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A Study of Intravascular Brachytherapy Treatment Planning in Peripheral Arteries

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Abstract—A two-step method to determine the seed parameters for the planning of peripheral intravascular brachytherapy, which took the actual vessel geometry into consideration, was developed. Firstly, the characteristics of the vessel geometry was obtained by using active navigation; Then a method combined genetic algorithm with BFGS algorithm was applied to optimize the number of seeds, and the parameters associated with each seed such as the position, and the dwell time. Application of the method to a phantom model and three animal models of stenosis shows that promising result could be obtained, and the planning of peripheral intravascular brachytherapy should take actual vessel geometry into consideration.

I. INTRODUCTION

Intravascular Brachytherapy (IVB) constitutes a new therapeutic solution to avoid iterative redilations practiced after minimally invasive treatment of peripheral arterial stenoses. Following percutaneous transluminal angioplasty (PTA) procedure, IVB aims at preventing intimal hyperplasia restenosis in a context which does not tolerate iatrogenic complications.

Although its principle is known, the application of IVB to peripheral arteries by means of a high dose rate (HDR) remote afterloader (¹⁹²Ir seed) remains at a preliminary stage. Peripheral arteries present some specific features compared to coronary arteries as for their shape, geometrical characteristics and the presence of surrounding anatomical structures. Conventional treatment planning still assumes a straight line vessel and a constant diameter circular cross-section. In order to use IVB on peripheral arteries in clinical practice, several issues have to be considered: (i) definition of the protocol, (ii) anatomical feature based dosimetric planning, (iii) implementation of the treatment plan, and (iv) evaluation.

This work deals with the optimization of the treatment plan for IVB in peripheral arteries. The objective is both to evaluate the difference between the straight line hypotheses and actual vessel geometry, and to contribute to the definition and the specification to a new optimized procedure. In the proposed approach, the planning process is divided into two steps: (i) characterization of the vessel geometrical parameters by active navigation, and (ii) optimization of the seed parameters using simulated annealing and BFGS algorithm. The first step was presented in a previous work[3].

We focus here on the optimization process in which the number of seeds, the position and dwell time associated with each seed are taken into account.

II. RELATED WORKS

The results of researches on IVB showed that less renarrowing of arteries and a reduced need for further treatment at the same site in patients with in-stent restenosis who received radiation along with angioplasty. And now intravascular brachytherapy has become a viable treatment option in preventing restenosis.

Nevertheless, in most current planning procedures of intravascular brachytherapy, the lesion path is supposed to be straight line and the dose distribution is specified with respect to the seed and the mean diameter of the artery. In order to make intravascular brachytherapy procedures more secure and reliable, recent works, on intracoronary brachytherapy notably, have shown that the morphological characteristics of the vessel should be taken into account in the planning process, because the doses closely depend on the geometry of vascular[1, 2]. One solution adopted in the case of coronary arteries is using IVUS to detect the inner surface of the vascular structure [1,7,8]. In the case of peripheral arteries, other solutions such as CT imaging can be used to obtain a better accuracy in 3-D boundary detection and description. We investigated the use of a solution based on active navigation, a virtual angiography like process which does not require a pre-processing of the patient-specific CT data. The general framework of active navigation, whose basic functions have already been reported in the literature[4], is summarized in the following.

Virtual image computation is performed according to a ray casting scheme integrating analysis functions. From the depth map associated to the virtual image, the scene analysis process is based on the detection of the depth maxima characterizing the vascular branches and border points featuring, in a bifurcation area, the frontier between two different regions associated to two single branches respectively. The depth maxima are labelled and matched along the successive positions of the virtual endoscope, so that, given a starting point and a target point, a particular branch can

be followed. The viewing direction of the virtual sensor is oriented towards the followed depth maximum whereas the displacement orientation is fixed initially by the center of a set of surface points selected in a single branch part.

The geometrical model of the virtual angioscope has been extended to include a quantification plane which allow it to construct, during the navigation, a precise surface description of the vascular structure [5].

