Advances in Quality Control of Intraoperative Radiotherapy

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Abstract. Intraoperative radiotherapy is the kind of radiotherapy where the remains of a surgically not completely removed tumour are irradiated at the open situ of the patient. The current main drawback of this radiotherapy is the insufficient documentation of the applied radiation and the lack of a possibility for an individual treatment planning. This work presents a system that is a common development of Fraunhofer IGD, Städtische Klinik Offenbach and MedCom GmbH which offers a possibility for supervision of the placement of the irradiation flabs through interactive navigation in CT data acquired from the patient, the creation of a documentation of the applied isodose as well as the possibility for an individual treatment planning. ...

1 Introduction

Intraoperative radiotherapy (IORT) is a radiotherapy that is applied during the operation at the open situ of the patient after the surgical removal of a tumour with the objective to irradiate remains of the tumour that could not be removed surgically. Such an irradiation can be performed in a procedure where an Iridium radiation source is placed over the remains of the tumour with the help of an carpet like "flab" (see Appendix). Such a flab consists of a number of rubber pellets connected to each other (Freiburger Flab, s. articles in [8],[7]). The flab also contains small plastic pipes, so called "applicators", through which the radiation source is dragged or shifted. The accurate and effective placement of the flab inside the body of the patient for the irradiation highly depends on the experience and knowledge of the radiotherapist. So far neither an individual therapy planning could be performed nor a documentation of the applied isodose in the CT scans could be made because the position of the flab in its relation to a CT data set of the patient in which a radiotherapy planning can be performed is not known. Objective of this common project of the Fraunhofer Institute for Computer Graphics, the Städtische Kinik Offenbach and MedCom GmbH was the development of a system to overcome this rather inaccurate, person and experience depend technique by computer support. With a digital acquisition and visualisation of the geometry of the points of irradiation an accurate documentation of isodose distribution and in a further step a radiotherapy treatment planning in this kind of brachytherapy is made possible.

The original working steps (s. fig. 1) of the IORT procedure are:

- Acquisition of CT data: A CT data set of the patient tumour region is acquired, this data is solely used for surgery planning.
- Tumour Operation: The patient is operated, the tumour is removed surgically as far as this is possible.
- Placement of the flab: The flab is placed at the previous tumour position over the remains of the tumour according to the experience of the surgeon.
- Irradiation: The radiation sources are drawn by the irradiation device through the flab pipes with stop positions and irradiation times according to the experience of the radiotherapist.

Fig. 1. Original IORT working steps

2 Implementation

The system (s. fig 2) is based on a PC workstation, with Microsoft NT operating system and an additional electromagnetic spatial tracking system (6 degrees of freedom, Polhemus or Ascension pcBird). Such a tracking system consists of a transmitter that builds up and controls an electromagnetic field and a receiver that detects its current spatial position and orientation within the electromagnetic field. The data with the geometrical information of the receiver is transferred to the workstation for further processing. The system is furthermore equipped with a foot pedal for controlling the recording of geometrical points with the tracking system.

The main part of the software is a system for visualisation of medical volume data, such as CT, MRI or three-dimensional ultrasound data, that has been developed over several years in the Fraunhofer Institute for Computer Graphics (s. [4],[5],[6]). In our case the data is acquired by a Siemens Somatom CT and transferred directly to the workstation via the hospital network in DICOM 3 format. With the visualisation software the data can be displayed as usual CT scans, oblique oriented slices in the volume data or as volume rendering. Additionally in the partner hospital the Nucletron Plato system (version BPS 2.4) is used for radiation treatment planning and visualisation of an isodose distribution in the CT data.

The procedure of registration of patient geometry and the CT data set of the patient assumes that the changes of the geometry of the body of the patient caused by the operation can be neglected. This is due to prior evaluations of the partner hospital not generally the case but can be assumed for the sacral region of the human body where the massive hip bones keep their previous geometry also during operation. Therefore this application focuses in the first step to intraoperative radiotherapy in the sacral region of the body.

