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Design of clinical intelligent percutaneous myocardial laser revascularization operating platform software

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Abstract. Percutaneous transmyocardial laser revascularization (PMLR), a kind of new percutaneous coronary intervention based on transmyocardial laser revascularization (TMLR) is to improve the circulation of ischemia myocardium by laser myocardial revascularization from the cardiac cavity. In our previous research, the characteristic of laser transmission in myocardium including photon reflection, absorption and scattering was introduced. The photon state at the emission, transmission and disappearance stage, the processes of photon weight decay and the change of photon movement step and direction were described and simulated by using Monte Carlo method. All of the above were simulated by MATLAB, and the relationship between different optical property parameters, absorption coefficient, scattering coefficient, anisotropic coefficient, and photon energy density in myocardium was discussed. In this study simulation of photon transport using Monte Carlo operating platform was programmed by C++ language to investigate the influence of increasing photons on the simulation at different optical properties parameters and clinical intelligent PMLR operating platform was established to achieve the optimal number of laser holes, aperture, single hole perfusion, threshold power and corresponding parameters of each hole, which provided a reference for the operation program.

Key words: ischemic cardiomyopathy percutaneous myocardial laser revascularization Monte Carlo software

1 Introduction

Coronary heart disease (CHD) is one of the most common diseases in the elderly and its incidence in the world has continued to increase over the past 50 years as one of the leading causes of death tending to increase in the young population, too[1,2]. The most basic principle is to improve the blood supply of ischemic myocardium for the treatment of CHD. The ischemic symptoms in 80% of patients with CHD can be alleviate by conventional drug therapy, or percutaneous coronary artery endovascular forming (PTCA) and coronary artery bypass grafting (CABG) etc[3-5]. But the treatment is often difficult to work for diffuse coronary lesions, small vascular lesions, vascular distal lesion and complex cases with several postoperation of PTCA, CABG or stent restenosis. Percutaneous myocardial laser revascularization (PMLR) irradiates from the heart cavity to the epicardium forming micro pores of nontransmural wall with many advantage such as avoiding stent restenosis after PTCA and CABG, small damage, restore fast and less medical costs compared with the epicardial irradiation (Transthoracic Myocardial Laser blood Revascularization, TMLR) which is accompanied with disadvantage such as large damage and more bleeding due to establishment of holes of cardiac penetration after opening the chest[6-8]. In our previous experiments, the characteristic of laser transport in myocardium including photon reflection, absorption and scattering was introduced using PMLR as theoretical background. Then, the states of photons at the emission, transmission and disappearance stage, the processes of photon's weight decay and the change of photon's movement step and direction were described and simulated by using Monte-Carlo method, which was helpful to make the flow chart of photon transport in the myocardium. All of the above were simulated by MATLAB, and the relationship between different optical property parameters, absorption coefficient, scattering coefficient, anisotropic coefficient, and photon energy density in myocardium was discussed. Moreover, quantitative relationship between the depth and aperture of laser hole, laser output power and myocardial optical property was deduced by heat transfer theory and tested by relative experiments. The analytical solution of the two-dimensional temperature distribution was obtained using Green function, quantitative analysis of the heat injury range during punching process was also done according to Arrhenius equation, and the model of thermal damage was built. In this study, simulation of photon transport operating platform using by Monte Carlo is firstly built by in C++ language to verify the authenticity and credibility of the Monte Carlo modeling by investigating the influence of increasing photons on the simulation at different optical properties parameters to describe their importance or weight value in the transport.

2 Simulation of Photon Transport Using by Monte Carlo Operating Platform

The platform mainly included three parts, the login interface, the operation interface and the graphical display interface, which were shown in Figure 1. The basic parameters such as photon number, laser type, laser power and laser radius could be selected and input by the dropdown menu and important data could be input by Loading button. Then the right side of the optical properties parameter settings became available and minimum and maximum values of the absorption coefficient, scattering coefficient and anisotropy coefficient could be set. The SET button would appear the dialog box to indicate error message, for example when the maximum was less than the minimum or the nonstandard number was input. The coordinate points, 8 vertices of hexahedral, were chosen in dropdown menu to investigate the influence of the photon energy density and button "simulation" was clicked to simulate and calculate. The graphic display interface after the end of the computation would appear as Figure 2. In the graphical display interface, the left side was the optical property parameters used in the simulation and the right side was the photon energy distribution curve.

