Prediction of thermal damage of three-dimensional bio-tissues in moving laser therapy

The thermotherapy is a useful approach in medical field, such as hyperthermia, laser soldering, laser ablation, laser surgery and other thermal treatment methods. In order to maximize the therapeutic efficiency while ensuring the patients' safety, the thermal damage induced by the laser beam need to be predicted precisely.

The thermal damage is due to the temperature increment. So the first step is to select a proper heat conduction model to obtain the temperature distribution. The heat conduction process in living tissues is complicated because of the involvement of the heat conduction between blood and tissues, blood perfusion in vascular beds and metabolic heat generation. In addition, the thermal relaxation time in skin can be of several seconds, so the non-Fourier effects should be considered. The dual-phase-lag bio-heat conduction model is adopted in this work by considering the phase lags of both heat flux and temperature gradient, which allowed either the temperature gradient to precede heat flux vector or the heat flux vector to precede temperature gradient.

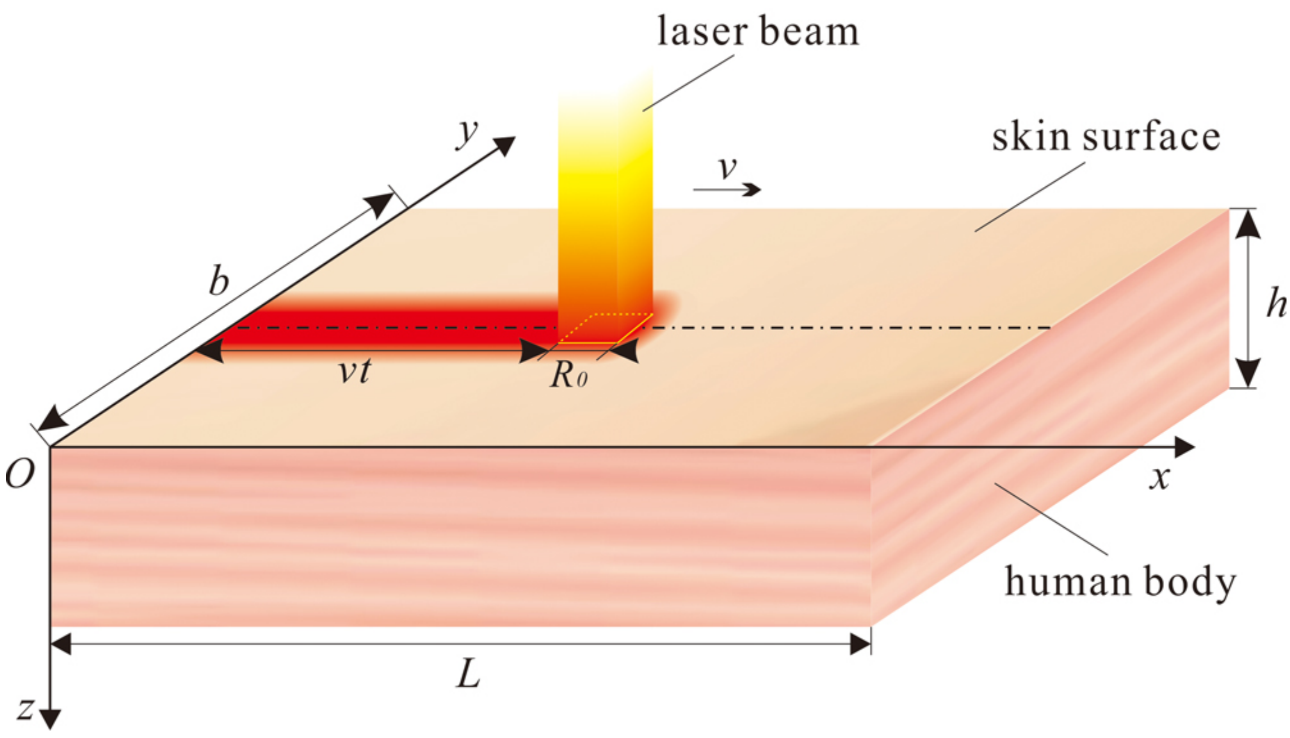

Fig. 1. Illustration of the human tissue irradiated to a moving laser beam.

