4D dosimetry and motion management in clinical radiotherapy

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Abstract: Many novel modulated radiation treatment techniques are sensitive to patient motion which may degrade the dose distribution considerably. As there may be a simultaneous movement of the tumour and treatment machine, undesired heterogeneities in the dose distribution can be resulted. Methods to estimate the dosimetric effect of motion and treatment deliveries for both photons and protons are needed. We have recently studied Hodgkin’s lymphoma, liver and left sided breast cancer cases and developed tools to be able to simulate simultaneous organ movement and treatment delivery. Furthermore, it is of great importance to validate potential simulations in a realistic quality control set-up, ideally including a complete dosimetry volume and movement/deformation (4D). Radiation sensitive deformable gels have the potential to meet this dosimetry challenge owing to the unique 3D characteristic to form both phantom and detector in one volume. Multi-array detectors together with a moving platform and a realistic object trajectory is an alternative to evaluate the clinical setting. The evaluation could then in principle be done on-line. Gel/plastic 3D dosimeters have the potential to also be irradiated during motion in a similar matter but have to be read-out post irradiation.

1. Introduction

As radiotherapy techniques progress there are new challenges to assure that there is a homogeneous high dose to the tumour while minimizing the dose to the surrounding healthy tissue. There is a considerable risk that the timing of the treatment delivery and volume movement result in an inter-play effect that may affect the treatment outcome but this assumption has to be thoroughly validated. The inherent problem of volumes that also change shape within the patient due to movement can also be simulated but the results is very difficult to verify.

To minimize the uncertainties owing to motion in a clinical setting, it is first essential to use suitable immobilization devices and image guidance. Secondly, organ changes/motions have to be handled on different time scales depending on their inherent characteristics. A patient can lose weight or have a large change in bowel filling (interfraction), alternatively be temporarily affected by breathing, swallowing, and for example eye movements (intrafraction).

Most important is tumour motion due to breathing as the tumour can follow complex trajectories, and the breathing pattern might change regarding magnitude, period, regularity, and baseline position. For both photon and particle therapy, breathing motion might result in deviations between the planned and delivered dose distributions, in the form of dose blurring, interplay effects and range uncertainties.
The combined effect might be difficult to predict and in clinical practice the treatment planning procedure often only include the static components of the incident beams (figure 1).

![Figure 1](image1.png)

**Figure 1.** Example of a static dose distribution (a), a dose distribution including dose blurring (b), and a dose distribution including both interplay effects and dose blurring (c). The motion is in the left-right direction. Figure adopted from Edvardsson 2018 [5].

In this communication we will discuss the clinical challenges and significance of relevant dosimetry and quality assurance in conjunction with motion management in clinical radiotherapy.

2. **Clinical motion management and treatment techniques**

To handle the effect of motion the treatment margin can be increased, but larger volumes of healthy tissue will then be irradiated. Further, this will not account for interplay effects. Other techniques include respiratory gating, breath-hold and various way of tracking the tumour. Methods are needed to reproduce and monitor the patient during CT/MRI/PET and treatment, several techniques are available to accomplish this [6, 7].

One example is surface scanning systems that can provide both feed-back to the patient and trigger the treatment machine and thereby facilitate for example deep inspiration breath hold (figure 2).

![Figure 2](image2.png)

**Figure 2.** Example of a reference surface (a) and a real-time live surface (b) obtained by the Catalyst system during a deep inspiration breath hold (DIBH) left-sided breast cancer treatment. The treatment delivery is triggered when the surfaces within the red circle coincides (c). In addition, the live position of the iso-centre, calculated from the live surface using a deformable algorithm, is continuously compared to the planed iso-center position. Figure adopted from Kugele et al 2018 [8].

Another approach is to try to follow markers/edges in the tumour during treatment or as in the MRI-linacc concept, to have the potential to follow complete volumes of interest during treatment. Ideally this will also incur advanced and new methods of gating and motion management, at least for certain diagnosis.

However, there will always be inherent difficulties regarding how to handle anatomical deformations during acquisition/treatment. This problem may require theoretical methods including deformable image registration (DIR) algorithms. By the use of DIR, and the associated deformation vector field describing
the motion for each voxel, the accumulation of dose from several different time points can be transferred into a common geometry [9-11]. This method was recently used and developed to evaluate the breathing-motion induced interplay effects for VMAT radiotherapy using relevant clinical data [5].

3. 4D verification dosimetry
To enable a reliable radiation treatment including motion management, control methods should be developed accordingly. On a patient by patient basis the treatment plans can now be optimized taking e.g. breathing into account. Consequently, it is of utmost importance to assure that the theoretical and practical methods are transferred to the patient in a safe way and that the dosimetric effects can be validated. There are also a number of basic motion control parameters that should be verified on a day-to-day/regular basis, including iso-center geometry, timing, latency, amplitude etc. and guidelines are needed as highlighted recently (eg. AAPM task group 302). This ideally include end-to-end tests with 3D and 4D dose measurements and several methods have been presented within the IC3DDose conference series (eg [12]).

