Geometrical characterization of the cavitation bubble clouds produced by a clinical shock wave device

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Abstract This study was to optically visualize the cavitation bubbles produced by a clinical shock wave and to look into their geometric features of the resulting cavitation bubbles in relation to the driving shock wave field. A clinical shock wave therapeutic system was taken for shock wave production. The shock wave induced cavitation bubbles were captured by a professional camera under the illumination of a micro-pulse LED light. The light exposure was set to last for the whole life time of bubbles from formation to subsequent collapses. It was shown that the cavitation bubbles appeared mostly in the vicinity of the focus. The bubbles became more and larger as approaching to the focus. The cavitation bubbles formed jet streams which became enlarged (stronger) as the shock wave device output setting increased. The bubble cloud boundary was reasonably fitted to an elongated ellipsoid characteristically similar to the acoustic focal area. The bubble clouds were enlarged as the output setting increased. The geometric features of the cavitation bubbles characteristically similar to those of the focusing acoustic field have

potential to provide the therapeutic focal information without time consuming hydrophone measurements of the shock wave field causing damages of the expensive sensor. The present study is limited to the static afterimages of the cavitation bubbles and investigation including the bubble dynamics is suggested to deliver the more realistic therapeutic area of the shock wave therapy

Keywords Extracorporeal shock wave therapy · Shock wave field · Cavitation bubble cloud · Visualization · Therapeutic focal region

1 Introduction

Extracorporeal shock wave treatment employs shock waves produced outside body focused on to a target at depth in tissue to give various desired therapeutic effects. First of all, extracorporeal shock wave lithotripsy (ESWL) emerged from the middle of 1980s in treating kidney stone diseases [1–3]. The concept of ESWL is demonstrated in Fig. 1. The initial acoustic waves generated outside the patient are focused on the stone at depth inside body through the coupling medium and surrounding tissues. The focused shock wave has the pressure soaring up to thousand times of atmospheric pressure which is strong enough to fragment the stone [4, 5]. The crashed tiny stones are physiologically discharged through the urinary track. ESWL is now in a routine clinical use and is the first choice of treating kidney stone diseases. More than 90% of the patients with kidney stones are treated with ESWL alone or with ESWL combined with other auxiliary methods [6].

ESWL was evolved to extracorporeal shock wave therapy (ESWT) in orthopedics [7–9]. Since ESWT was approved for treating plantar fasciitis by FDA in 2000, it has been

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Fig. 1 The physical principle of ESWL (*top left*), the sequence of focusing of an initially cylindrically diverging waves by a parabolic reflector (*bottom*) onto the target stone, and the therapeutic process of

the clinical ESWL including stone disintegration by shock waves and discharge of the fragmented tiny stones through the urinary tract (*top right*)

rapidly accepted into clinical practices [10] and its main indication includes chronic tendinitis and pseudoarthrosis [11–14]. After the advent of orthopedic ESWT, the extracorporeal shock wave treatment has continuously evolved to various therapeutic forms for erectile dysfunction [15], wound healing [16, 17], lipolysis [18], and ischemic heart failure treatment [19–23]. The standard indications approved by International Society for Medical Shockwave Treatment (ISMST) apply to urology (extracorporeal and endocorporeal lithotripsy), chronic tendinopathies (plantar fasciitis with or without heel spur, achillestendon, radial epicondylopathy, rotator cuff with or without calcification, patella tendon, greater trochanteric pain syndrome) and impaired bone healing function (delayed bone healing, stress fractures, early stage of avascular bone necrosis, early stage osteochondritis dissecans, post-skeletal maturity) [24].

Extracorporeal shock wave therapy employs the intensive shock wave field tightly focused to target tissues [5, 25]. Such acoustic power is strong enough to always produce cavitation bubbles which are understood to play a critical role in the desired therapeutic effects [26–29]. Accordingly, the region treated by the shock wave therapy is likely mapped to the cavitation field rather than the driving shock wave field. However, the performance test of the therapeutic device and the treatment planning still rely on the shock wave field, such as beam focus, acoustic focal region and acoustic intensity. What's worse, the measurement of shock wave field requires an expensive

hydrophone, time consuming scan, and high level expertise, so that the precise information of the shock wave field is not readily available to clinical users.

In order to resolve those problems, we consider the shock wave induced cavitation field, in particular, its geometry which is expected to be effectively related to the targeted therapeutic area. In the present study, a relatively simple, economical, optical method was devised by which the cavitation bubbles were visualized under a micro pulse light and captured with a professional camera. The light was set to illuminate for the time period which covers the whole life time of bubbles from formation to collapse.

The aim of the study was to characterize the geometry of the shock wave induced cavitation bubble clouds which is expected to effectively disclose the therapeutic region of the shock wave therapy. The optical images of the cavitation bubble clouds were obtained for a clinical extracorporeal shock wave system and their geometric features are discussed in relation to the acoustic field which induces the cavitation.

