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Ultrasound tracking for intra-fractional motion compensation in radiation therapy

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ABSTRACT

Modern techniques as ion beam therapy or 4D imaging require precise target position information. However, target motion particularly in the abdomen due to respiration or patient movement is still a challenge and demands methods that detect and compensate this motion. Ultrasound represents a non-invasive, dose-free and model-independent alternative to fluoroscopy, respiration belt or optical tracking of the patient surface. Thus, ultrasound based motion tracking was integrated into irradiation with actively scanned heavy ions. In a first *in vitro* experiment, the ultrasound tracking system was used to compensate diverse sinusoidal target motions in two dimensions. A time delay of ~200 ms between target motion and reported position data was compensated by a prediction algorithm (artificial neural network). The irradiated films proved feasibility of the proposed method. Furthermore, a practicable and reliable calibration workflow was developed to enable the transformation of ultrasound tracking data to the coordinates of the treatment delivery or imaging system – even if the ultrasound probe moves due to respiration. A first proof of principle experiment was performed during time-resolved positron emission tomography (4DPET) to test the calibration workflow and to show the accuracy of an ultrasound based motion tracking *in vitro*. The results showed that optical ultrasound tracking can reach acceptable accuracies and encourage further research.

Introduction

Modern techniques in radiation therapy such as ion beam therapy or intensity modulated radiation therapy (IMRT) can achieve delivery accuracies at the millimeter scale. However, target motion particularly in the abdomen due to patient movement or respiration imposes inaccuracies that cannot be neglected [1]. In addition, these difficulties arise not only in radiation therapy but also in diagnostic imaging. Therefore, methods that detect and compensate this motion are in strong demand [2]. Many approaches have been proposed already to avoid substantial dose errors and distorted images. Optical systems [3] or breathing belts – as used in the Respiratory Gating System AZ-733V (ANZAI Medical Co., Ltd., Tokyo, Japan) – generally only return 1D tracking information of the abdominal surface. Fluoroscopy yields the desired information on inner structures but implies an additional radiation burden for the patient [4]. The Calypso System (Calypso Medical Technology, Seattle, WA) which is used in prostate radiation therapy uses implanted RF-transponders for continuous motion tracking of a tumor [5]. However, this is highly invasive as fiducials (small beacons) have to be implanted accurately near the tumor.

Here diagnostic ultrasound (sonography) represents a non-invasive, dose-free, model-independent, real time capable and cheap alternative. First experiments to integrate ultrasound tracking to radio surgery using the CyberKnife (Accuray Inc., USA) have already been performed successfully. Blanck et al. [6] replaced the standard optical tracking system by a GE Vivid 7 (General Electronics, USA) ultrasound device to follow the motion of fiducials in a water bath. The fiducials were coupled rigidly to a simple

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beam target and moved by a robotic arm. Schlosser et al. [7] combined telerobotic diagnostic ultrasound with projection X-ray imaging in image guided radiation therapy (IGRT). The two modalities complemented each other during IGRT delivery on a tissue mimicking phantom with gold fiducial markers.

While these two approaches rely on the tracking of fiducial markers that might need to be implanted to the patient, the final goal of this project is to develop an ultrasound based motion tracking for real time motion correction notably in ion beam therapy that works without markers. It is favorable to avoid the use of fiducial markers as they require an implantation and might influence the dose distribution during therapy [8]. In this work, two first steps towards this goal were performed *in vitro*: First, ultrasound tracking was integrated into treatment delivery with actively scanned heavy ions [9]. Thus, this study represents a new technical combination of two modalities. Secondly, a workflow was developed to enable the transformation of ultrasound tracking data to the coordinates of the treatment delivery system – even if the ultrasound probe was moved itself during acquisition. This may be the case if the probe is attached directly to the patient's skin instead of being hold by a static holder.

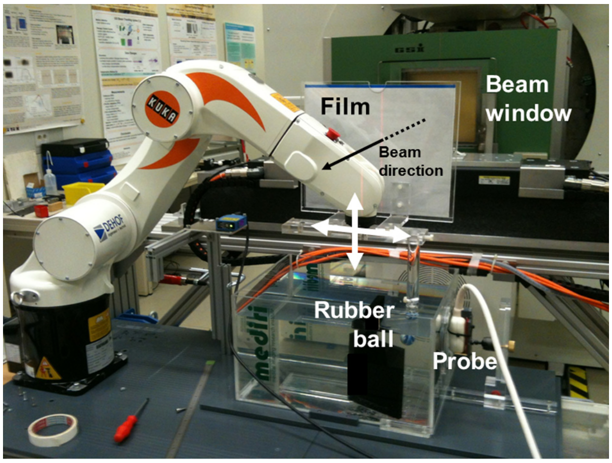

Figure 1. Experimental setup for ultrasound tracking in ion beam therapy: Both, the radiosensitive film and the rubber ball were moved by the robotic arm in two directions perpendicular to the ion beam. The motion was detected by the ultrasound tracking system and transferred to the treatment delivery system.