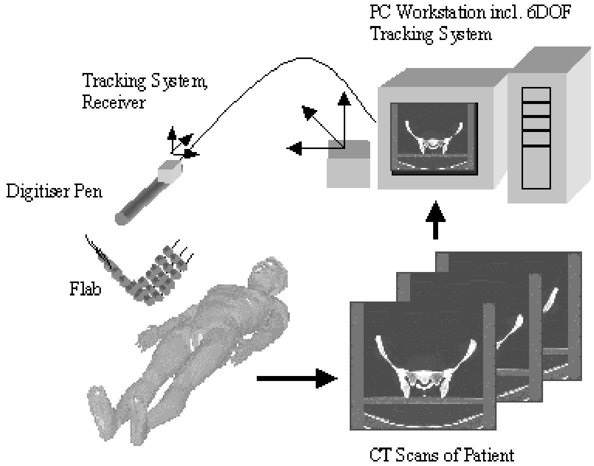

Fig. 2. System Overview

With this system the acquisition of the flab geometry can be performed with the following additional working steps (s. fig. 1,3) :

- Acquisition of CT data: A CT data set of the tumour region of the patient is acquired. This data can be used for operation planning as before, additionally it is used for the advanced IORT procedure in the steps described below. The CT scans must be acquired in the highest possible spatial resolution to guarantee the highest possible accuracy for the placement of the CT landmarks (see below). In our case the distance between two subsequent CT scans is 1mm, the spatial resolution within one scan is 0.625 mm.
- CT landmarks: As a preparation step landmarks (at least four) are manually selected in the CT data at typical anatomic positions, e.g. anatomical points at the Promontory or the Os Sacrum.
- Patient landmarks: The spatial coordinates inside the body of the patient of the anatomical landmarks defined in the CT data are acquired with the tracking system.
- Registration patient - CT: With these pairs of landmarks a transformation from the spatial position of the tracking system to the CT data can be calculated by the solution of the according (over estimated) equation system. Both kinds of data - a spatial coordinate and a position in a slice of the CT data - can be merged together afterwards.
- Navigation in CT data: When pointing at a specific anatomic position in the body of the patient with the digitiser pen mounted on the receiver of the tracking system the visualisation software displays the according position in the CT data. With this navigation tool a the physician can evaluate if a possible position for the placement of the flab is suitable for the irradiation of the remains of the tumour.

- Placement of the flab: The flab is placed at the previous tumour position according to the evaluation in the navigation step.
- Digitalisation of flab geometry: The flab is now digitised by recording a necessary number of spatial positions of pellets of the flab with the digitiser pen.
- Visualisation: The flab can now be displayed embedded in the CT data, as CT scan images or in a volume rendering to supervise the chosen position. With this supervision the position of the flab inside the body of the patient can be corrected if it does not guarantee a sufficient irradiation.
- Documentation / therapy planning: The acquired flab geometry can be exported to the Nucletron irradiation planning system where it is used for documentation and individual radiotherapy planning.

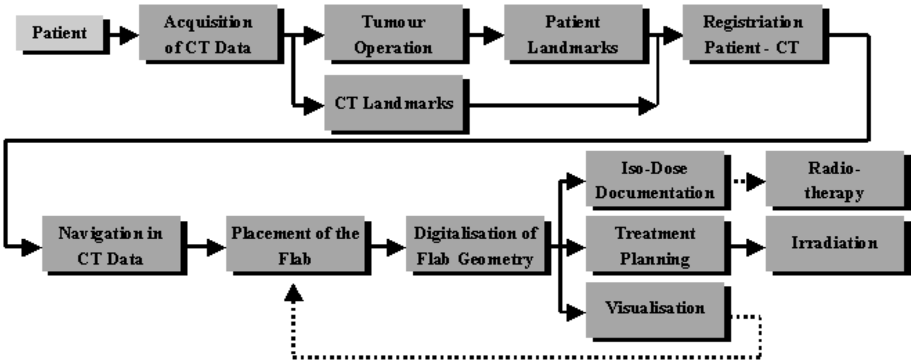

Fig. 3. Advanced IORT working steps

3 Results

3.1 Accuracy

The most problematic issue concerning the accuracy of the system is the electromagnetic tracking system. The overall accuracy of the system mainly depends on the distortion free recording of spatial points - both landmarks at the patient' s body and pellet positions - with the tracking system. All electromagnetic tracking systems have the common weakness that they easily can be disturbed by other electromagnetic fields or the influence of metal in the measurement range. The environment in a operation room contains lots of disturbing metals e.g. the surgery table, metal clamps, scalpels, etc. This influence of metal can be almost completely compensated by a careful definition and evaluation of the surgical working environment and selection of objects made of alternative materials like plastic.

