Software Suite for 3D Dose Analysis: Demonstrating the Importance of Image Registration in RT Dose Verification

Mohammad Al Sa'd[1]
alsadm@bcs.org
James Graham[1]
jim.graham@manchester.ac.uk
Gary P Liney[2,3]
Gary.Liney@sswahs.nsw.gov.au
Tom Murray[3]
Tom.Murray@hey.nhs.uk

[1] Imaging Sciences, Institute of Population Health, University of Manchester, Manchester, UK
[2] Ingham Institute for Applied Medical research, Liverpool Sydney NSW, Australia
[3] Radiation Physics Department, Queen's Centre for Oncology & Haematology, Hull, UK

Abstract

There is now an internationally recognised need to improve 3D verification of highly conformal radiotherapy treatments. This is because of the very high dose gradients used in modern treatment techniques, which can result in a small error in the spatial dose distribution leading to a serious complication. In order to gain the full benefits of using 3D dosimetric technologies, it is vital to use 3D evaluation methods and algorithms. We present in this paper a software solution that provides a comprehensive 3D dose evaluation and analysis. Evaluated dose distribution is spatially aligned with the reference distribution prior to verification analysis. The B-spline registration algorithm has demonstrated a higher reliability in dose image registration than the demon algorithm. The software is applied to gel dosimetry, which is based on magnetic resonance imaging (MRI) as a read-out method. The software can also be used to compare any two dose distributions, such as two distributions planned using different methods of treatment planning systems, or different dose calculation algorithms.

1 Introduction

Advanced radiotherapy technologies, such as intensity-modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT), can provide considerable improvements to the result of radiotherapy both in terms of maximising the therapeutic effect of dose distribution on tumour, and minimising its damaging effect on surrounding healthy tissues and organs at risk (OAR). The increasing complexity of irradiation techniques has driven the development and adoption of 3D dosimetery methods, in order to optimise treatment planning and delivery systems, as well as to quality-assure their functionality. The adoption of 3D dosimetry methods has been increasing over the last decade [1, 5]. However, software applications (both freeware and commercial) that are used for dose evaluation and quality assurance (QA) purposes are primarily based on 2D evaluation

methods. These 2D evaluation methods are prone to error in evaluating the accuracy of a particular dose distribution, mainly because of the mismatch that can happen in selecting the corresponding slices from the dose distribution volumes being compared (Figure 1).

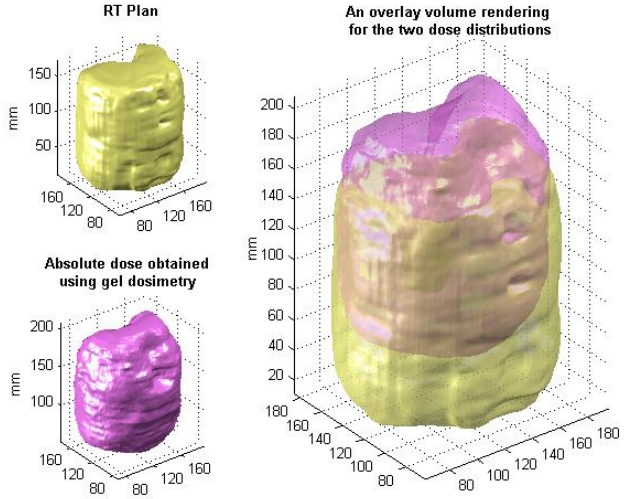

Figure 1: An example for an IMRT head and neck case showing how a mismatch can happen in selecting corresponding slices.

In principle, QA based on 3D verification is assumed to provide more quality indicators for further analysis. Also, it makes it possible to define tolerance criteria in 3D in order to account for setup inaccuracies of the dosimeter phantom and/or detector. In order to derive the full benefits of using the 3D dosimeter, it is essential to use a software tool that provides analysis and evaluation results based on 3D methods and techniques. In fact, there is no software solution that provides comprehensive 3D dose evaluation and analysis. In this paper, we present a software suite that covers a wide range of 3D dose evaluation techniques. We have particularly applied the software to gel dosimetry, based on magnetic resonance imaging (MRI) as a read-out method [3]. In addition to comparing the measured and calculated dose distributions, the software can also be used to compare plans produced using different methods such as commercial treatment planning system (TPS) or Monte Carlo (MC) algorithms. The software has been evaluated using datasets of different radiotherapy plans and MRI gel dosimeter scans.