Material and methods

The ultrasound tracking software used, Sonoplan II, is developed by mediri GmbH, Heidelberg, Germany, and runs on a DiPhAS (Digital Phased Array System, Fraunhofer IBMT, St. Ingbert, Germany) ultrasound device. The DiPhAS comprises the beam former and a PC such that the necessary raw data can be accessed easily and processed directly on the machine. The ultrasound probe that was used during these experiments consists of two orthogonally oriented phased arrays with 64 elements, respectively. This allows quasi-simultaneous imaging in two perpendicular image planes. The tracking algorithm uses active contours and conditional density propagation as described in detail by Zhang et al. [10]. Based on the brightness values of a manually segmented structure, the algorithm yields up to five features of the moving target in real-time (5 ms per frame): translation and scaling in *x*- and *y*-direction, respectively, as well as rotation within the *x*–y-plane. Taking all image processing and tracking calculations together, the software needs about 40 ms to calculate tracking data out of the incoming raw data of one frame. As the two image planes are generated alternately, it takes about 80 ms to get the complete tracking information of both the frames. In our experiment, additional image processing and data transfer operations lead to a sampling rate of 150 ms for the two frames.

Integration into active ion beam delivery

As this experiment should serve as a first proof of principle for the use of ultrasound tracking information in active ion beam delivery, a straightforward setup was chosen. A rubber ball target inside a water bath was moved by a robotic arm in two dimensions orthogonal to the ion beam at GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany (see Fig. 1). The robotic arm generated various sinusoidal trajectories having a period of 3s and a peak-to-peak amplitude of 20 mm. Squares of 3×3 cm^2 should be homogeneously irradiated by a calcium ion beam with an energy of 200 MeV/u and a beam width (FWHM) of 6mm on radiosensitive films using the beam tracking (steering) technique. Each field was irradiated by one single scan, the distance between the single beam spots was 2 mm in both directions. Thus, each field was created by $15 \times 15 = 225$ beam spots. The mean irradiation time for one beam spot was around 1 ms, nevertheless, caused by the ion beam delivery system, the total irradiation time for one field was several minutes. This brings out again the need for a motion correction that works reliably over a time span of several minutes. The films were attached to the same robotic arm as the rubber ball. Thus, the motions of the tracking target and the beam target were coupled directly. The displacement of the rubber ball was continuously measured by the US tracking system and sent to the therapy control system (TCS). Hence, the study relies on the already established TCS which is indeed capable to track (steer) the ion beam according to incoming target position information in real-time. However, to our knowledge, it is the first time that ultrasound tracking information was used to adapt the beam position. Image processing, tracking calculations and data communication introduced a delay of ~200 ms leading to a position error of several millimeters. An artificial neural network (ANN) was implemented in the TCS to predict motion from US measurements and thus to compensate for the delay. Note, that the tracking information for both ultrasound image planes was generated, but as the target motion was two dimensional, we only used the tracking data of the plane perpendicular to the beam. The irradiated films were developed and digitized with a resolution of 150 pix/inch (1 pix = 0.17 mm) and 16 bit depth using a medical film scanner (Vidar DosimetryPro Advantage).

Tracking in absolute coordinates

In order to perform ultrasound tracking, it is necessary that the probe stays in contact with the patient. This can be achieved either by a static holder in combination with a gel pad that compensates breathing motion or by a probe that is attached directly to the skin. In the latter case, the probe position has to be registered to allow tracking in absolute coordinates. For this part of the study, the ultrasound probe was equipped with an optical marker in order to be detected by an optical tracking system, the Passive Polaris Spectra measurement system (Northern Digital Inc., Waterloo, Ontario). After calibration of both, the ultrasound system and the optical tracking system, the setup was tested in a PET/CT (Positron Emission Tomography/Computed Tomography) scanner at the Heidelberg Ion-Beam Therapy Center (HIT) to show the feasibility of the proposed workflow. The target was a combination of a rubber ball in a water bath and a radioactive point source. The target was moved by a QUASAR respiratory phantom (Modus Medical Devices Inc., London, Canada) with a peak-to-peak amplitude of 40 mm and