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Laser-induced bubble dynamics inside and near a gap between a rigid boundary and an elastic membrane

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ABSTRACT

Aspects of laser-induced bubble dynamics in sample geometry closely resembling intraocular environment were studied. Laser pulses with a few millijoules of energy were focused into the sample, producing optical breakdown followed by formation of single bubbles. The sample consisted of a piece of polymethyl methacrylate (PMMA) material and a thin polyethylene (PE) elastic membrane which was carefully positioned parallel to the flat PMMA surface, creating a small and adjustable gap between them. The arrangement was placed in distilled water. Such geometry is frequently encountered in ophthalmology, specifically in posterior capsulotomy where there is a gap present between the intraocular lens and the posterior capsule. The formation and evolution of the laser-induced bubble was recorded with a high speed camera for different positions of the laser focus, i.e. inside the gap as well as outside the gap, in the water. The bubble dynamics was compared to the dynamics of the bubbles created near a rigid boundary alone and near an elastic membrane alone. The comparison showed that the evolution of the bubble created inside the gap can be described as a combination of the features which are characteristic for the rigid boundary and the elastic membrane cases, depending on relative dimensions of the gap and the bubble and on their relative positions. Possible influence on related medical procedures is discussed.

1. Introduction

Numerous laser medical procedures and other biomedical applications involve generation of bubbles in tissue, in various possible geometric configurations, e.g. bubbles near a rigid or elastic boundary or bubbles near a combined boundary, consisting of a rigid surface and an elastic membrane in close proximity (Walsh et al., 2011; Vogel and Venugopalan, 2011). Such complex boundary geometry occurs, for example, in posterior capsulotomy surgical procedure where a membrane-like elastic tissue called posterior capsule surrounds a rigid artificial intraocular lens. During the procedure the opacified elastic capsule is ruptured with a focused laser beam, improving the patient's vision (Aslam et al., 2003; Vogel et al., 1990). During the procedure a laser-induced bubble is formed inside or near a narrow gap between the intraocular lens and the posterior capsule. Understanding the mechanisms of laser-tissue interaction is of great importance for improving efficiency and safety of the procedure (Vogel et al., 1990). These mechanisms include dielectric breakdown and plasma formation in the focal area, subsequent bubble generation and growth, accompanied by shock wave emission and possible damage to the nearby tissue.

The bubble dynamics near a rigid boundary has been extensively studied by several authors (Vogel et al., 1989; Zhang et al., 1993; Blake and Gibson, 1987) as well as the bubble behavior near an elastic boundary (Brujan et al., 2001a, b; Klaseboer et al., 2006; Ohl et al., 2009) and near an elastic membrane (Turangan et al., 2006; Orthaber et al., 2014; Aghdam et al., 2012). The case of bubble evolution near a membrane is in many aspects different from the one near an elastic boundary (Turangan et al., 2006). The thickness of the membrane is expected to influence the bubble dynamics and should therefore be considered.

No reports were found on study of bubble dynamics in the case of a complex double boundary, i.e. a thin membrane stretched parallel to a rigid boundary, as it is encountered in the human eye in the case of posterior capsulotomy. Single bubbles generated near a thin membrane were experimentally studied in (Orthaber et al., 2014) where it was recognized that additional research is needed to create experimental conditions as similar as possible to the real conditions inside the eye during the posterior capsulotomy

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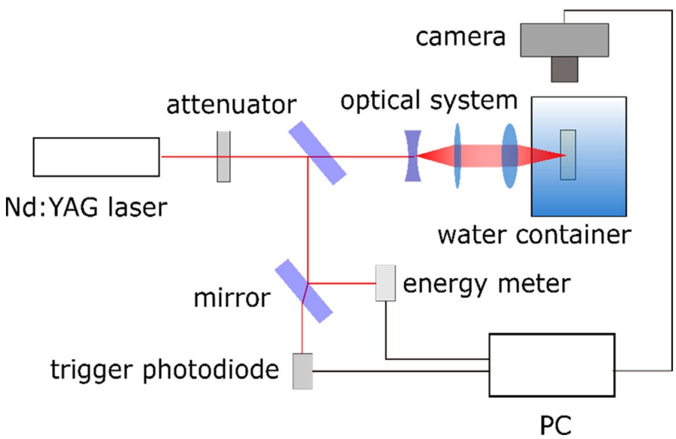

Fig. 1. Experimental system.

