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Real-time tumor tracking with an artificial neural networks-based method: A feasibility study

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Abstract The purpose of this study was to develop and assess the performance of a tumor tracking method designed for application in radiation therapy. This motion compensation strategy is currently applied clinically only in conventional photon radiotherapy but not in particle therapy, as greater accuracy in dose delivery is required.

We proposed a tracking method that exploits artificial neural networks to estimate the internal tumor trajectory as a function of external surrogate signals. The developed algorithm was tested by means of a retrospective clinical data analysis in 20 patients, who were treated with state of the art infra-red motion tracking for photon radiotherapy, which is used as a benchmark. Integration into a hardware platform for motion tracking in particle therapy was performed and then tested on a moving phantom, specifically developed for this purpose.

Clinical data show that a median tracking error reduction up to 0.7 mm can be achieved with respect to state of the art technologies. The phantom study demonstrates that a real-time tumor position estimation is feasible when the external signals are acquired at 60 Hz.

The results of this work show that neural networks can be considered a valuable tool for the implementation of high accuracy real-time tumor tracking methodologies.

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Introduction

In radiation therapy, ionizing radiation is used to damage malignant cells as part of a treatment course to cure cancer. Radiation therapy is actually used in approximately 60% of patients as curative, adjuvant or palliative treatment strategy. The fundamental principle of radiation therapy is to cause the highest possible damage to the neoplastic target while, at the same time, sparing surrounding healthy structures. However, tumors placed in the thoracic and abdominal areas are often influenced by intra-fractional organ motion, caused by physiological processes such as breathing and heartbeat [1—3]. In these cases, uncertainties in target localization force to expand the geometric margins around the clinical target volume [4,5]. The end result is an increase in the volume of healthy tissues which is irradiated, thus reducing the ballistic potentialities and the geometrical selectivity of the treatment. As a consequence, motion monitoring assumes a very significant role in radiation therapy.

External motion tracking is typically performed for patient set-up and respiratory motion monitoring [6]. Moreover, it can also be exploited as a surrogate of the internal motion, either for 4DCT reconstruction [7] or when the treatment is delivered by means of motion mitigation techniques, such as beam gating and beam tracking, which will be specifically described later in this section. The displacement of the external body surface is generally detected relying on infra-red devices [8]. For example the Real-Time Position Management (RPM, Varian Medical Systems, Palo Alto, CA) system is able to localize a single object placed on the patient's abdomen [9]. However, in order to detect the motion in all its complexity, multiple passive markers can be placed on the thorax and/or on the abdomen of the patient. Alternative solutions that do not require external markers, whose placement is time consuming and requires very high reproducibility, have been developed relying on surface imaging [10].

Also the internal motion can be directly monitored in radiation therapy [11]. For this purpose, a metallic marker is typically implanted inside or near the tumor and its position is tracked in real-time by means of fluoroscopic imaging. In this case, Real Time Radiation Therapy (RTRT) [12] can be implemented by continuously detecting the internal tumor position. Results show that targets moving at a speed up to 40 mm/s can be tracked at a frequency of 30 images per second with an accuracy better than 1.5 mm [13]. However, the main drawback of this technique consist in the amount of non therapeutic dose that is delivered to the patients as a consequence of the fluoroscopic acquisition that is performed during the entire duration of the treatment.

In order to achieve an accurate dose delivery even on moving targets, internal motion monitoring is generally combined to motion mitigation techniques, whose aim is to compensate for intra-fractional organ motion [14]. Among these techniques, the breath hold consists of a forced [15] or voluntary [16,17] suspension of respiration during irradiation; conversely, respiratory gating limits irradiation to a pre-defined respiratory phase identified by a respiratory related signal, which is provided by external surrogates [18,19]. Another possible approach to motion mitigation is tumor tracking, which implies the dynamic steering of the therapeutic beam in order to follow in real-time the target motion along its trajectory. Tumor tracking shows significant advantages with respect to both breath hold and gating: in particular, it allows the patient to breath freely for the entire duration of the treatment, without requiring any suspension of the respiratory cycle, which may result difficult in subjects suffering from respiratory impairment. Moreover, since tumor tracking allows the dose to be delivered almost continuously, a high duty cycle can be achieved, thus reducing the total treatment duration with respect to respiratory gating and breath hold.

At present, tumor tracking is implemented clinically in the CyberKnife system (Accuray Inc., Sunnyvale, CA) equipped with the Synchrony module [20,21]. This device provides real-time tumor tracking relying on the correlation between internal target and external marker motion. It works as follows: before the irradiation the tumor position is determined at multiple distinct time points in different breathing phases with two orthogonal X-ray acquisitions. Then a linear, quadratic or constrained fourth order polynomial correspondence model is generated to relate tumor position to the three external markers. During treatment, this correlation model is used to estimate the internal tumor position as a function of external markers motion. Additional X-ray images at limited temporal frequency are acquired during treatment, in order to check and update the correlation model when needed. Since Synchrony uses three optical external markers, the system builds a correlation model for each marker; then the outputs of each model are averaged to obtain a unique estimation. Moreover, to take into account communication latencies and the inertia of the manipulator ($\approx$115 ms overall), a time predictor is used to compensate for these delays. It has been reported that in real patient treatments the accuracy of the CyberKnife equipped with Synchrony RTS ranges from 0.2 mm to 1.9 mm in superior-inferior direction, from 0.1 mm to 1.9 mm in left-right direction and from 0.2 mm to 2.5 mm in anterior-posterior direction [23]. Recent studies [22,23] have shown that its accuracy in tumor tracking is mostly dependent on uncertainties in the internal/external correlation model, rather than on the prediction.

Starting from these findings, we recently performed a comparative study to assess the accuracy of different correlation algorithms for tumor tracking [24]. This was conducted on a population of twenty patients who received extra-cranial radiotherapy with real-time compensation of tumor motion by means of the Synchrony RTS. A linear/quadratic model was compared with more complex strategies, including artificial neural networks and fuzzy logic: results showed that complex methods provide better accuracy in tumor tracking with respect to a polynomial correlation model, particularly in irregularly breathing patients. However, the algorithms and the method proposed in this study are meant for offline data analysis. As consequence, they cannot be integrated into a motion monitoring system and exploited for online data acquisition and processing.

Starting from the results of our previous work [24], we propose a study with the following goals: