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Independent Verification Program for High-Dose-Rate Brachytherapy Treatment Plans

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Purpose: The planning of High-Dose-Rate (HDR) brachytherapy treatments are becoming individualized and more dependent on the treatment planning system. Therefore, computer software has been developed to perform independent point dose calculations with the integration of an isodose distribution curve display into the patient anatomy images.

Materials and Methods: As primary input data, the program takes patients' planning data including the source dwell positions, dwell times and the doses at reference points, computed by an HDR treatment planning system (TPS). Dosimetric calculations were performed in a $10 \times 12 \times 10 cm^3$ grid space using the Interstitial Collaborative Working Group (ICWG) formalism and an anisotropy table for the HDR Iridium-192 source. The computed doses at the reference points were automatically compared with the relevant results of the TPS. The MR and simulation film images were then imported and the isodose distributions on the axial, sagittal and coronal planes intersecting the point selected by a user were superimposed on the imported images and then displayed. The accuracy of the software was tested in three benchmark plans performed by Gamma-Med 12i TPS (MDS Nordion, Germany). Nine patients' plans generated by Plato (Nucletron Corporation, The Netherlands) were verified by the developed software.

Results: The absolute doses computed by the developed software agreed with the commercial TPS results within an accuracy of 2.8% in the benchmark plans. The isodose distribution plots showed excellent agreements with the exception of the tip region of the source's longitudinal axis where a slight deviation was observed. In clinical plans, the secondary dose calculations had, on average, about a 3.4% deviation from the TPS plans.

Conclusion: The accurate validation of complicate treatment plans is possible with the developed software and the quality of the HDR treatment plan can be improved with the isodose display integrated into the patient anatomy information.

Keywords: Quality assurance, HDR brachytherapy

Introduction

Brachytherapy is a well-established procedure that uses encapsulated small radioactive sources and delivers high dose to a short distance. The traditional brachytherapy treatment with low dose rate (LDR) source has been replaced with remote afterloading high dose rate (HDR) treatment, because it provides a more convenient treatment to patients and safer work environment to medical personal.

The modern HDR brachytherapy treatment planning relies heavily on a dose-optimization computer software that can tailor dose to specific clinical needs. The optimization process involved the computation of dwell times for a set of dwell positions delivering a prescribed dose to a set of target or dose constraint points, and provided isodose distribution in a three-dimensional space.

With the availability of sophisticated imaging, such as

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magnetic resonance images or computed tomography images, HDR brachytherapy treatment planning is becoming more individualized, which increases the dependency of isodose distribution in the treatment plans. One of the accompanying problems with the described development is the necessity of quality assurance of HDR treatment planning system that verifies not only the point dose accuracy but also isodose distributions independently.

In external radiation therapy treatment planning systems, the accuracy of isodose display is required to be accessed in a quality assurance, since it plays an important role in the determination of a proper plan.[1,2] If isodose distribution plays a significant role in the individualized HDR brachytherapy planning, the same standard of quality assurance needs to be applied.

We, therefore, developed computer software that can independently verify the accuracy of dose optimization module as well as the isodose distribution of HDR treatment planning systems. Additionally, the developed software has a function that allows to superimpose user selected isodose lines on the simulation and MR images of a patient, that potentially serves to improve the quality of treatment plans.

Materials and Methods

1. Dose computation algorithm

The QA software was originally developed to work with Gamma-Med 12i HDR remote afterloading planning system and later modified to apply to Nucletron remote afterloader. The two versions, however, have an identical algorithm and a structure except for the source information. The software was coded using an IDL 5.2 (Intersys, USA) and employed an Interstitial Collaborative Working Group ICWG formalism for dose computation.[3,4]

The dose calculation formula is briefly introduced for comprehensive understanding. The dose rate (?) at a point (r,θ) is

$$? (r,\theta) = \frac{S_K \Gamma G(r,\theta) F(r,\theta) g(r)}{G(1,\pi/2)} \qquad \text{Eq(1)}$$