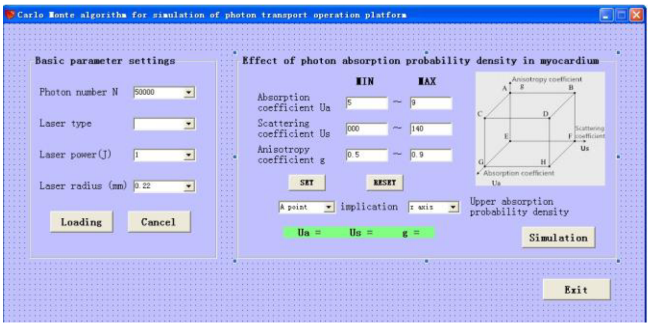

Fig. 1 Simulation of photon transport using Monte Carlo operating platform

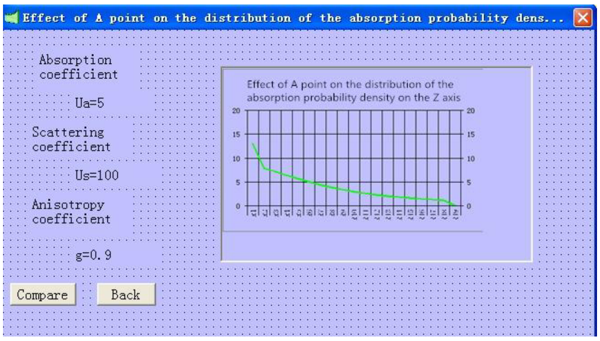

Figure 2 Graphical display interface

3 Clinical Intelligent PMLR Operating Platform

"Clinical intelligent PMLR operating platform" is hoped to be compatible with the medical image acquisition device to display the cardiac image and calculate the depth, radius and number of laser holes at various simulation of relative parameters to help the surgeons to formulate the best surgical plan.

3.1 Software design process

The design of clinical intelligent PMLR operating platform had the following objectives: (1) The number of myocardial drilling was as less as possible, which means the secondary trauma to the myocardium would be smaller; (2) The distribution of drilling holes on the myocardial surface was uniform to guarantee the microcirculation. (3) The myocardial surface image was segmented by using the finite element method / boundary element technique when the myocardial thickness was uneven. The segmented mesh region was labeled and the mesh information was collected. The grid number was seen as 1 when the thickness of myocardium was uniform.

Here is the preliminary design steps of the clinical intelligent PMLR operating platform.

The first step was to determine the scope of myocardial ischemia and to assess the total required blood flow. Left ventricular internal pressure Δp was measured through hemodynamics, blood viscosity η was determined by blood rheology, and myocardial ischemia was detected by positron emission tomography before operation. The total blood flow of ischemic myocardium V_1^0, V_2^0 was quantitatively assessed when the perfusion range of a single hole $[V_{s\min}, V_{s\max}]$ and aperture range of a single hole $[d_{\min}, d_{\max}]$ was set up.

The second step was to segment ischemic myocardial region. The uniform myocardium was determined by three-dimensional dynamic enhanced magnetic resonance imaging, while the uneven myocardial wall was segmented using boundary element or finite element technique according to the different myocardial thickness. The myocardial wall in the mesh region was labelled $1, \cdots, N$ and its depth was evaluated H_k^1, H_k^2. The minimal depth of ischemic myocardium was H_k^1, H_k^2 and the maximum thickness was $H_{\max} = \max\{H_1^2, H_2^2, \cdots, H_N^2\}$.

The third step was preliminary determination of laser output power P .The laser type was selected and the output power of the laser was selected as P . The position of hole i and the grid area at the position k was selected.