III. SEED MODEL

To determine the parameters that may influence the treatment plan, it is first necessary to choose an appropriate formulae for computing the dose distribution at an arbitrary point. The standard Nucletron ^{192}Ir cylindrical seed we considered is 3.5 mm long and 0.6 mm in diameter, encapsulated in a 5.0 mm long $\times$ 1.1 mm diameter stainless steel housing.

The computation of dose distribution often uses the basic dosimetry data, including dose rate constants, radial dose functions, and anisotropy functions. According to the formalism proposed and recommended by the AAPM in TG43 and TG60[1,6], the dose distribution, for a cylindrically symmetric source, can be described in terms of a polar coordinate system with its origin at the source center where r is the distance to the point of interest and θ is the angle with respect to the long axis of the source. The dose rate, $D(r, \theta)$, at point (r, θ) , is defined as follows:

$$D(r, \theta) = S_k [G(r, \theta)/G(r_0, \theta_0)] g(r) F(r, \theta) \quad (1)$$

where S_k is the air kerma strength of the source, Λ is the dose rate constant, $G(r, \theta)$ is the geometry factor, $g(r)$ is the radial dose function, and $F(r, \theta)$ is the anisotropy function. The reference point (r_0, θ_0) is chosen to lie on the transverse bisector of the source at a distance of 1cm from its center, i.e., $r_0 = 1$ cm and $\theta_0 = \pi/2$.

When the number of sources used in a treatment is N , the dose rate received at a point P is the weighting sum of $D(r, \theta)$:

$$I(P) = \sum_{j=1}^N w_j D(r_j, \theta_j) \quad (2)$$

where w_j corresponds to the irradiation time of the j th source.

IV. IVB PLANNING OPTIMIZATION

In order to fit the calculated dose distribution to the dose prescribed according to the 3D surface description of the vessel wall, and to minimize the damage to critical or normal tissues, a quadratic, least-square objective function was used to optimize the irradiation parameters. Let X denotes the set of parameters to be optimized, we have:

$$\begin{aligned} \min f(X) &= \alpha \sum_{i=1}^{N_T} (D_T - I(p_i))^2 \\ &+ \beta \sum_{i=1}^{N_N} \delta(I(P_i) - D_N)(I(P_i) - D_N)^2 \end{aligned} \quad (3)$$

$$\text{with } \delta = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{otherwise} \end{cases} \quad \text{subject to } w_j \geq 0$$

where N_T is the number of 3D surface sampled points in the lesion area; N_N is the number of 3D surface sampled points distributed on the normal tissues; D_T is the prescribed dose at the point P_i of the lesion surface; D_N is the prescribed dose at the point P_i of the normal tissues; $I(P_i)$ is the calculated dose at point P_i . The coefficients α and β are the degree of desirability weighting factors for target points and normal or critical points, respectively.

Many algorithms are available to solve the optimization problem (3), most of them are stochastic methods. Here we firstly replaced the parameter w_j with y^2 to eliminate the problem of solutions with negative dwell time, thus the problem (3) became an unconstrained optimization problem; then a method combined simulated annealing algorithm with BFGS algorithm was used to optimize the number of seeds, the dwell position as well as the dwell time associated with each seed.

In this paper, BFGS algorithm was used to determine the dwell times for a given number of seeds and corresponding dwell positions, while simulated annealing algorithm was used to determine the positions of the seeds, the parameters were set as follows; the initial temperature was set to 1000, the cooling factor was set to 0.85, the final temperature was set to 1.0, and the number of iterations per fixed temperature was set to 100.

The range of the number of seeds depends on both the length of plan path, given here by the vessel centreline, and the seed length. Let L_s be the seed length, and L_p the plan path length, the number of seeds is assumed to vary from $L_p/(1.2 \times L_s)$ to $L_p/(0.8 \times L_s)$. For each given number of seeds, Eq. (3) was solved by the combined method to determine the corresponding optimal solution. Among them, the one fits best to the prescribed dose distribution was selected as the final result.