where r is a radial distance from the origin of the coordinates and θ is a polar angle from the longitudinal axis of the source. Cylindrical symmetry is assumed. S_K is air kerma strength that decays exponentially, i.e. $S_K(T)=S_{Ko}\exp(-\ln 2T/Tf)$, where T is the elapsed time from the date of calibration. Tf is half life, and S_{Ko} is calibrated strength. Here, the unit of the S_K is U that is defined as cGy cm^2 h^{-1}. Γ is a dose rate constants that is defined as $?(1, \pi/2)/S_{Ko}$ in the water. For Ir 192 source, Λ was set to 1.12 cGy hr^{-1}U^{-1} following the recommendation by TG-43 report.[3] $G(r,\theta)$ is a geometry factor that approximates the source geometry. In the developed software, we used a point source approximation that was an inverse square function of the radial distance r, i.e. $1/r^2$. g(r) is a radial dose function which is approximated by Meisberger's polynomial, which is $g(r)=a_0+a_1r+a_2r_2+a_3r_3$ (a_o= 1.0128, $a_1=5.01\times10^{-3}$, $a_2=-1.178\times10^{-3}$, $a_3=-2.008\times10^{-3}$).[5] $F(r,\theta)$ is an angular anisotropy factor provided by the source vendor. The source specific values of S_{Ko} and Tf need to be entered into the code.

The dose at a point (r,θ) can be computed by summing all source's contributions to that point with the assumption that the dose rate is constant during the treatment period. The dose at a point can be expressed as,

$$D(r,\theta) = \Sigma^{i=N} ?i (ri,\theta i) Ti. \qquad \text{Eq(2)}$$

N is the number of source dwell positions, Ti is dwell time of i^{th} source, and $(ri,\theta i)$ is a vector from the center of the i^{th} source to the dose computation point (r,θ).

2. Dose computation process and isodose display

For the verification of plans, the software needed user input data, which were a prescribed dose, number and positions of source dwellings, dwell times, and the date and time of patient plan generated. A user also needed to enter the three orthogonal plans where the dose distributions should be displayed. For the given information, the program firstly computed the activity of the source at the time of patient planning. Then a set of linear equations was solved to find the source dwell times that satisfied the prescriptions. For the computed source dwell times, the dose distribution on a $10\times 12\times 10$ cm^3 (or $10\times10\times10$ cm^3 for benchmark plans) of grid space was computed for the given source information. The computation grid size was 1 mm for the

benchmark plans, but was changed to 2 mm for the clinical plans in order to increase the computation speed while keeping the accuracy at a reasonable level. The dose distribution was normalized to the dose at a prescription point.

Next, the selected patient digital image files, which were posterior and lateral simulation images and axial and saggital MR images, were imported into the computerprogram. After that, the images popped up on the monitor automatically and the user was asked to click the OS point on each of the images. Thesoftware then matched the point (5 cm, 5 cm, 5 cm) of the grid space to the OS point and superimposed the user selected isodose lines on each of the images. Finally, all dosimetric information, plan-specific source information, and computation results were printed out on papers. The flow of the computation process is summarized in Fig. 1.

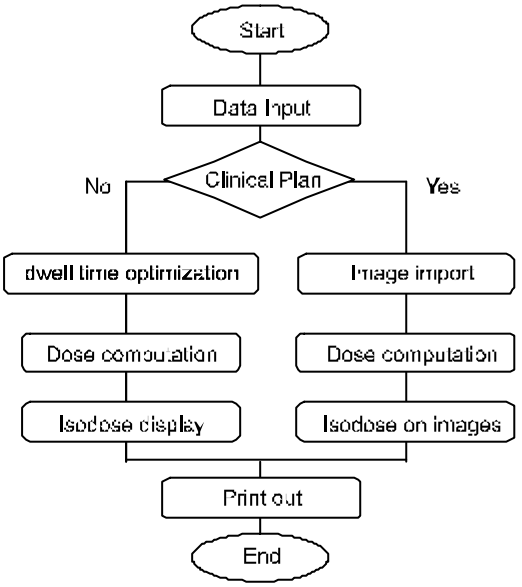

Fig. 1. Flow chart of the QA software.

3. Generation of benchmark plans

In order to test the accuracy of the developed QA software, three benchmark plans were generated. The three plans consisted of one, three, and five dwell positions which were located on the y-axis of the coordinate respectively (x-axis: left-right direction, y-axis: superior-inferior direction, z-axis: anterior-posterior direction). 100 cGy was prescribed to the point located 1 cm away from the source dwell axis. The computed source dwelltimesandisodoselines of theQA software were compared to RTP results.

Table 1. Source Dwell Time Comparison of the QA Software with GammaMed

Number of source	Source dwell time (total dw	
	Percentage difference	
	GammaMed	QA software
1	10.7	10.45
3	8	7.87
	2.7	2.47
	8	7.87
	Total dwell time (18.7)	(18.2)
5	6.7	6.51
	4	3.94
	4	3.83
	4	3.94
	6.7	6.52
	Total dwell time (25.4)	(24.7)

For the comparison of the isodose lines of the two software, the prescription point on the x-axis was selected and the dose distribution was normalized to that point. The comparison wasmadebyprinting out the isodose lines ofQA software on transparent papers and superimposing them on the RTP results.