The fourth step was determination of the drilling time. The time between laser emission and the start of myocardial vaporization induced by the laser was $t_0 = \frac{\pi K^2 T^2}{4kI_0^2} = \frac{\pi K^2 (100-37)^2}{4kI_0^2} = \frac{3969\pi K^2}{4kI_0^2}$.

And the actual drilling time could be determined by $\frac{P(t_i - t_0)}{\rho(q+63c)} = \frac{\lambda^2 z_i^3}{3\pi\omega_0^2} + \pi\omega_0^2 z_i$ based on the relevant parameters of the myocardial tissue in the hole when the laser power was selected as a fixed value P as long as the required depth of the hole was given $z_i < H_{\min}$.

The fifth step was comparison of laser output power with threshold power. The drilling time t_i was put into formula of laser threshold power in the unit area: $P_{c,i} = 2q\rho k^{\frac{1}{2}} t_i^{\frac{-1}{2}} = 203 t_i^{-\frac{1}{2}}$.When the threshold power $P_{c,i}$ was compared with the set output power of laser P, if $P < P_{c,i}$, the output power of the laser and the drilling time was set again, otherwise the next step would be carried out.

The sixth step was determination of the hole aperture. The drilling time t_i in the fourth step and the laser output power P in the fifth step were put into the following formula

$$d_i = \frac{\omega_0}{\sqrt{2}} \sqrt{\ln \frac{\mu_a P(t_i - t_0)}{\pi\omega^2 \left[1 + \left(\frac{\lambda z}{\pi\omega_0^2}\right)^2\right](63c\rho + \rho q)}}.$$

When the laser hole aperture d_i was determined; if $d_i \in [d_{\min}, d_{\max}]$ then started the next step. Otherwise the hole depth and drilling time would be selected again.

The seventh step was to verify blood perfusion V_i of hole i. The parameters such as aperture d_i, depth h_i, left ventricular internal pressure Δp and blood viscosity η were substituted into the formula $V_i = \frac{\pi d_i^4 \Delta p}{128\eta h_i}$, the blood flow V_i of the drilling holes could be calculated; if $V_i \in [V_{s\min}, V_{s\max}]$, the laser stared to perforate hole, otherwise drilling would be abandoned and the hole depth, aperture and laser power were selected again.

The eighth step was to output relevant data in the drilling operation. The amount of cumulative perfusion $V_{i,sum} = \sum_{j=1}^{i} V_j$ for i times was calculated, meanwhile data $(i, P, P_{c,i}, t_i, h_i, d_i, V_i, V_{i,sum})$ were output.

The ninth step was whether the next drilling would be started. When the cumulative volume $V_{i,sum}$ of drilling i time was compared with the maximum blood flow in the ischemic myocardium, if $V_{i,sum} < V_2^0$, the minimum amount of perfusion was $V_{1,R}^0 = V_1^0 - V_{i,sum}$, the residual maximum amount of perfusion was $V_{2,R}^0 = V_2^0 - V_{i,sum}$, the remaining minimum number of holes was $n_{1,R}^i = \frac{V_{1,R}^0}{V_{s\max}}$, the remaining maximum number of holes was $n_{2,R}^i = \frac{V_{2,R}^0}{V_{s\min}}$, and the data $([V_{1,R}^0, V_{2,R}^0], [n_{1,R}^i, n_{2,R}^i])$ was output. Then the next drilling started and the next drilling $i+1$ was determined repeating the above process. Otherwise $([V_{1,R}^0, V_{2,R}^0], [n_{1,R}^i, n_{2,R}^i]) = ([0,0],[0,0])$ was output and the calculation process was over.

