Numerical Simulation of the Micro-explosion during Ho:YAG laser lithotripsy

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Abstract: The micro-explosion during Ho:YAG laser lithotripsy may cause calculus fragmentation and migration. It plays an important role to the surgery. A numerical simulation of the micro-explosion during Ho:YAG laser lithotripsy has been developed. The explosion problem in water environment was solved by the Euler algorithm and the piecewise parabolic method (PPM) was selected in the calculation. This simulation investigated the explosion dynamics evolution in the lithotripsy area. The pressure and intensity of the calculus surface were calculated for different laser pulse energy and different distance between calculus and fiber tip. The calculation results indicate that the micro-explosion’s properties are determined by the pulse energy, pulse duration and the water distance. Though Short pulse duration and large pulse energy cause high ablation efficiency, it mains more calculus retropulsion at the same time. The ideal surgery results need property laser parameters.

Key words: laser lithotripsy, numerical simulation, micro-explosion, Ho:YAG laser

1. Introduction

Laser lithotripsy is considered to be a most convenient, economical and less painful technique for destruction of calculus formed in human body. The Ho:YAG pulse laser energy is delivered to the calculus by a thin fiber and ablated it in water environment1,2. The water between calculus and fiber tip high absorbs the pulse infrared laser energy and induced micro-explosion threshold3. The micro-explosion dynamics may give help to the ablation ability and make calculus migrates away from the laser delivery fiber tip on one hand, on the other had it cause the calculus retropulsion during laser lithotripsy. This retropulsive calculus movement will prolong operative time and affect the surgery precision, so the investigation of micro-explosion evolution in the lithotripsy is important to the operation. The micro-explosion evolution was simulated for different laser pulse energy and different distance between calculus and fiber tip here. The pressure and intensity of the calculus were calculated and the retropulsion would be predicted. It will give help to the operation.

2. Theoretical model
The pulse laser is delivered to calculus by a thin fiber and had a small spot during laser lithotripsy. The micro-explosion effect area on the calculus is very small\(^2\), so the calculus surface will be assumed to be plan and the laser beam irradiates perpendicularly in our numerical model. As shown in fig.1, we will investigate micro-explosion process from the axis-symmetric two-dimensional (2D) model.

![Figure 1. Scheme of the numerical model](image)

The experimental investigations indicate that the explosion process of water for free infrared laser irradiation is sudden vaporization and expansion\(^4,5\). No plasma is observed in the explosion process, so the explosion may be considered from thermodynamic viewpoint\(^6-9\). The explosion dynamics problem may be solved from the model with the fluid equations for the conservation of mass, momentum and energy. The Euler algorithm is applied to simulate the explosion problem in the calculation field. The piecewise parabolic method (PPM) is selected in the calculation\(^10,11\).

During the explosion the water absorbs great energy suddenly and transits to vapor rapidly. The heat conduction can be ignored because of the explosion duration is so short and the water heat conductivity is very small relatively. The inviscid fluid 2D Euler equations (continuity, momentum and energy) for axisymmetric geometries are as follows:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z} (\rho u) + \frac{1}{r} \frac{\partial}{\partial r} (rpv) &= 0 \\
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial z} + v \frac{\partial u}{\partial r} \right) &= -\frac{\partial p}{\partial z} \\
\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial z} + v \frac{\partial v}{\partial r} \right) &= -\frac{\partial p}{\partial r} \\
\rho \left( \frac{\partial e}{\partial t} + u \frac{\partial e}{\partial z} + v \frac{\partial e}{\partial r} \right) &= -p \left[ \frac{\partial u}{\partial z} + \frac{1}{r} \frac{\partial}{\partial r} (rv) \right] + S
\end{align*}
\]

Where the \(u\) and \(v\) is the velocity vector in respective axial (\(z\)) and radial (\(r\)) co-ordinates; \(\rho\) is the mass density; \(p\) is the pressure and \(e\) is the specific internal energy. The source term, \(S\), represents the laser energy absorbed by water.

In this study the reflection and the influence to the absorption by the water temperature and phase transition is not been considered. According to the Lambert-Beer theory, the intensity of the laser beam inside water at every instant is given by:\(^12,13\)

\[
I(r, z) = I_0 \exp(-k_0 \rho z) \exp(-2r^2/w^2)
\]
Where \( z \) is the laser transmit depth in the water; \( I_0 \) is the radiation intensity of the central point on the fiber tip. It may be calculated from the pulse energy and pulse duration; \( k_0 \) is the absorption constant of water and be calculated from the absorption coefficient listed in table 1; \( w \) is the beam waist and \( r \) is the radial distance from the center of the laser spot. It should be noted that the intensity of the laser beam is constant over time. The local heat deposition, \( S \), per unit area and time over a slice of material with thickness \( z \) is given by:

\[
S(r, z) = -\frac{\partial I(r, z)}{\partial z} = k_0 \rho I(r, z)
\] (6)

The absorption of radiation by the water was simulated by generating heat in certain elements. The heat generating value was considered constant over each element and calculated according to Eqs.(5,6) by taking the coordinates of one of the element’s nodes.

| Laser   | Laser Wavelength (\( \mu m \)) | Absorption Coefficient of H\(_2\)O (cm\(^{-1}\)) |
|---------|---------------------------------|-----------------------------------------------|
| Ho:YAG  | 2.1                             | 25                                            |