4. Apply to clinical plans

For the application to the clinical plans, the QA code was changed tousetheRTPcomputedsourcedwelltimesinstead of the independently computed dwell times in order to increase the computation speed. The accuracy of the absolute dose was compared at A and B points for 9 intracavitary treatment patients.

Results

The source dwelltime comparisons of the benchmark plans are presented in Table 1. As shown, the total dwell times agreed within 2.8% errors. This deviation was possibly due to the parameter values used in the RTP, since different values of dose rate constant (Λ) and coefficients of Meisberger's polynomialwerefoundintheliteratures.[4,6] Truly, when 1.11 cGy hr^{-1} U^{-1} was used for dose rate constant, according to

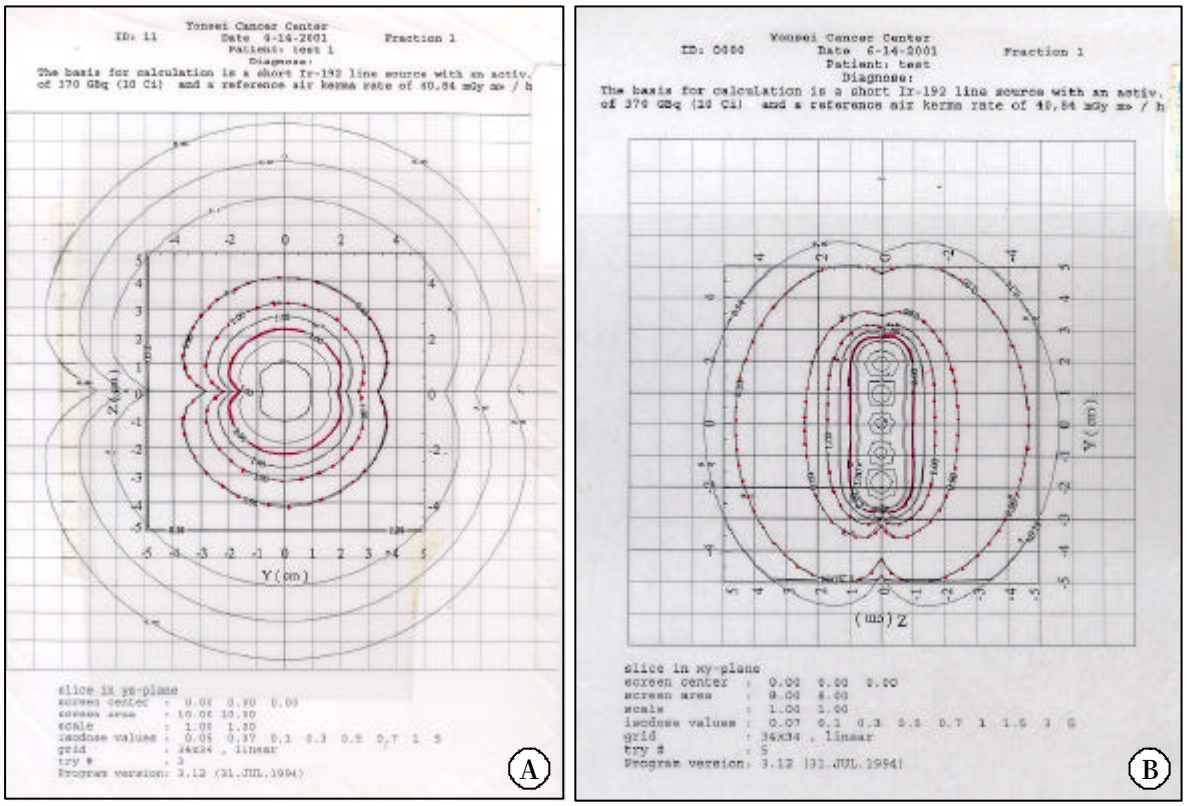

Fig. 2. Isodose comparison of the QA software with GammaMed on (A) a sagittal plane and (B) a coronal plane. Black solid lines: TPS generated isodose lines. Red dots or lines: QA software generated isodose lines.

the reference 6, the agreement was improved with the average error of 1.7%. This error could partly attribute to the different time of plan generation, that resulted in different activity of the source and could partly attribute to numerical noise in solving equations. The isodose lines for all of the three benchmark plans agreed very well as presented in Fig. 2 even though a slight deviation was observed near the tip of the source, where the source had high anisotropy. This could relevant to the limitation of the spatial accuracy of the software.