2 Materials and methods

The software tool presented here was produced using the MATLAB® computing language and interactive environment (version R2011a), which provides convenient and flexible high-level language and advanced graphical capabilities including 3D rendering. Also, the C programming language was used along with OpenMP API in order to optimise the speed of complex computational processes. The analysis is presented in a friendly user interface, which allows manipulation of the settings of each type of analysis. The software accepts different data formats as an input for the analysis, including DICOM and Analyze 7.5. The tool was designed to meet the analysis requirements of MRI gel dosimetry, such as

calculating R2 rate data (which is proportional to the absorbed dose), and applying calibration data to produce absolute dose values.

Dose distributions may have different coordinate systems. However, they are initially aligned using the corresponding slices at iso-centres of both volumes. This is valid based on the assumption that markers on the phantom were used to place it at the iso-centres of both radiation and read-out machines. Then the software tool automatically detects and calculates the global and local 3D deviation between the reference and evaluated dose distributions by using rigid and non-rigid volume registration techniques [2, 6, 9]. The user is informed about inaccuracies arising from sources of error such as misplacements of the dosimeter during radiation delivery or read-out stage. The user can choose whether to account for this deviation in the comparison calculations. Together with the 3D analysis methods, the software tool also provides some analysis in 2D so that the 3D evaluation methods can be compared to the more conventional 2D forms.

2.1 Image registration algorithm

The B-spline registration algorithm [6] has demonstrated a higher reliability in dose image registration than the demon algorithm [9]. In fact, the demon algorithm failed to register most of the samples. This may be due to the peculiarities of dose distributions in that they usually exhibit low gradient edges compared to those found in medical images of anatomical structures. The sum of squared differences was used as a similarity measure. Image registration is used in two stages of the analysis. Firstly, rigid registration is used at the pre-processing stage in order to globally align the evaluated distribution with the reference distribution. Secondly, B-spline registration is used at the analysis stage in order to calculate the 3D deviation at each voxel.

2.2 Evaluation methods used

The software provides both qualitative and quantitative analysis. The qualitative analysis includes various types of volume visualisation methods offered by MATLAB. The quantitative analysis includes the following: dose volume histograms (DVH), absolute dose difference, relative dose difference (either globally relative to a specific dose value or locally relative to the dose at each reference point), absolute spatial difference between each reference point and the closest point (of the same dose value) in the evaluated dataset, distance-to-agreement (DTA) test (whereby a spatial tolerance is used as a pass/fail criterion), gamma evaluation (which combines a DTA criterion with a dose difference criterion through a composite analysis) [4], gamma volume histograms [7], and gamma-angle analysis (which indicates which of the DTA or dose difference criteria had more influenced the calculated gamma value at each reference point) [8].

2.3 Comparison datasets

Three reference/evaluation 3D sample pairs were compared using the software in this paper. Sample A is a standard uniform intensity conformal treatment plan which was delivered to two MRI gel dosimeter phantoms; one was stationary during the irradiation as a reference distribution, and the other was moving to simulate human respiration whilst being irradiated at full inhalation using the respiratory gated radiotherapy technique (RGRT). Sample B is for an IMRT head and neck case, where the reference distribution was measured using MRI gel dosimetry in order to evaluate its corresponding TPS plan.

Sample C is for another IMRT head and neck case with an MC calculated reference plan and an evaluated TPS plan, wherein there was no experimental uncertainty involved. All the samples share the same size of 256 mm in each direction and a voxel resolution of 1 mm, which forms cubic datasets of 256^3.