2 Materials and methods

Cavitation bubbles were produced by a clinical shock wave and were visualized under the illumination of a short pulse light. The experimental setup is shown in Fig. 4, which mainly consists of a shock wave generator, water tank, a micro-second LED pulse light and a professional camera.

2.1 Shock wave generator

A clinical extracorporeal shock wave therapeutic system (ShineWave-Sonic, HnT Medical System, Seoul, Korea) was taken in the present study as the shock wave generator. Figure 2 shows a schematic diagram of the shock wave generator which is composed of a pulse power supply unit, an electromagnetic cylindrical shock wave transducer and a parabolic reflector (not shown in Fig. 2 but in Fig. 4). The capacitor (0.15 μF) in the pulse power supply is charged up to 20 kV and then discharged through the shock wave transducer which is simply a solenoid surrounded by a metallic membrane between which a thin insulating membrane is placed [30–32]. A strong current pulse (~ 10 kA) flowing through the solenoid, induces an electromagnetic force that enables the metallic membrane to vibrate, which eventually results in a mechanical pulse [33, 34]. The acoustic pulse is cylindrically diverging and focused on a target location by the parabolic reflector (Fig. 4). The intensity of the shock wave is controlled by the charging voltage [34].

2.2 Acoustic output measurement

An optical hydrophone (FOPH2000, RP Acoustics, Germany) was used to measure shock waves. The hydrophone detects the variation of light reflection at the fiber-water interface caused by instantaneous changes in the pressure or density of water. A schematic principle of the pressure detection via light reflection at the tip of the optical fiber is illustrated in Fig. 3, together with a photograph of the main unit and the photodetector. The hydrophone is preferred in

Fig. 2 A schematic diagram of the electromagnetic cylindrical shock wave transducer used in a clinical extracorporeal shock wave therapeutic system (ShineWave-Sonic, HnT Medical System, Korea), together with a photograph of the therapeutic system (top right) (by courtesy of ref. 36)

measuring shock waves because it has a wide band width (several hundred MHz) enabling it to sense the nano-second shock front. In addition, it is robust to such strong electromagnetic noises generated by the pulse power supply unit employed in the shock wave generator [35].

As reported in Kang et al. [36], the hydrophone can not only measure shock waves but also record the signals resulting from the cavitation bubbles produced by the shock wave, if the hydrophone is set to record signals for a long time more than several hundred times of shock wave life time (several micro-seconds). The focal acoustic outputs were measured using the optical hydrophone as the shock wave generator settings varied. The signal detected by the optical hydrophone was acquired by and stored on a digital oscilloscope (NI-5122, 100MS/s, 8 M RAM, National Instruments, USA) to display as well as to further process.

2.3 Visualization of cavitation bubble clouds

The shock wave induced cavitation bubbles have a life time of several hundred micro-seconds [36]. They were visualized under the illumination of a micro-second pulse light. Figure 4 illustrates schematically the main part of the experimental setup for visualizing the cavitation bubbles produced by the shock wave generator under the micro-pulse LED light. A trigger pulse from the function generator (33250A, Agilent Tech., USA) was used to operate the shock wave generator and the light system controller (MPLL, KIS tech, Korea). After a preset time (50 μs), the MPLL controller triggered the micro pulse LED light (MPLL, KIS tech, Korea) to illuminate the cavitation bubbles in the dark space.

The cavitation bubble cloud visualized under the micro-pulse light was captured using a professional camera (EOS

Fig. 3 A schematic principle of the pressure detection via light reflection at the tip of the optical fiber hydrophone FOPH2000, together with the photographs of the main unit and the photodetector (bottom left). (http://www.rp-acoustics.de/english/Hydrophone_FOPH2000.htm. Accessed on 11 Nov 2016)

Fig. 4 A schematic illustration of the main part of the experimental setup for visualizing the cavitation bubbles produced by the shock wave generator under a micro-pulse LED light

5D Mark III, Canon Inc., Japan) with a macro lens (EF 100 mm F2.8L Macro IS USM, Canon Inc., Japan). The shutter and iris of the camera remained open to acquire the optical image of the bubbles during the light exposure. It should be noted that the cavitation bubbles are dynamically activated (non-linearly oscillate, rapidly move) and the captured optical image is an afterimage which accumulates a series of the temporally varying behaviors of bubbles during light exposure. The light exposure time was set to cover the whole life time of bubbles from formation to collapses which is in the order of several hundred micro-seconds.

3 Results

3.1 Focal acoustic signals

The shock waves was generated in tap water at a room temperature of 25 °C where the subsequent shock wave induced cavitation bubbles were formed. The resulting acoustic signals were recorded for 350 μ s after triggering the shock wave generator using the optical fiber hydrophone whose sensing tip was located at the focus (F) as the charging voltage settings varied.

