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Analysis and evaluation of periodic physiological organ motion in radiotherapy treatments

Sergio Díez[a,b,*], Javier García[b], Francisco Sendra[c]

[a]*Service of Radiation Physics and Radiation Protection, Hospital Clínico Universitario de Valencia, Av. Blasco Ibañez 17, 46010 Valencia, Spain*
[b]*Department of Optics, Universitat de València, València, Spain*
[c]*Department of Radiology and Physical Medicine, Universidad de Málaga, Málaga, Spain*

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Abstract

Background and purpose: A system for the detection, measurement and analysis of the periodic physiological organ motion during radiotherapy treatment is proposed and clinically tested in this paper.

Material and methods: The procedure is based on the acquisition of fluoroscopic sequences, followed by an automatic detection of the movement using cross-correlations with matched filters.

Results: The system generates a probability density function (PDF) of finding a mobile organ in a position at a certain time. The maximum path of the mobile structures can be determined to define the planning target volume (PTV) without ambiguities.

Conclusions: Physiological movements can be accurately included in the daily planning routine, which is not essentially modified, without needing previous patient training.

Keywords: Radiotherapy; Organ motion; Fluoroscopic images; Clinical target volume; Margins

1. Introduction

Recent advances in conformal radiotherapy and IMRT now allow the delivery of dose distributions that tightly conform to the target volumes. Prediction of the dose delivered by a complex beam arrangement relies on the accurate description of the patient anatomical and tumoral data. Imaging techniques like spiral CT allow to obtain virtual representation of the patient to calculate target volumes and dose distribution, although the virtual representation of the patient is still and unchanging, while the real patient has involuntary organ motion (mainly due to breathing) and therefore, does not remain in the exact planning conditions along the treatment.

Following the ICRU recommendations [10,11], radiotherapists have to decide the margins around the clinical target volume (CTV) to accommodate uncertainties in the treatment planning and delivery process, which also include uncertainties due to organ motion. At present, the precise delineation of the target volume that requires the 3D treatment calculation technology is limited by the physiological organ motion and by the daily patient set-up inaccuracies [15]. Both sources of uncertainty in the target position and size have great influence in the dose delivered to the tumour and surrounding critical organs, and can cause important modifications of tumour control probability and complications to healthy tissue [19]. Set-up uncertainties can be reduced via immobilization techniques and careful daily repositioning of the patient using portal imaging and alignment tools. But tools to include the effect of organ motion in the treatment planning are needed.

The physiologic organ motion can be classified, according to their temporal behaviour, in: (i) non-periodic motion, produced by the filling status of structures such as the bladder or the rectum, (ii) periodic motion, due to breathing and cardiac motion (these movements are repeated many times during a single treatment session), and (iii) quasi-periodic motion, like the peristaltic movement of the stomach.

* Corresponding author.

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The largest variation in organ position and shape during radiotherapy is due to breathing. Moreover, its high frequency in comparison with other movements makes essential to take it into account, since any irradiation volume wrongly estimated will be kept during the whole treatment. In this work, a system for the detection and quantification of periodic physiologic movements (breathing and cardiac movement) for each individual patient in a way that can be incorporated to the calculation prior to the treatment is developed. The system is based on real-time acquisition of digital fluoroscopic image sequences of 1 min duration while the patient is freely breathing. An automatic analysis of such sequences allows the accurate computing of the frequency and amplitude of the periodic movement under investigation. With the obtained information, a synthetic image is generated, which represents a two-dimensional PDF of finding a mobile organ in a given spatial position.

2. Material and methods

2.1. Image sequence acquisition

The fluoroscopic sequences used in the proposed method are obtained by digitizing the image intensifier output of a conventional radiotherapy simulator.

As breathing amplitude and frequency are not constant [17,18], an acquisition time similar to the duration of a treatment fraction (1 min, approximately) was needed. This permits to take into ac count any variation in the normal respiratory rhythm during the irradiation. Sequences of 256×256 or 512×512 images are acquired at 5 or 10 images per second, which is fast enough to sample, either breathing or heart movement [5]. This acquisition time, together with the selected sampling interval determines the final number of images per sequence.