Our preliminary results of the clinical plans were 3.3% of deviation (ranged from 0.7% to 7%) at point A and 3.4% of deviation (ranged from 1.2% to 8.5%) at point B as presented in Table 2. The larger deviation compared with the benchmark plans possibly attributed to the increased dose grid size and complicated source dwell positions that had sub-milimeter scales. One representative image of isodose superimposed on simulation images is illustrated in Fig. 3.

Discussion and Conclusion

For the safe treatment of HDR brachytherapy, the quality assurance for the treatment planning system as well as the individual plan is a legal requirement in some country.[7] Various point dose verification algorithms that meet the requirement, therefore, have been developed. Some of them, however, were specific to particular procedures such as single- catheter or two catheter-types.[8-12] A software that could be applied to vazrious procedures was, later, developed by using commercial LDR algorithm.[13] A fully automated software that employed Meisberger's polynomial and anisotropy table was introduced by Cohen et al.[14] None of the software, however, had a function that verified the dose distribution.

Point dose verification of each patient treatment plan is an essential item recommended by AAPM, but it is minimal for the quality assurance of the patient plan.[15] All plans' isodose distribution may not necessarily need to be double-checked,

Table 2. Dose Difference between the QA Software and Plato for 9 Intracavitary Brachytherapy Plans. NegativeValue Means That theQA Software PredictionsAreSmallerthan Those of TPS

Patient number	Differences (%)			
	A point (positive)	A point (negative)	B point (positive)	B point (negative)
1	−1.80	−0.79	−4.54	−2.21
2	−1.96	−3.36	−1.96	−2.89
3	−4.03	−4.68	−5.63	−5.66
4	−2.83	−2.35	−2.52	−1.85
5	−1.29	−2.86	−1.21	−2.09
6	−6.99	−5.51	−1.74	−1.92
7	−0.66	−4.27	−3.63	−4.17
8	−4.41	−4.99	−3.98	−8.48
9	−3.17	−3.04	−2.95	−3.28
Average	−3.02	−3.54	−3.13	−3.62