Figure 5 shows the acoustic signals measured at the charging voltage 16.75, 17.75 and 19.75 kV, which were overlapped with 50 repeating measurements. As pointed out in the figure, the shock wave appears first and lasts for about 5 μ s. It produces cavitation bubbles which persist for

several hundred micro-seconds. The light reflection by the bubbles in front of the optical fiber tip results in a strong optical signal output for a long time which is called cavitation related signal [36]. The magnitude of the shock wave and the subsequent cavitation related signal increases with the setting voltages.

Detailed plot of the shock waves is presented in Fig. 6a for the different charging voltages (16.75, 17.75 and 19.75 kV). Note that the waveforms represent the mean of 50 repeated measurements. The shock wave has a very short rise time to the peak positive pressure (p+) up to more than 40 MPa and followed by the relatively slow reduction to the negative peak pressure (p-) down to -10 MPa. The large acoustic pressures, in particular, the large negative pressure lasting for a relatively long time (3 times longer than the positive pressure period), engender cavitation bubbles. The peak positive and negative pressures can be controlled by the voltage settings as shown in Fig. 6b illustrating that the magnitude of the peak pressures increases almost linearly with the output setting.

The shock wave induced cavitation bubbles are in nature chaotic, unstable, non-linearly oscillate, gradually grow and eventually violently collapse [5, 26, 27, 31, 36]. As marked in the cavitation related signals in Fig. 5, the characteristic stages of the bubble formation and the subsequent violent inertial collapse are easily noticed in the hydrophone measurements. Note that the time delay to the inertial bubble collapse from the bubble formation increased with the charging voltage setting [31, 36].

Fig. 5 The time history of the acoustic signals recorded for 350 μ s after triggering the shock wave generator with the optical fiber hydrophone located in water at the focus of the shock wave generator whose charging voltage was **a** 16.75 kV, **b** 17.75 kV and **c** 19.75 kV. The signals were overlapped with 50 repeated acquisitions. The shock wave appears first which lasts for about 5 μ s and produces cavitation bubbles (bubble formation) followed by the noticeable broad band acoustic emission when they violently collapse (inertial bubble collapse). The light reflection by the bubbles in front of the optical fiber tip results in a strong optical signal output for a long time (cavitation related signal) illustrating the characteristic structure of the bubble formation and the subsequent violent inertial collapse

3.2 Cavitation bubble cloud

The shock wave induced cavitation bubbles were visualized under the micro-pulse light illuminated for the 300 μ s which covers the whole life time of the bubbles from formation and violent inertial collapse. Figure 7 shows a series of 20 images of the cavitation bubbles captured repeatedly under the illumination of the micro pulse LED light for the time delay from 50 to 350 μ s after the shock wave generator was triggered. The time waiting for the subsequent shock wave generation for repeating measurement was set to 1 min so as to assure that all the remaining bubbles produced by the preceding shock wave were completely dissolved. Note that the shock wave propagates from right to left on the image. It is shown that the cavitation bubbles sparsely appear near the focus. The more

Fig. 6 The detailed plots of **a** shock waveforms and **b** their peak positive and negative pressures which were measured at the focus at the charging voltage **a** 16.75 kV, **b** 17.75 kV and **c** 19.75 kV of the shock wave generator

and the larger bubbles are observed as the voltage setting increases. Small bubbles appear in the pre-focal region (right side of the images). Such features are well kept on the images repeatedly captured.

The 20 images were merged into one image so as to clearly feature the bubble clouds including their silhouette (Fig. 8). The bubbles mostly appeared in the acoustic focal regions, as seen in Fig. 8, and, as approached to the focus, the bubbles become more and larger. The silhouettes of the cavitation bubbles look like bubble jet streams. The jet streams get stronger as the setting increases. The boundary of the bubble clouds is well fitted to an elongated ellipsoid centered at the focus which is characteristically similar to the acoustic focal region. The geometrical parameters, the width, depth and area of the ellipsoidal bubble clouds, defined in Fig. 9, were measured and displayed in Fig. 10 as the voltage setting increased. As seen in Fig. 10, the values of each parameter almost linearly increase with the setting voltage.