2.2. Sequence analysis tools

To characterize the periodic movement a method based on image correlation using matched filters [6,9] has been used in order to determine when an image is repeated in a sequence. First, a filter matched to an arbitrary image (reference image) within the sequence is first calculated. Afterwards, cross-correlations between the reference image and each other image in the sequence are computed.

The correlation is a measure of similarity. Thus, it will exhibit a maximum when the reference image is correlated with itself (autocorrelation) or with a very similar image in the sequence (i.e. when the mobile organs are in the same position and have the same shape). If the organs are in a different position or they are distorted the correlation value decreases in comparison to the autocorrelation value. In this fashion, the correlation values grow and decrease following the periodic movement of the respiration, in a wave shape that it will be called from now on a correlation wave. The procedure has been previously tested with the known periodic movement of a metronome, showing that it can be accurately sampled and detected [4,5].

2.3. Application to physiological movements

Once the correlation wave has been computed for a real patient, his/her breathing frequency is calculated from a Fourier analysis of the detected periodic movement. A correlation wave along with its Fourier transform are shown in Fig. 1. This analysis permits to extract the images corresponding to a semi-period and to build new synthetic

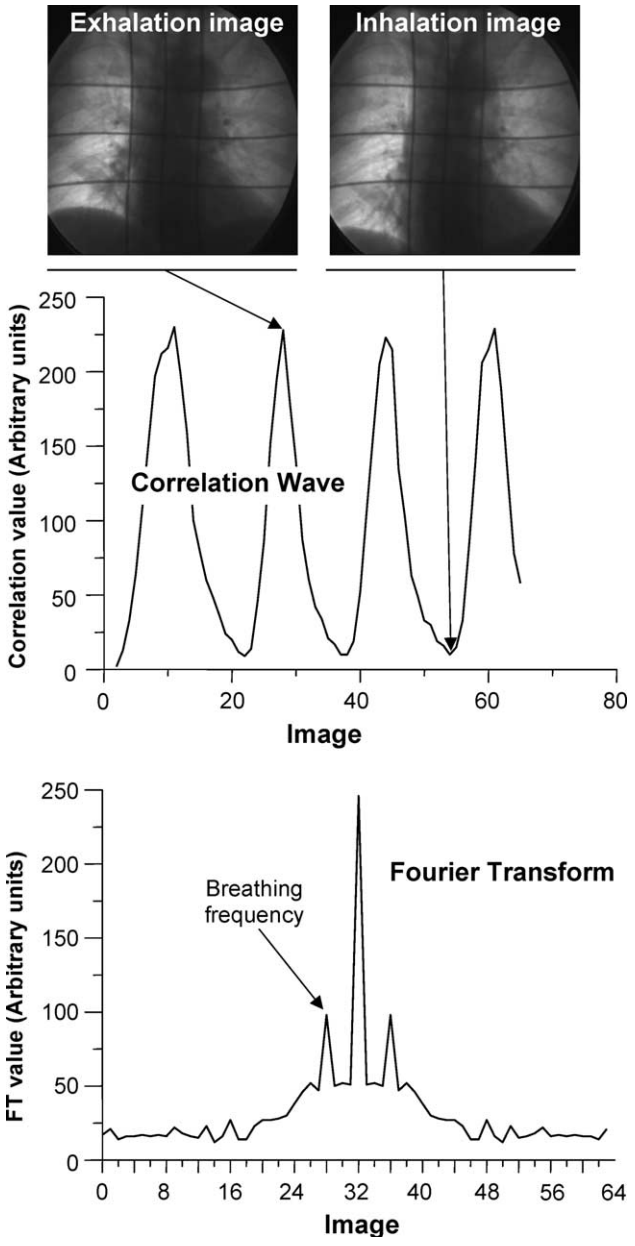

Fig. 1. Movement analysis applied to an actual breathing motion. It can be seen the maximum exhalation and inhalation images, the correlation wave and its Fourier Transform. Two sample occurrences of extreme breathing situations are pointed out. Values are given in arbitrary units.

