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附骨边壁约束下激光诱导非球形空泡溃灭射流消融机理

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激光诱导微射流技术是利用激光在液体介质中诱导空泡产生高速微射流消融靶组织的医疗手段，具有热损伤小、精度高等优点。在附骨边壁约束下，激光诱导的空泡在垂直方向上受到骨壁面限制，该空泡呈现非球形，激光诱导非球形空泡的研究更适合骨科临床。因此，本文分析基于不同无量纲距离处的空泡半径及泡壁运动速度等统计参数，重点探究空泡溃灭过程中的非球形特征及其随时间和距离的变化，最终阐明激光诱导非球形空泡溃灭微射流矢量的动力学及其与输出组织消融的标度关系。研究表明，空泡质心到骨边壁的无量纲距离（γ）对空泡非球形演化与骨组织消融具有显著的影响。当 γ 值从 0.1 提升到 0.7 时，激光诱导空泡溃灭射流平均速度从 35 m/s 降低至 24 m/s，射流冲击压力从 124 MPa 降至 85 MPa，骨组织表面的消融蚀坑深度从 1020 μm 降低至 260 μm，消融蚀坑的径深比从 0.7 增至 1.9；消融蚀坑的直径与射流直径呈正相关关系，消融蚀坑的深度与射流速度呈正相关关系，消融蚀坑的径深比与射流速度呈负相关关系，调整无量纲距离（γ）能够有效调控射流矢量。通过激光诱导空泡非球形溃灭射流消融骨组织机理的研究，提供一种高时空精度的光能转变为机械能的可控手段，为实现激光诱导微射流高效消融生物硬组织的应用提供理论依据和技术支撑。

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关键词：激光诱导空泡；骨壁约束；空泡溃灭；非球形特征；组织消融

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Ablation mechanism of laser-induced cavitation non-spherical bubble collapsing micro-jet under the constraint of the bone wall

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Laser-induced liquid micro-jet technology is a medical method that uses lasers to induce cavitation bubbles used to generate micro-jets to ablate target tissue with the merits of low thermal damage and high precision. However, a laser-induced cavitation bubble is not-free standing but rather is confined in one direction by the bone wall. Therefore, the assumption of a non-spherical shape has a better fit for a cavitation bubble according to real clinical circumstances. Therefore, this paper explores the statistical parameters such as bubble radius and bubble wall velocity based on different dimensionless distances, the dynamics of a laser-induced non-spherical bubble collapsing micro-jet vector as well as its scaling relationship with the output tissue ablation are described. Results show that the velocities of the micro-jets with normalized stand-off distances (γ) from 0.1 to 0.7 are determined in the range of 24-35 m/s, while the corresponding micro-jet impact strength on the bone tissue is about 85.2-123.5 MPa, the corresponding crater depths are in the range of 260-1020 μm with a diameter-to-depth ratio of 0.7 to 1.9. The crater depth and diameter are positively dependent on the micro-jet velocity and diameter, and the micro-jet vector can be effectively adjusted via the control of γ. The study on the mechanism of laser-induced cavitation non-spherical bubble collapsing micro-jet ablation of bone tissue, providing theoretical basis and technical support for the application of laser-induced micro-jet ablation of biological hard tissue. This work was supported by Beijing Natural Science Foundation (3214041), Scientific Research Key Program of Beijing Municipal Commission of Education (KZ202110005012) and National Natural Science Foundation of China (51975017).

Keywords: Laser induced cavitation; Bone wall restraint; Bubble collapse; Non-spherical characteristics; Tissue ablation.

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