Fig. 7 The images of the cavitation bubble clouds captured under the light exposure during the whole life time of the bubbles, 50–350 μ s after triggering the shock wave generator at the charging voltage of the shock wave device **a** 16.75 kV, **b** 17.75 kV and **c** 19.75 kV

(repeating 20 times). Note that shock wave production interval was 1 min and the shock wave propagated from *right to left* side on the images

Fig. 8 The cavitation bubble cloud which are merged with the 20 images shown in Fig. 7, at the charging voltage of **a** 16.75 kV, **b** 17.75 kV, and **c** 19.75 kV. Note that the intersection of the *dotted line* indicates the location of geometric focal point, and the shock wave propagates from *right to left* on the images

Fig. 9 The boundary of cavitation bubble cloud fitted to an elongated ellipsoid with the parameters of width (w) and depth (d). Note that the shock wave propagates from *right to left* side on the image

4 Discussion

In this study the shock wave induced cavitation bubbles were successfully visualized under the micro-pulse light. The light was set to illuminate for the time period of 300 μ s which covers the whole life time of the bubbles from formation to collapse. The captured images demonstrate that the silhouettes of the cavitation bubbles appear like bubble jet streams centered at the focus. The jet streams are

Fig. 10 The measured geometrical parameter **a** area, **b** depth and **c** width of the cavitation bubble cloud boundaries against the setting voltages

stronger with the shock wave generator output setting. The bubble density and size are observed to be subject to the output settings and locations. The boundary of the bubble clouds was reasonably fitted to an elongated ellipsoid centered at the focus, which is similar to the acoustic focal region. The ellipsoid size of the bubble cloud is found to almost linearly increase with the setting voltage.

As observed, the density and size of bubbles vary with the relative location from the focus, suggesting that they are closely associated with the spatial distribution of the acoustic pressure. Figure 11 contrasts the cavitation bubble cloud image (bottom) to the axial profiles of the shock wave peak pressures measured at the charging voltage settings of 19.75 kV using an x–y–z positioner assembled with three linear translation stages. Note that the shock wave propagates from right to left. It is shown that the density and size of the bubbles vary characteristically along

Fig. 11 Axial acoustic peak pressure profiles of the shock waves in contrast to the cavitation bubble cloud image at the charging voltage settings of 19.75 kV. Note that the shock wave propagates from *right to left*

with the axial distance being similar to the axial peak pressure distributions, even if it is not feasible to quantify the variations from the image yet. However, since the boundary of the bubble clouds are easily identified and well fitted to an elongated ellipsoid, a quantitative comparative analysis between the acoustic and the cavitation regions is possible in the focal width and depth.

As described in the introduction, the measurement of shock waves requires an expensive hydrophone and high level expertise. To obtain the precise acoustic focal field, time consuming scanning hydrophone damaging process is required. The image of the cavitation bubbles is optically captured quickly and easily. Accordingly, the present optical method is practically useful to deliver the geometrical features of the acoustic focal region, even if the precise shock wave measurement is not possible. The conditions for obtaining the optical image of the cavitation bubbles such as the illumination time and the number of images to overlap need to be optimized for making better estimation of the geometry of acoustic field.

The present study is limited to the static images of the cavitation bubbles which are overlapped over the whole life time of bubbles. In fact, the bubbles are dynamically activated by shock waves and their temporal behaviors are chaotic throughout from formation to collapse (Fig. 5). The therapeutic effect is more closely associated with bubble dynamics, in particular, the violent inertial collapses. To

observe the dynamic variations of the bubbles, we may need to look into a number of the sequential images captured at a very short time interval in the order of nano-second for the whole bubble life time. In order to obtain such images, we need a fast speed camera which may not be currently readily available. Note that the present micro-pulse light can reduce the illumination time to several ten micro-seconds. Nevertheless, the captured afterimages which accumulate all the temporal histories of cavitation bubbles are still valuable, because they provide the information of the probable area and location of the significant bubble activities. The geometrical information about the cavitation bubbles which is easily obtainable may be practically useful to predict the size and location of therapeutic region. Investigation to include the dynamic activities of the cavitation bubbles is required to effectively deliver the realistic therapeutic regions of the shock wave therapy.

The present practical optical method may have potential for the quality assurance of the therapeutic devices. The present performance test of the therapeutic device requires the precise information of the focal intensity and region which are technically difficult for clinical users to obtain. In order to assure if the device works as it was released from manufacturers, the relative deviation from the standard working condition needs to be examined. If we regularly obtain the optical images of the cavitation bubbles which are easily captured by clinical users, the comparison of them to the standard image obtained under the normal working condition enables clinical users to test the performance of the therapeutic device. A future work for the construction of a simplified tool kit for the quality assurance purpose is suggested for clinical users to assure the clinical efficacy as well as patient safety.

5 Conclusions

The optical images of the shock wave induced cavitation bubble clouds were successfully captured under the illumination of a micro-second LED light, demonstrating that they hold the geometrical features of the acoustic focal region. This result suggests that the cavitation bubble image may in part be substituted for a time consuming expensive hydrophone damaging scanning process for accurate shock wave field measurements. Admitting that cavitation plays an important role in therapeutic effects and the cavitation bubble geometry is closely associated with the true therapeutic region, the optical bubble image has clinical potential over the acoustic field. Further studies are suggested to relate the cavitation bubble images to clinical outcomes.

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