3 Results

For the entire 256^3 volume and using a PC equipped with Intel i7 processor, the average computation times for the rigid and non-rigid image registrations were 2 minutes and 10 minutes, respectively. The average calculation time for the 3D gamma was less than 1.2 seconds. The screenshot in Figure 2 shows the 3D deviation map at the 10% isodose surface between reference and evaluated dose distributions from sample A. This demonstrates the degree of deviation that was introduced by irradiating the moving phantom using the RGRT technique. Figure 3 shows the results computed using the 3D gamma evaluation method for sample A. The gamma histogram in Figure 3 shows that the proportion of points passing a 3% dose difference criterion and a 3mm DTA acceptance criterion (whereby gamma index ≤ 1) was 94.2% within the 80% isodose surface. The gamma values were rendered on a 3D visualisation of the same isodose level. The gamma 2D maps were also displayed across the axial, sagittal and coronal slice orientations.

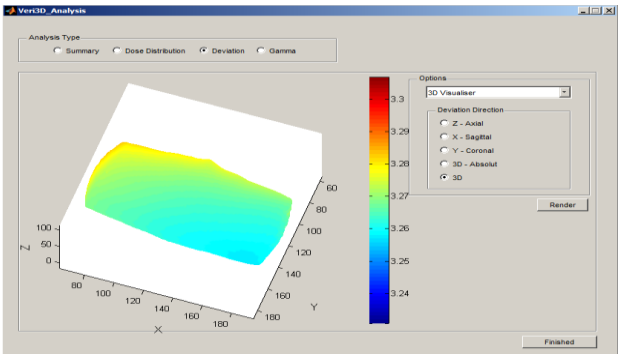

Figure 2: A screenshot showing a 3D deviation map between the two dose distributions in sample A.

For sample B an average 3D deviation of ~6mm was detected by volume registration, which may have been introduced by inaccurate positioning of the gel phantom in irradiation or read-out phases. This spatial error invalidates the entire principle of 2D evaluation, which is based on comparing the corresponding slices of the two volumes and stacking up the axial 2D results into a 2.5D volume. With the option to account for the spatial uncertainties selected, the proportion of points passing a 3% dose difference criterion and a 3mm DTA acceptance criterion for the entire dose volume were 88.23% and 95.71%, for the 2.5D and 3D gamma calculations, respectively. Despite the high gamma passing rate for the entire volume, it may not be a reliable indicator by itself for quality assurance in radiotherapy. As it is demonstrated in Figure 4, there is an obvious spatial mismatch between the two dose distributions at the 90% isodose. This suggests the need to further investigate gamma analysis for the points within the 90% isodose, in order to obtain results that are not affected by the entire volume.

For sample C, there was no 3D deviation detected, because both datasets are for calculated plans, which did not involve experimental uncertainties. For sample C, the proportion of points passing a 3% dose difference criterion and a 3mm DTA acceptance criterion were 83.44% and 98.64%, for the 2.5D and 3D gamma calculations, respectively.

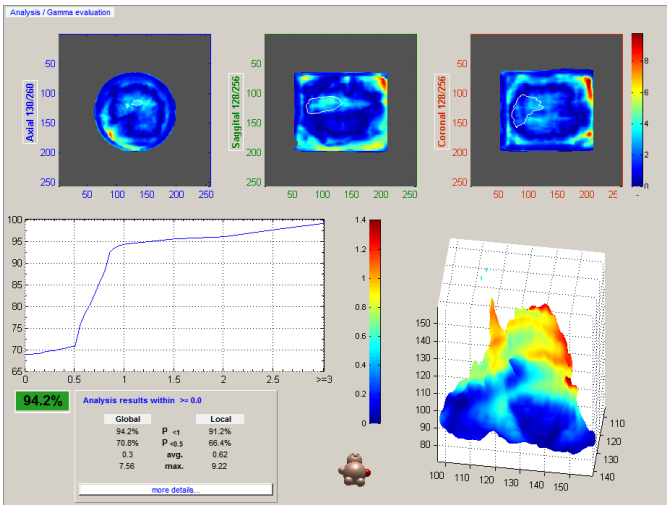

Figure 3: A screenshot for the analysis of Sample A, showing the results of the 3D gamma evaluation method. Gamma histogram (left) shows the proportion of points for gamma values within the 80% isodose, including the points passing the 3%/3mm pass criteria (where gamma index ≤ 1).