The system of Eqs.(1-4) with definitions by Eqs.(5,6) is closed by means of an equation of state (EOS). During the explosion process the water will be in liquid, vapor or liquid vapor coexisting phase. Precisely describing the water thermodynamic properties during the phase evolution needs water thermodynamic state line or water thermodynamic state database. In this study the water thermodynamic properties will be simply described by bender equation.\(^{15,16}\)

\[
p = \rho T[R + B \rho + C \rho^2 + D \rho^3 + E \rho^4 + F \rho^5 + (G + H \rho^2) \rho^2 \exp(-a_{20} \rho^2)]
\] (7)

Where \( T \) is the water temperature; \( R \) is the constants. \( B, C, D, E, F, G \) and \( H \) is the function of \( T \) and \( \rho \). The expression of them and the parameters \( a_{1r}-a_{20} \) for water have been given in the literature\(^{15}\). The water temperature \( T \) is given by\(^{17}\):

\[
e = e_p + c_v (T - T_0)
\] (8)

Where \( c_v \) is the specific heat, here using the average value; \( e_p \) and \( T_0 \) are the specific internal energy and temperature determined at the water melting point.

Modeling the micro-explosion formal approach to the PPM programming, firstly, the fluid dynamic equations are solved in Lagrangian co-ordinates for the Riemann problem and get the average velocities and energy of the every unit. Secondly, the results remapped on to the original finite difference Eulerian grid.\(^{11}\)

In our calculation model, a boundary condition of rigid wall is used at the surface of the hard target and the symmetry axis. The conditions at the outer boundary can be taken as free boundary condition. The water parameters are taken as at normal conditions.

### 3. Calculation results and discussion

According to the general operation, we sat the fiber diameter 0.4mm and pulse duration 400\( \mu \)s in our calculation. The numerical model provides all of the details of the laser induced explosion process. Fig.2 shows the pressure evolution in the calculation field during the explosion process \((E=2J,\)
$h = 0.5\text{mm})$. The water absorbs great laser energy and transits to vapor rapidly. The rapid phase transition leads to strong expansion and the explosion takes place. The pressure of the water between calculus and fiber tip is increasing rapidly after the beginning of the laser pulse. The vapor plume and water droplets formed during the explosion are accelerated by the rapid expansion and eject around. The great shock wave caused high pressure on the calculus surface. The vapor pushed aside the water and a vapor hole came into being. These properties of the numerical model accord well with the experiment results in the literature.\textsuperscript{2} Fig.3 shows the vapor and water density evolution during the explosion. The vapor and water density in the explosion area decreasing rapidly and the Ho:YAG laser may transmit to the calculus through the vapor hole at that time.

![Figure 2](image1.png)  
(t=5\mu s)  
(t=20\mu s)  
**Figure 2.** Pressure distribution evolution during the explosion ($E=2\text{J}, h=0.5\text{mm}$)

![Figure 3](image2.png)  
(t=5\mu s)  
(t=20\mu s)  
**Figure 3.** Water vapor density distribution evolution during the explosion ($E=2\text{J}, h=0.5\text{mm}$)

Fig.4 gives the pressure distribution evolution induced by the explosion shock wave on the calculus surface. It indicates that the pressure on the calculus doesn’t have a steady increase during the explosion. There is a particular duration for the special parameters. The high-pressure area centralizes under the laser spot and the peak pressure takes place near the symmetry central point A (see Fig.1). From the figure we should find that the pressure evolution of point A approximately represents the pressure evolution process of the whole calculus surface. The dynamics characters for the special parameters will be got from the pressure of point A. Fig.5 shows the pressure evolution of point A for different laser pulse energy. It indicates that the pressure increases rapidly and has a high peak pressure value for high laser pulse energy. The peak pressure value for the laser pulse energy 2J is about 70MPa and the value for the laser pulse energy 0.3J is only about 15MPa. The micro-explosion caused pressure on the calculus surface increases rapidly with the laser pulse energy increase.
Figure 4. Pressure distribution evolution on the calculus surface ($E=2J$, $h=0.5\text{mm}$)

Figure 5. Pressure evolution of the point A for different pulse energy (a. 2J, b. 0.8J, c. 0.3J, $h=0.5\text{mm}$)

Fig. 6 gives the comparison of the pressure evolution in different distance between calculus and fiber tip. It indicates that the high pressure duration increases with the water distance increase. From fig. 7 we can see that the intensity of impulse increases rapidly with the distance between calculus and fiber tip increase. It will cause more calculus retropulsion in the laser lithotripsy.

Figure 6. Pressure evolution of point A for different water distance (a. 0.2mm, b.0.5mm, c. 1.5mm, $E=2J$)

Figure 7. Intensity of impulse distribution on the calculus surface for different water distance (a. 0.2mm, b.0.5mm, c. 1.5mm, $E=2J$)

4. Conclusions

In summary we have developed a fluid dynamics model to describe the water vapor micro-explosion during Ho:YAG laser lithotripsy. From the calculation results, we can see that the micro-explosion has its special duration and dynamic characters. They are mainly determined by such parameters—laser pulse energy, pulse duration and water distance between calculus and fiber tip. High pulse laser energy gets high force on the calculus surface and mains high efficiency during ablation process. The Intensity of impulse on the calculus surface will increase rapidly with the water distance increasing. This may cause the calculus retropulsion more and has disadvantage to the surgery, so the fiber tip should be put near the calculus during laser lithotripsy. The
ideal surgery results need property parameters.

This simulation investigated the water vapor explosion dynamics evolution only. The Ho:YAG laser will act on the calculus directly after the water vapor hole formed. The more detail in laser lithotripsy needs more investigation.

5. References

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