometry

Horvat D[(1)*], Agrež V[(1)], Požar T[(1)], Starman B[(1)], Halilovič M[(1)], Petkovšek R[(1)]

(1) Faculty of Mechanical Engineering, University of Ljubljana, Ljubljana, Slovenia

*Corresponding author's email: darja.horvat@fs.uni-lj.si

Background – Lasers are used routinely in many kinds of medical procedures, surgical and other, as well as for diagnostic purposes. Because of the versatility of laser methods their use is still growing. In any procedure, the optical energy absorbed in the tissue is converted to other forms - heat, chemical and mechanical energy. Following laser-induced breakdown in liquids or tissue the mechanical energy is often manifested in the rapid formation of a bubble and creation of shock waves which propagate into surrounding tissue. The evolution of the propagating wave depends on the geometry and can in special cases lead to effects that up to the present time were not researched or even understood enough and can in even be potentially harmful. Such a case could occur in eye surgery where the geometry is spherical, since the curved boundaries of the eye can focus also the generated shock waves, not just light.

In the study we investigate the propagation of laser induced shock waves in spherical geometry and the subsequent phenomenon of secondary cavitation.

Methods – Experiments were performed in distilled water in geometry exactly imitating the geometry of a human eye which is approximately a spherical object. Single shot laser pulses were tightly focused in various points inside the "eye" and the resulting phenomena, mainly the growing bubble and the propagating shock wave were recorded using schlieren technique, at several key points in time. In addition, a detailed simulation of the shock wave propagation using finite elements method (FEM), similar to the one described in [1] and [2] was performed to find the shape of the transient positive and negative pressure field of the shock wave.

Results – The experimental setup is based on a highly adaptable laser-diode-based illumination system which generates arbitrary trains of pulses having variable pulse duration and adjustable energies per pulse. The illumination system can be synchronized with an external trigger, in this case a camera. The system is designed to capture multiple snapshots of the same region at several times during a single frame. An example of a triple exposure showing the propagating shock wave at three instances (before it reaches the acoustical focal point, at the focal point and after it passes it) is shown in Fig. 1 (top row), together with the corresponding computed three pressure fields and the resulting simulated shadowgraph (second row). A single exposure shadowgraph of the same event, 5 µs later, is shown in the top row (right), with already visible secondary cavitation bubbles.

The experimental results allowed us to identify regions of secondary cavitation, that is the volume in which small bubbles occur after the passage of the negative pressure transient of the shock wave which was reflected at the curved boundary of the "eye" and thus focused.

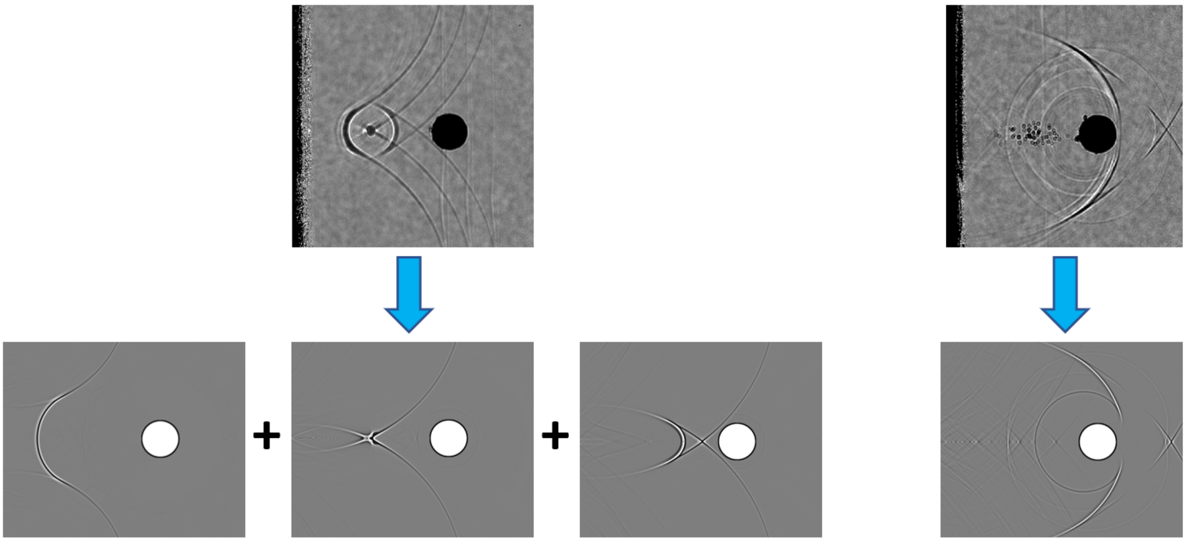

Fig. 1. Top row: A triple exposure schlieren shadowgraph of the reflected and focused shock wave approximately 10 μs after the laser induced breakdown with 0,75 μs between exposures (left) and a single exposure shadowgraph of the same event 5 μs later, at 15 μs after the breakdown. The secondary cavitation bubbles are already visible. The black circle is the bubble at the breakdown. Bottom row: numerical shadowgraph (simulation results) of the same event at approximately the same times. Here the bubble is white.

The comparison with the computation shows very good agreement and in general gives the expected results. In addition, the analysis reveals new features regarding the onset of secondary cavitation. The results namely suggest that the nanobubbles which are the prerequisite for the secondary cavitation are much more abundant in the volume which has recently been illuminated, supporting the findings of recent study by Roselló et al. [3]).

Conclusions – The secondary cavitation is initiated at the nanobubbles sites and is caused by the transient negative pressure of the propagating shock wave. The results of the study suggest that one possible mechanism for the introduction of nanobubbles into the liquid bulk is illumination. The knowledge of this effect allows one to avoid the possible unwanted consequences, while on the other hand, it can be a means to spatially and temporally control the generation of secondary bubbles in dedicated applications (drug delivery, bulk water cleaning).

References

[1] T. Požar, D. Horvat, B. Starman, M. Halilovič, R. Petkovšek, Pressure wave propagation effects in the eye after photoablation, J. Appl. Phys. 125(20) (2019) 204701. https://doi.org/10.1063/1.5094223.

[2] D. Horvat, T. Požar, B. Starman, M. Halilovič, R. Petkovšek, Pressure wave focusing effects following laser medical procedures in human eyes, Appl. Phys. A-Mat. Sci&Proc. 126(6) (2020) 414. https://doi.org/10.1007/s00339-020-03539-w.

[3] J.M. Rosselló, C.-D. Ohl, On-demand bulk nanobubble generation through pulsed laser illumination, Phys. Rev. Lett. 127(4) (2021) 044502-(1–6). https://doi.org/10.1103/PhysRevLett.127.044502.