An infrared tracking system cannot be used in this application because it would need a direct line of sight from the digitiser pen to a detection camera which cannot be guaranteed in the IORT scenario, for example when recording the applicator pellets inside the body of the patient.

The accuracy of the system has been validated with a special phantom (s. fig 4). This Phantom consists of a U - shaped plastic frame containing a small flab with two applicators mounted at a fixed position inside the frame. The phantom contains small marker holes that are additionally filled with a contrast media for easier detection of these markers in the CT data when the CT landmarks are placed. With this markers an optimal registration of the CT data with the phantom geometry can be performed. A CT data set of this phantom is acquired where the rubber pellets of the flab are clear to see in the CT data. The centre of each pellet is marked manually in the CT slices. After the registration of the CT data with the phantom has been performed and the flab pellets geometry has been recorded these marked pellet positions positions in the CT data can be compared with the recorded positions and the error can be calculated. We found that our system works under clinical conditions in the surgery room with an overall accuracy of 3 mm.

This procedure takes the advantage that the registration can be performed optimal because of the marker holes in the phantom. A "real life" registration must be performed with bone structures where the exact landmark position depends on the interpretation of the physician. The magnitude of this error has been evaluated in the same way as with the phantom described above but with a human hip bone. The location error found in this validation was below 2 mm.

It must be emphasised that it was not possible so far to obtain a documentation of what tissue of the patient is irradiated with a concrete placement of the flab. Also it could not be said if the remains of the tumour have been irradiated sufficiently. This application now enables the radiotherapist to document a specific constellation of patient, tumour remains and flab. Furthermore the acquired geometrical data can be used to calculate the stop positions for the Iridium radiation source to optimise the individual radiation dose.

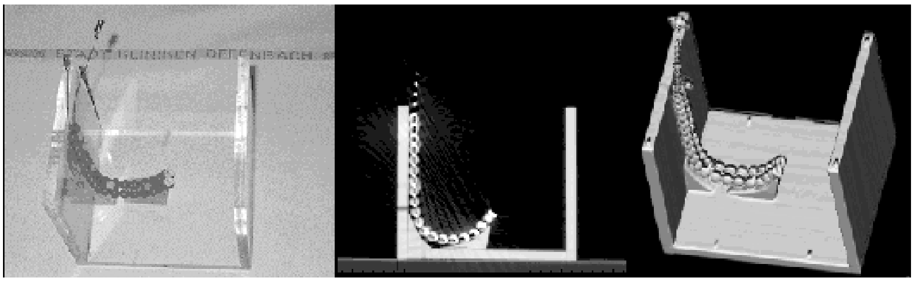

Fig. 4. Phantom for the validation of system accuracy: photo, CT scan and surface Volume Rendering

3.2 Visualisation

The visualisation software of the system is based on a direct volume rendering software which uses the ray casting algorithm. This method calculates the resulting image directly from the three-dimensional scalar data omitting an intermediate representation such as polygons (s. [1],[2],[3]). The available modes for the volume rendering are:

- Maximum/minimum intensity projection
- X-ray simulation
- Surface reconstruction (semitransparent cloud or gradient shaded)

3.3 Composition of Pellet Geometry and Rendered Images

The common visualisation of the acquired geometric coordinates of the applicator pellets and the volume rendering of the CT data is achieved with a bump mapping method. A pellet is hereby modelled by a two-dimensional array containing the gradients of the surface of a hemisphere. The dimensions of this quadratic bump map array represent the size of a pellet in the resulting image and depend for the concrete case on the current parameters of the viewing transformation of the volume rendering system.