The Henriques' thermal damage model was employed to study the burnt damage. Usually three burn degrees are accepted according to the evaluation parameter of burn damage which is related to the denaturation rate.

The human tissue is modelled as a cuboid as shown in Figure 1. The top surface of the human tissue is irradiated by a square laser spot, which moves along the middle axis at a constant speed.

The thermal conductivity of bio-tissue is small, so the burn mainly occurs in a small vicinity region of the irradiated area where the laser energy is concentrated.

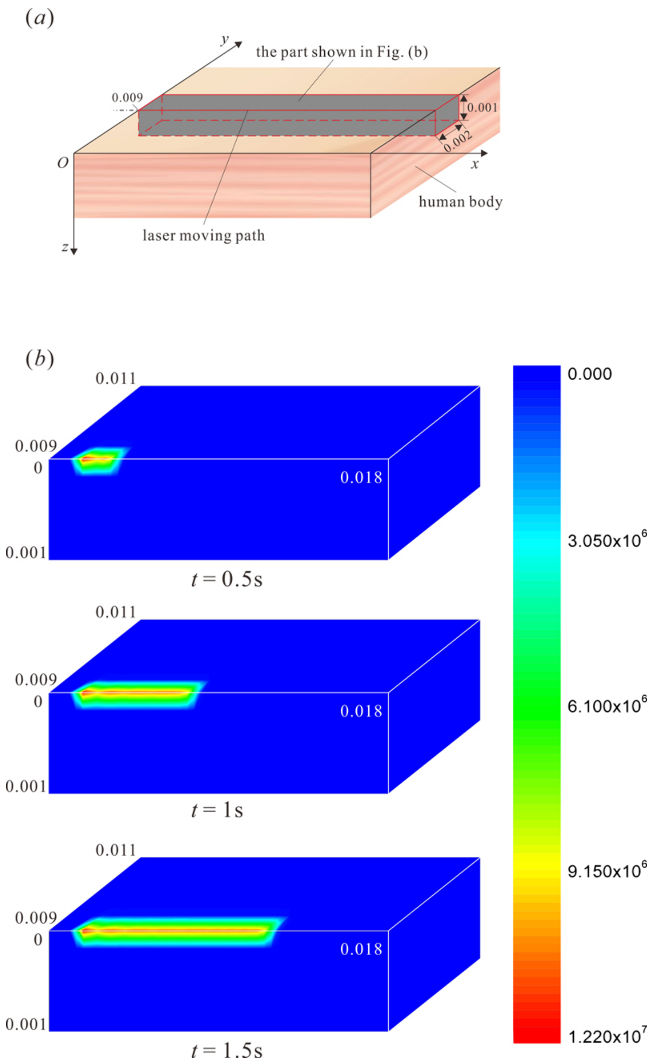

Fig. 2. Distribution of thermal damage in the tissue. (a) The sketch of the selected part for the exhibition of thermal damage distribution; (b) Empyrosis distribution in the heat-affected zone.

The empyrosis distribution in an appropriate part of the target tissue (the grey part in Figure 2(a)) is exhibited in Figure 2(b) in order for a clarified description of the thermal damage. It is obvious in Figure 2 that the empyrosis occurs in the area subjected to the laser irradiation. The most severe burn appears along the center line of the affected area on the top surface.

The laser moving speed and the laser spot size greatly influence the thermal damage by affecting the energy concentration degree. The increases of the laser moving speed and laser spot size can enlarge the irradiated region and reduce the burn degree. With the comparison with spot size, the laser moving speed has greater influence on the burn depth.

The two thermal relaxation parameters of heat flux and temperature gradient also show distinct influences on the thermal damage. The phase lag of heat flux delays the thermal energy propagating from the irradiated region to the vicinity. Consequently, the thermal accumulation and burn degree increase with the increment of the phase lag of heat flux. The depths of first- and second-degree burn reduce gently with the phase lag of heat flux, but the depth of third-degree burn is more sensitive. On the contrary, the phase lag of temperature gradient delays the temperature response in the target tissue, implying the energy transmission occurs before the temperature varying. The phase lag of temperature gradient impedes the thermal accumulation and reduces the burn degree in the irradiated region. The depth of third-degree burn decreases obviously with the increasing of the phase lag of temperature gradient.

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