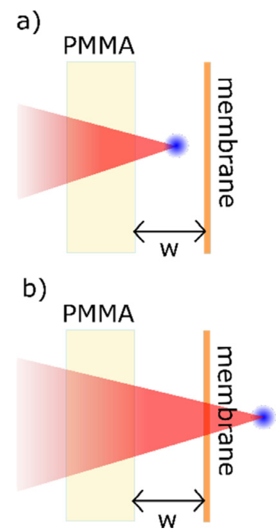

Fig. 2. Sample geometry. The laser beam is coming from the left and is focused a) inside the gap of width *w* between the PMMA and the membrane and b) to the right of the membrane, outside the gap.

procedure, mostly regarding the existence of a combined boundary, composed of solid material and elastic membrane.

After expansion to its maximum diameter, the laser-induced bubble collapses, then expands again and often goes through more than one such cycle. When the bubble is situated near a boundary, liquid jets are generally created during the bubble collapse which are directed towards the boundary in the case of a rigid boundary and away from it in the case of a free surface (Turangan et al., 2006). The dynamics depends on parameters such as maximum bubble diameter and distance between the bubble and the boundary as well as on the material properties. In an extended study of bubble interaction with elastic boundary (Brujan et al., 2001a, b) complex behavior was described, such as boundary deformation, bubble evolution into mushroom shaped formation and bubble splitting. Similar behavior was observed near a relatively thick membranes (Turangan et al., 2006; Aghdam et al., 2012) and near a very thin membrane (a few micrometers) in (Orthaber et al., 2014). The latter study showed how the cavitation bubble expansion and collapse causes significant deformation of the thin membrane and even its rupture. The behavior of the bubble created at different distances from the membrane was analyzed, revealing that the process is most destructive to the membrane at intermediate distances when the distance between the membrane and the bubble center was smaller than 70% of the bubble maximum radius. In this case the rupture produced in the membrane is largest and has well defined borders.

The present paper addresses the question of bubble dynamics near a complex boundary, which has characteristics both of the elastic membrane and of the rigid boundary. The goal of the study is to assess which of the two boundaries has more influence on the bubble dynamics, how the bubble dynamics is changed in the presence of the gap between them and how it is influenced by the gap width.

2. Experimental system

To gain further insight into the real processes in the eye during the capsulotomy procedure, a polyethylene (PE) elastic membrane was placed in close proximity (a few hundreds of microns) of a rigid boundary made of polymethyl methacrylate (PMMA) material, representing the intraocular lens. We experimentally analyzed the behavior of the bubble in the vicinity of this complex boundary, for different relative positions of the bubble with respect to the boundary. The analysis of the bubble dynamics in the vicinity of such a combined boundary is intended to contribute to accurate description of the medical procedure.

The experimental setup is shown schematically in Fig. 1. A Nd:YAG laser was used with pulse duration of approximately 5 ns (FWHM), at 2.5 mJ and 10 mJ of energy. The beam was first expanded to a diameter of approximately 40 mm and then tightly focused with a lens of 115 mm focal length to a diameter of a few micrometers into the sample. Optical breakdown occurred in the focal area, followed by bubble formation. The pulse energy was adjusted with a custom-built attenuator and measured with a calibrated energy meter.

The evolution of the laser-induced cavitation bubble inside the sample was recorded with a high-speed camera (HSFC PRO, 12 bit ultra-speed intensified imaging) with a frame rate of 100 kframes/s. Pulses from a 100 W laser diode with a wavelength of 808 nm were synchronized with the high-speed camera to serve as illumination. The time between consecutive frames was 10 µs and in some cases 5 µs.

The key component of the experimental system was the sample inside the water-filled glass container, designed with the intention to mimic the real conditions inside the human eye during the posterior capsulotomy. It consisted of a PMMA block representing the intraocular lens and an approximately 6 µm thick PE membrane, representing the posterior capsule. The membrane was placed parallel to the PMMA boundary, leaving a small gap between the PMMA and the PE membrane. The tension in the membrane, which was uniformly stretched in the radial direction, was approximately 2 N/m. The Young's modulus of the PE membrane was 0.24 GPa. The sample was placed in the center of the container, approximately 3 cm below the water surface. The gap between the PMMA and the PE membrane was adjustable and was set at 300, 800 and 1600 µm. The laser beam was precisely focused at various positions outside and inside the gap. The described sample geometry is shown in detail in Fig. 2.

3. Results and discussion

Several sequences were recorded with the described experimental setup, with different parameters. Results are presented here for laser pulse energies of 2.5 and 10 mJ, gap width of 300, 800 and 1600 µm and several relative positions of the bubble with respect to the boundary.

Sequences showing the dynamics of laser-induced bubbles and membrane deformation and rupture were analyzed and compared

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