The acquired real world coordinates of the pellet centre is first transformed into the volume coordinate system and then with the viewing transformation of the volume rendering system into the resulting image. A bump map with the proper dimensions according to the viewing parameters is vitually placed at this position in the resulting image and used to modify pixel values according to the gradient information in the bump map. The Z-position of an entry in the bump map is calculated accordingly and compared with the depth information in a surface Z-buffer calculated by the volume rendering system. If the calculated Z-coordinate of a bump map entry indicates that it is nearer to the spectator than the surface calculated by the volume renderer the new value of the according pixel is calculated. By combining the original pixel value with a gradient shaded illumination, in which the gradient of the according bump map entry and a virtual light source are combined a semitransparent sphere is placed over the surface rendering. Figure 5 shows images from two different views and according close-up views. The consideration of the Z-coordinate is not necessary for the transparent visualisation modes (e.g. maximum intensity projection) of the volume rendering system.

The system offers several modes for interactive visualisation during the intraoperative navigation. All modes support the display of the flab and the position of the digitiser pen.

1. CT Scans: Medical users of the software are currently used two work with 2D CT scan images and therefore the system supports a view of the original CT scans with an integrated view of the pellets of the flab intersected by this scan (see Appendix).

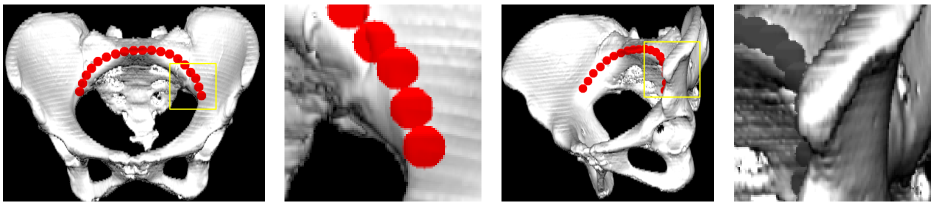

Fig. 5. Composition of pellet geometry and volume rendering with bump mapping: total view, close view, total view from a viewpoint where pellets are covered by parts of the hip bone, close view of the covered pellets.

2. 3 Orthogonal Cuts: The CT volume can be displayed as a wire frame cube with three intersecting orthogonal planes that can be chosen freely by the user. The cutting point of all three plans is coupled to the current position of the digitiser pen for navigation (see Appendix).
3. 3D Volume Rendering: In this mode 3D reconstruction of the volume with overlaid pellets can be displayed. The pellets are embedded in the volume rendering resulting image via a semitransparent bump mapping technique regarding the depth position of the surface that has been calculated by the volume renderer (see Appendix).

The first two modes allow a interactive working with the system which means the resulting images are calculated in less then 0.1 second on a double Pentium II 200Mhz system. The third visualisation mode described above is based on volume rendering and therefore the interaction rate is less good than for the first two modes. The volume rendering calculation time mainly also depends on the size of the CT data set and the size of the resulting output image. Typical data sets in the practical use of this application have a size from 20 up to 50 MB.

Table 1. Rendering times of CT data set with size 29MB, two sizes for the resulting image on a double Pentium II 200MHz system

Volume rendering mode	av. time (200x200)	av. time (400x400)
Maximum intensity projection	1.5 s	4.3s
Surface (gradient shading)	1.2 s	3.5s

4 Conclusions & Further Work

The introduced system offers a methods for optimised placement of the flab and an isodose documentation of applied radiation first as a quality control, second as an input to a long term radiation therapy. Furthermore the introduced working scheme offers an individual treatment planning for this kind of brachytherapy. The system is currently in the stage of a first clinical evaluation in the hospital in Offenbach, Germany.

One drawback of the current system is that all the positions of the pellets must be recorded with tracking system which means that depending on the concrete used flab up to fifty positions must be recorded. This high number and therefore the time consumption of this time critical procedure can be significantly reduced by introducing a mathematical description of a flab template (e.g. a spline interpolation) that is formed by the geometrical positions of some of the pellets. Another important issue is to improve the user friendliness of the system by introducing a voice control of the user interface.