Another approach to undertake a dose verification, including motion, inter-play effect, linacc output MLC movements etc, was to use a multi-array detector and a motion platform (figure 3, Delta4 and HexaMotion, Scandidos, Uppsala, Sweden). For the measurements during motion, the present system to synchronize the motion and the treatment delivery should be used. In our setting the results showed good agreement between the measured and simulated dose distributions during motion, comparable to the results obtained for the measured and simulated static dose distributions. Based on these results, the clinical simulation tool was considered validated, and could be used for further patient treatment optimisation. Gel/plastic 3D dosimeters [13, 14] have the potential to also be irradiated during motion in a similar matter but have to be read-out post irradiation [eg [15-17]].

To include verification of deformations, and other changes in the irradiated volumes of interest, new approaches are needed. One example is the use of microMOSFET dosimeters and an electromagnetic positioning system for real-time tracking purposes [18] which also could be used together with anthropomorphic and deformable phantoms [19]. Time-resolved in-vivo dosimetric verification techniques have recently also been presented using radio-luminescence detectors in Brachytherapy [20]. Further, deformable dosimeters forming both phantom and detector (e.g. gel dosimeters) have the potential to validate the complete treatment procedure. Also assumptions made in the treatment planning phase, regarding for instance image registration and inter-play effects for motion or deformation, will then be included in the validation. Achieving a valid gel-phantom model of any individual patient case

Figure 3. The virtual phantom of the Delta4 used for simulations of interplay effects, containing a CTV (purple), ITV (green), PTV (blue) and two OARs (yellow and red) (a), with a magification of the white dashed box in (a) displayed in (b). The actual Delta4 phantom, positioned on the HexaMotion platform in the setup used for the verification measurements, is displayed in (c). Figure adopted from Edvardsson 2018 [5].
may be impractical, however mathematical approaches such as deformable dose accumulation based on DIR can be investigated [21, 22]. Potentially problematic cases such as those deficient in visible contrast or leading to interplay effects can be identified and the magnitude of those effects can be quantified [23]. Initial results have been presented for a deformable gel dosimeter which was dynamically deformed within a QUASAR respiratory phantom (figure 4) [24] along with other gel/readout approaches [25, 26].

Figure 4. DEFGEL with dynamic deformation applied (a) and static planned dose distribution (b).

Ideally the dosimetric verification should be directly related to the actual patient irradiation in a complete 4D measurement (time resolved 3D dose distributions) for any treatment equipment and Cherenkov imaging is a promising technique (e.g. [27]). The patient geometry is clearly also in place for EPID based dosimetry and the method have also been developed in the direction of 3D/4D verification [28].

4. References
[1] Bortfeld T et al 2004 Semin. Radiat. Oncol. 14 41-51
[2] Netherton T et al 2018 Med. Phys. 45 2369-76
[3] Lomax A J 2008 Med. Biol. 53 1043-56
[4] Bert C and Durante M 2011 Phys. Med. Biol. 56 113-44
[5] Edvardsson A 2018 Dosimetric effects of breathing motion in radiotherapy (Lund: Lund University) PhD thesis ISBN 978-91-7753-804-2
[6] Boda-Heggemann J et al 2016 Int. J. Radiat. Oncol. Biol. Phys. 94 478-92
[7] Korreman S S 2012 Phys. Med. Biol. 57 161-91
[8] Kügele M et al 2018 J. Appl. Clin. Med. Phys. 19 25-38
[9] Brock K K et al 2017 Med. Phys. 44 43-76
[10] Rietzel E et al 2005 Int. J. Radiat. Oncol. Biol. Phys. 61 1535-50
[11] Keall P 2004 Semin. Radiat. Oncol. 14 81-90
[12] Ceberg S et al 2010 J. Phys.: Conf. Ser. 250 012051
[13] Mather M L et al 2003 Phys. Med. Biol. 48 N269-75
[14] Hurley C et al 2006 Nucl. Instrum. Meth. A 565 801-11
[15] Edvardsson A et al 2018 Phys. Med. Biol. 63 085012
[16] Edvardsson A et al 2015 J. Phys.: Conf. Ser. 573 012048
[17] Ceberg S et al 2013 J. Phys.: Conf. Ser. 444 012098
[18] Gholampourkashi S et al 2017 Med. Phys. 44 299-310
[19] Gholampourkashi S et al 2018 Physica Medica 51 81-90
[20] Graversen Johansen J et al 2018 17 122-32
[21] Yeo U J et al 2012 Med. Phys. 39 5065-5072
[22] Juang T et al 2013 Rad. Oncol. 97 414-21
[23] Yeo U J et al 2013 Med. Phys. 40 101701
[24] Franich R D et al 2015 *J. Phys.: Conf. Ser.* 573 012024
[25] De Deene Y et al 2015 *Phys. Med. Biol.* 60 1543-63
[26] Maynard E et al 2018 *Phys. Med. Biol.* 63 075014
[27] Andreozzi J M et al 2018 *Med. Phys.* 45 2647-59
[28] Spreeuw H et al 2016 *Med. Phys.* 43 3969-74