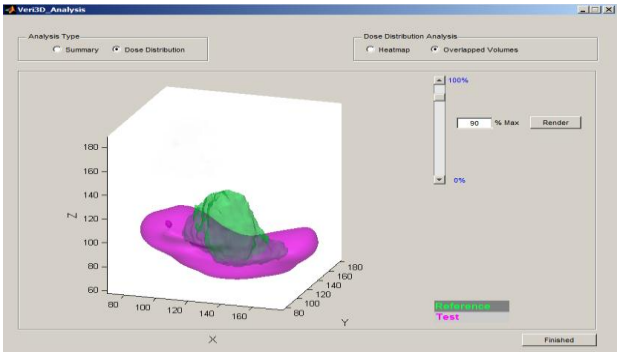

Figure 4: A screenshot for the analysis of Sample B, showing an overlay volume rendering for the reference and evaluated dose distributions at the 90% isodose surface.

4 Discussion and Conclusions

We present in this paper a software tool for 3D dose evaluation. In addition to 3D volume rendering for dose distributions being compared and analysis results, the software provides a catalogue of dose evaluation methods that are based on three-dimensional calculations and analysis. The settings of various analysis methods can be manipulated via a friendly graphical user interface, which allows the user to interactively examine the results of any

changes in processing parameters. While the main application of the software would be to quantify the absolute accuracy of MRI gel dosimetry for planning verification, it also can be used to compare any two dose distributions. Moreover, it is planned to integrate the algorithms needed to process data obtained using other read-out techniques (such as optical CT) in future.

Without a true 3D evaluation analysis it becomes impossible to really determine and quantify the expected accuracy of gel dosimetry as a technique. It is anticipated that if this software is accepted routinely then it would become invaluable in routine QA checks. The analysis using the software to compare dose distributions, which ought to be identical, showed that the proportion of points passing the DTA and dose difference criteria is higher using the 3D evaluation methods than with 2.5 D analysis. This demonstrates that extending the search to points in the 3D space, rather than just in the 2D space, enhances the chance of passing the evaluation criteria. It also shows that the image registration functionality built into the 3D evaluation methods account for the small movements and setup error; therefore, they produce more reliable evaluation results than the 2D evaluation methods.

References

[1] C. Baldock, Y. D. Deene, S. Doran, G. Ibbott, A. Jirasek, M. Lepage, et al. Polymer gel dosimetry. Physics in Medicine and Biology, 55(5):R1, 2010.

[2] D. J. Kroon, C. H. Slump. MRI modalitiy transformation in demon registration. Biomedical Imaging: From Nano to Macro, 2009. ISBI '09. IEEE International Symposium on, June 28 2009-July 1 2009 2009. 963-6.

[3] G. P. Liney, A. Heathcote, A. Jenner, L. W. Turnbull, A. W. Beavis. Absolute radiation dose verification using magnetic resonance imaging: feasibility study. Journal of Radiotherapy in Practice, 3(03):123-9, 2003.

[4] D. A. Low, W. B. Harms, S. Mutic, J. A. Purdy. A technique for the quantitative evaluation of dose distributions. Medical Physics, 25(5):656-61, 1998.

[5] A. Mans, P. Remeijer, I. Olaciregui-Ruiz, M. Wendling, J.-J. Sonke, B. Mijnheer, et al. 3D Dosimetric verification of volumetric-modulated arc therapy by portal dosimetry. Radiotherapy and Oncology, 94(2):181-7, 2010.

[6] D. Rueckert, L. I. Sonoda, C. Hayes, D. L. G. Hill, M. O. Leach, D. J. Hawkes. Nonrigid registration using free-form deformations: application to breast MR images. IEEE Transactions on Medical Imaging, 18(8):712-21, 1999.

[7] E. Spezi, D. G. Lewis. Gamma histograms for radiotherapy plan evaluation. Radiotherapy and Oncology, 79(2):224-30, 2006.

[8] M. Stock, B. Kroupa, D. Georg. Interpretation and evaluation of the γ index and the γ index angle for the verification of IMRT hybrid plans. Physics in Medicine and Biology, 50(3):399, 2005.

[9] J. P. Thirion. Image matching as a diffusion process: an analogy with Maxwell's demons. Medical Image Analysis, 2(3):243-60, 1998.