V. EXPERIMENTAL RESULTS

In order to evaluate our methodology, we considered four data sets acquired from helical CT scanner, one from a phantom model, one from pre-PTA iliac artery and two from post-PTA sheep iliac artery. Several kinds of parameters intervene in the proposed approach. The aim is to evaluate the difference of the result between the straight line assumption and the actual vessel geometry. The criteria considered to quantify the results of the planning process is the dose surface histogram(DSH) which represents the dose homogeneity over the treatment area. The geometrical description of vascular inner surface was detected by active navigation. The activity of the seed was set to the maximum possible value (10Ci or 370Gb).

A dose of 14Gy has been specified at a distance of 2 mm to each considered surface points (radius + 2 mm). Preliminary results are reported in figure 1(a-l), (a), (b), (c), (d) are the automatic reconstruction of the vessel inner surfaces and their center lines for phantom model, pre-PTA iliac artery and two from post-PTA sheep iliac artery respectively; (e), (g), (i), (k) are the optimized DSHs corresponding

to the above four data set, taking actual vessel geometry into consideration; (f), (h), (j), (l) are the optimized DSHs corresponding to the above four data set, with straight line assumption. The results list in figure 1 show that DSHs taking actual vessel geometry into consideration are much better than those with straight line assumption.

VI. CONCLUSION AND FUTURE WORKS

This study demonstrates that the method can give promising result, and the planning of peripheral intravascular brachytherapy should take actual vessel geometry into consideration. Future work will take into account the currently available afterloader parameters.

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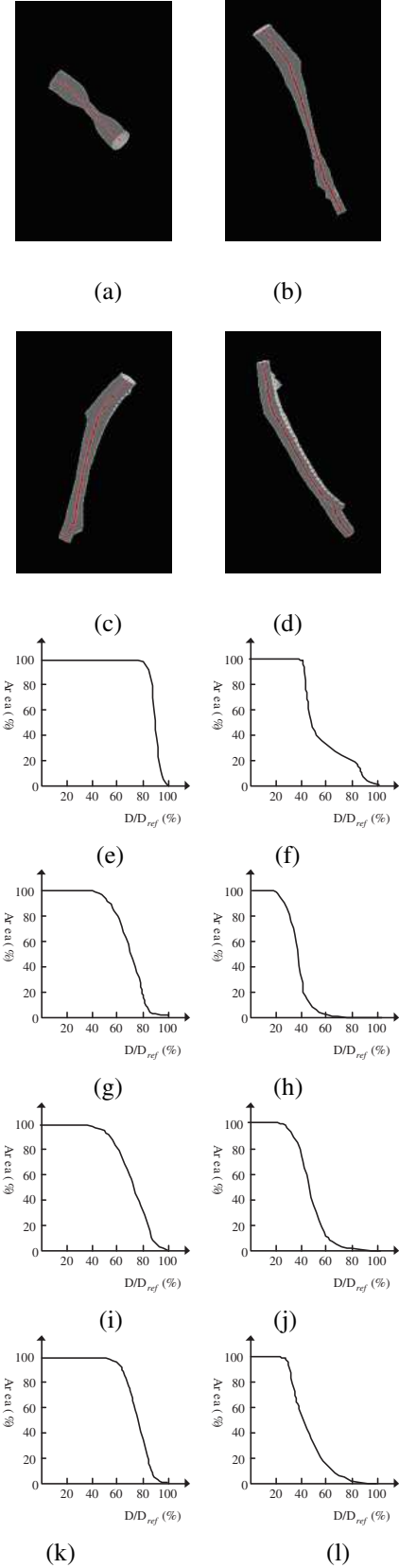


Fig. 1. (a), (b), (c), (d) Automatic reconstruction of the inner surfaces of vessels and their center lines; (e), (g), (i), (k) optimized DSHs taking actual vessel geometry into consideration; (f), (h), (j), (l) optimized DSHs with straight line assumption.