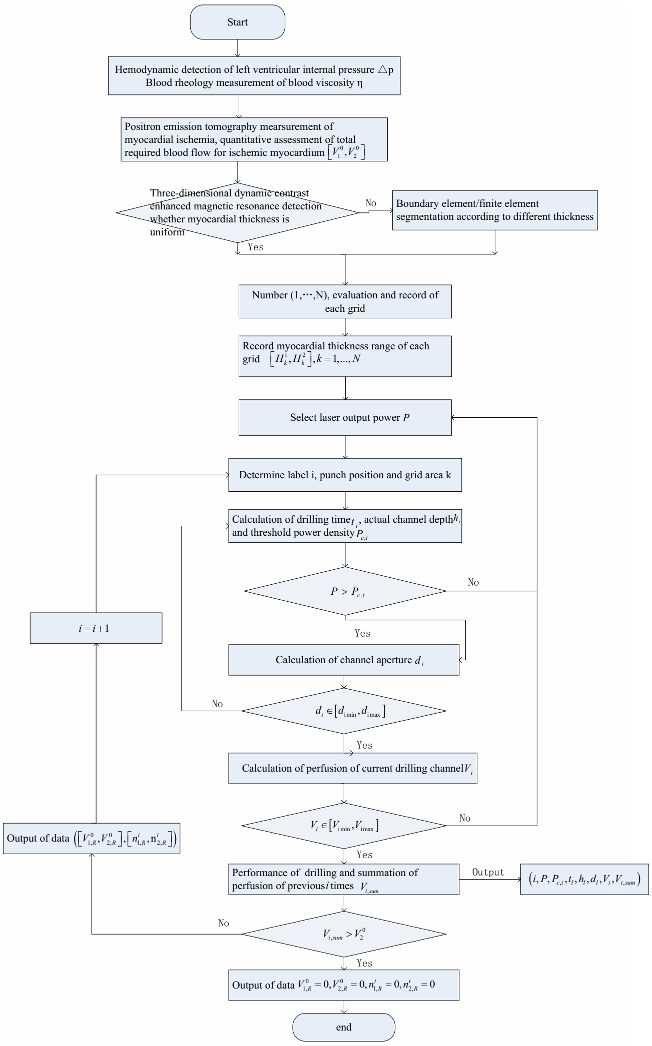

Fig. 3 "Clinical intelligent PMLR operating platform" software design flow chart

3.2 Software introduction and operation instructions

The clinical intelligent PMLR operating platform mainly included login interface and operation interface, which was shown in Figure 4.

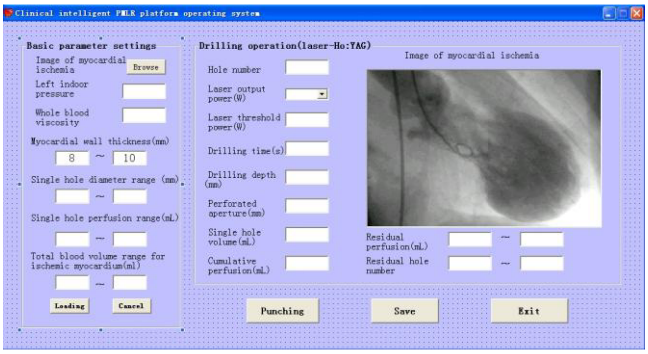

Fig. 4 Operation interface of clinical intelligent PMLR operating platform

In "basic parameter settings section", when "browse" was clicked, the existing cardiac medical image could be selected and the corresponding parameters range could be filled in as a condition for future calculation. "Loading" could determine whether the parameters were correct and reasonable, for example if the maximum value was greater than the minimum, warning dialogue box would be given. If the parameter was correct, the existing settings could be saved. The output power of the laser (YAG Ho: laser) was selected, and then clicked "Punching" to start the calculation. After the calculation it could be saved as txt or dat format file by "save", which was helpful to view and analyze data. "Cancel" could cancel the current settings and empty all the data.

In summary, the study gave simulation of photon transport using Monte Carlo operating platform programmed by C++ language to investigate the influence of increasing photons on the simulation at different optical properties parameters and gave clinical intelligent PMLR operating platform to achieve the optimal number of laser holes, aperture, single hole perfusion, threshold power and corresponding parameters of each hole, which provided a reference for the operation program.

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