Acknowledgement We herewith want to thank all the person that contributed during the development of the system with their opinions and their experience especially the medical supervisors in Städtische Kliniken Offenbach as there are Prof. Dr. Nier, Chirugische Klinik , Prof. Dr. Dr. Zambouglu and OA Dr. Kolotas.

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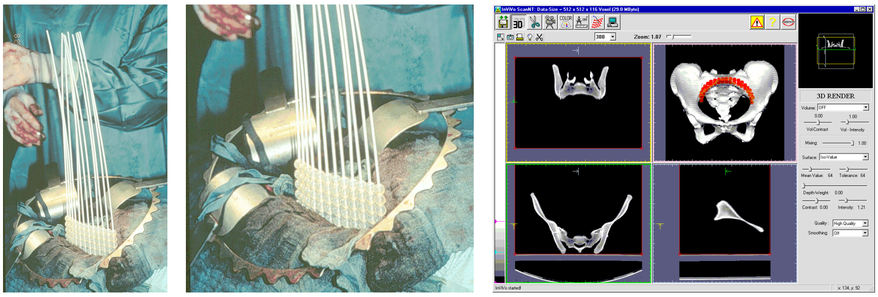

Fig. 6. Left:Flab with rubber pellets and flab in situ with applicator pipes; right:InViVo-IORT user interface: three windows with orthogonal cutting planes through the CT volume data and a 3D surface reconstruction (upper right window)

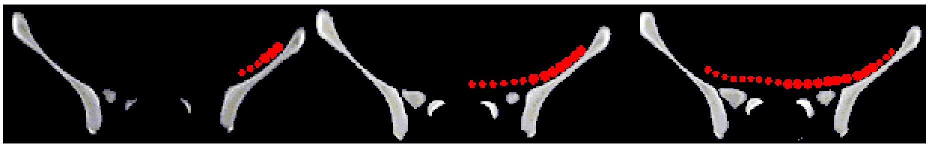

Fig. 7. Display of CT scans and intersected pellets

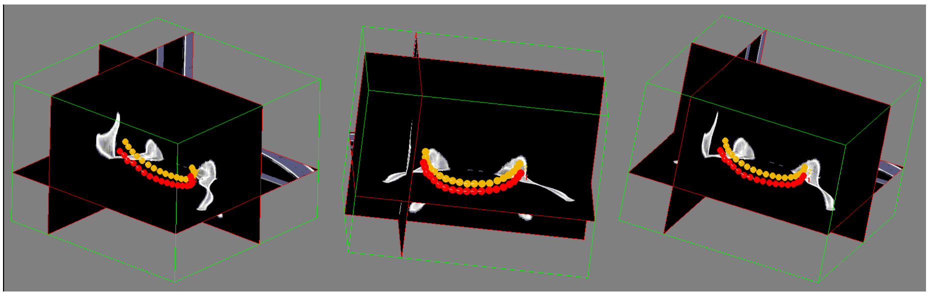

Fig. 8. 3D Visualisation as 3 orthogonal cutting planes with overlaid flab pellets of two applicators

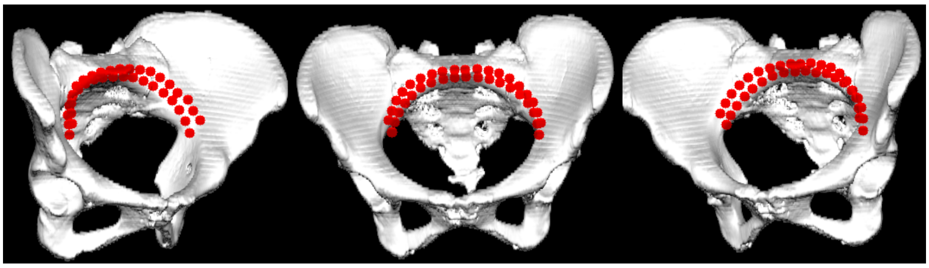

Fig. 9. 3D visualisation (surface volume rendering) with overlaid flab pellets of two applicators