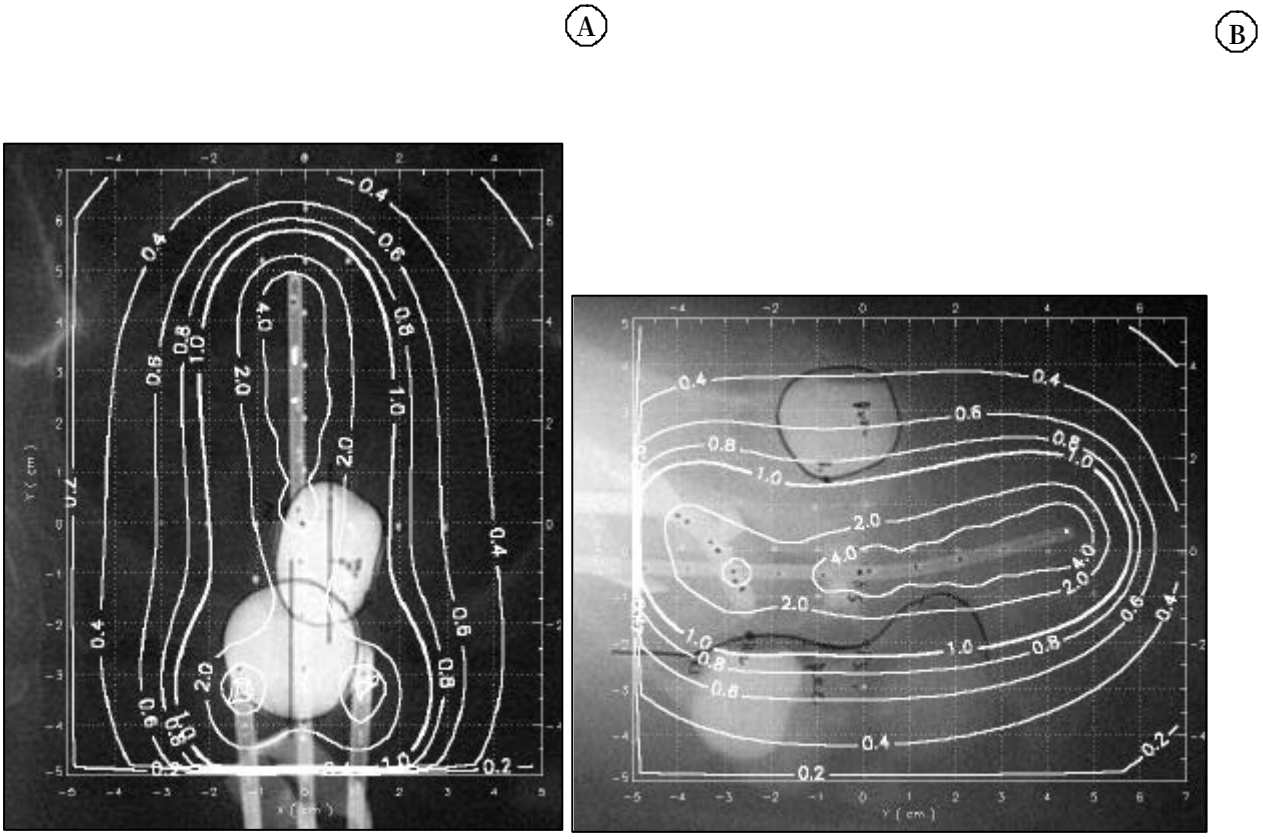

Fig. 3. Isodose distributionsuperimposed onasimulation image of (A) coronalplane and (B) sagittal plane that intersects theOSpoint.

but any specially individualizedplanneedtobeverified.Also this software is helpful when commissioning a new HDR system or a new version of HDR planning software. The function that can display isodose distributions superimposed on the simulation images potentially serves to increase the quality of the individual plan. When MR or CT images are used, however, it is necessary to recognize the perceived error that resulted from the positional difference of the patients when images were taken.

Additionally, the developed QA software not only double check the source strength of the day by itself, but it helps the physicist intercept common human errors, such as mistaken data entries in the optimization routine or incorrectly specified length. The developed software, however, has limited accuracy since uses a semi-empirical formula without considering any inhomogeneity, such as bony structures, air cavities, and metallic part of the applicators.

In summary, we have developed a RTP system comparable QA software for HDR treatment planning, that assists physicists in the pretreatment review of various treatment parameters, and provides an additional dose verification. The software canbeeasily implemented into various treatment planning systems and can be applied to a various kinds of brachytherapy procedures. The accuracy of the software allows to use the QA software as a backup method as well.

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국문초록

고선량률 근접치료계획의 정도보증 프로그램

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목 적: 개별화되어 가는고선량률 근접치료계획의 추세에따라, 고성량률근접치료계획의 절대적선량과 상대적인 선량분포를 독립적으로 계산하여 환자의 해부영상위에 겹쳐 표시할수있는품질보증용컴퓨터프로그램을개발한다.

대상 및 방법: 컴퓨터 프로그램은 먼저, 환자의 치료계획에서 계산된 선원의 위치, 각 위치에서의 조사시간, reference point에서의선량, 치료계획이 실시된날짜등의자료입력을필요로한다.ICWG 권고 수식과선원의 비등방성 표를 이용하여 10×10×12 (cm^3)의공간에서선량분포가계산된후 reference point에서의 선량이 자동적으로 치료계획의 결과와 비교된다. 모의치료의 영상이나 자기공명(Magnetic Resonance) 영상을입력하고 사용자가 선택한 점을 수직으로 교차하는 3개의 평면에서 등선량곡선을 겹쳐서 보여준다. Gamma Med사의 Gammadot (MDS Nordion, Germany)에서 표준 치료계획을 실행하여 정확성을 확인하였으며, Plato (Nucletron Corporation, The Netherlands)에서 실행된 9명의 환자치료계획과 비교하였다.

결 과: 3개의 표준치료계획에서 절대선량은 2.8% 내에서 일치하였으며등 선량분포도 좋은일치를보였다. 9명의 환자에 대하여 시행된 치료계획과의 비교에서는 평균 3.4%의 오차를 보였다.

결 론: 개발된 컴퓨터 프로그램은 정확하고 신속하게 고선량률 치료환자의 치료계획의 정확성을 확인할 수 있게 해주며, 등선량 곡선을 환자의 해부적 영상에 결합할 수 있는 기능은 치료계획의 질을 높이는데 기여할 수 있을 것으로 기대된다.

핵심용어: 정도보증, 고선량률 근접치료