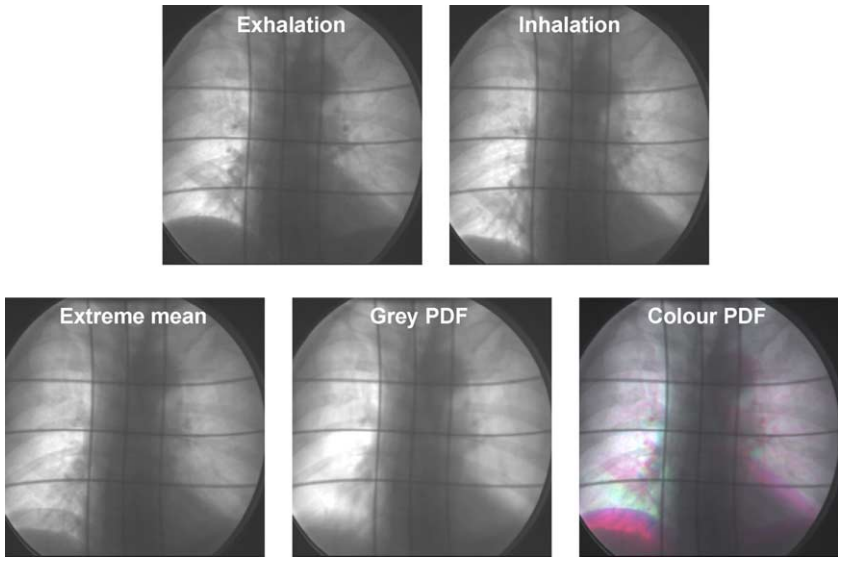

Fig. 2. Resulting images of a patient sequence analysis: extremes of a semiperiod of maximum amplitude (exhalation and inhalation images), mean image of extremes, sum of a complete semiperiod or grey scale probability density function (PDF) and colour PDF.

images, which allows the evaluation of the movement for the dose distribution calculation. The resulting images that are extracted or built from the sequence (Fig. 2) are:

The images corresponding to the instant of maximum inhalation and exhalation (extreme movements), which are used to quantify the actual motion amplitude of those organs affected by respiration.

The mean of the two extreme images, which shows the above information in a single image, although slightly blurred.

All the images obtained between the two extremes (half cycle) are added together, thus providing information of the position of a moving organ with regard to time, and giving in fact a probability density function (PDF) of finding a mobile organ in a position at a given time, which is, in fact, an image version of those PDFs described by Lujan et al. [13] or McKenzie [16].

Finally, the PDF is constructed again by building a false colour (RGB) image, where the Red and Green channel contains the inhalation and exhalation images, while the Blue channel contains the gray-PDF image. The resulting RGB is gray-scale, except in those areas where movement occurs. This is a useful image for motion detection, since the human observer is more sensitive to changes in colour than in grey levels.

3. Results: clinical application

The clinical use of the proposed detection system has two important applications:

- The recording of movement images documents how the treatment is delivered.
- The PTV can be defined without ambiguities for the treatment of mobile structures, assuring the adequate irradiation of the CTV area and avoiding an excessive irradiation of healthy tissue.

As it was pointed out in the introduction, the usual technique for taking movements into account either in conventional or virtual simulation consists on assigning validity limits wide enough to include all possible displacements that the CTV can suffer, thus generating wide treatment fields which may provoke the unnecessary irradiation of healthy tissue.

This can be illustrated with the treatment of a malt lymphoma. The irradiation of the stomach in this kind of lymphomas is curative; hence, it is especially important to achieve the complete irradiation of the CTV and the minimum irradiation of the surrounding healthy tissue. Ideally, the irradiation target would be just the stomach, so it would be defined as an irregular field, protecting the surrounding healthy tissue, as shown in Fig. 3. The existence of movements of the stomach due to breathing can provoke the incorrect tumour irradiation if the field is excessively adjusted to the tumour in a static image, either conventional radiography or digitally reconstructed radiography (DRR), extracted from a movement sequence. When the radiotherapist (who is aware of this movement) is not provided with an organ motion evaluation tool, has to define wide security limits around the stomach to assure its complete irradiation. The proposed sequence analysis applied to this patient allows the maximum path of the stomach to be determined, so that the security limits for the irradiation can be qualified. The final result of the analysis permits the conformed irradiation of the mobile volume in an accurate way. In this example, with the information provided, the irradiation of up to a 30% of healthy tissue is

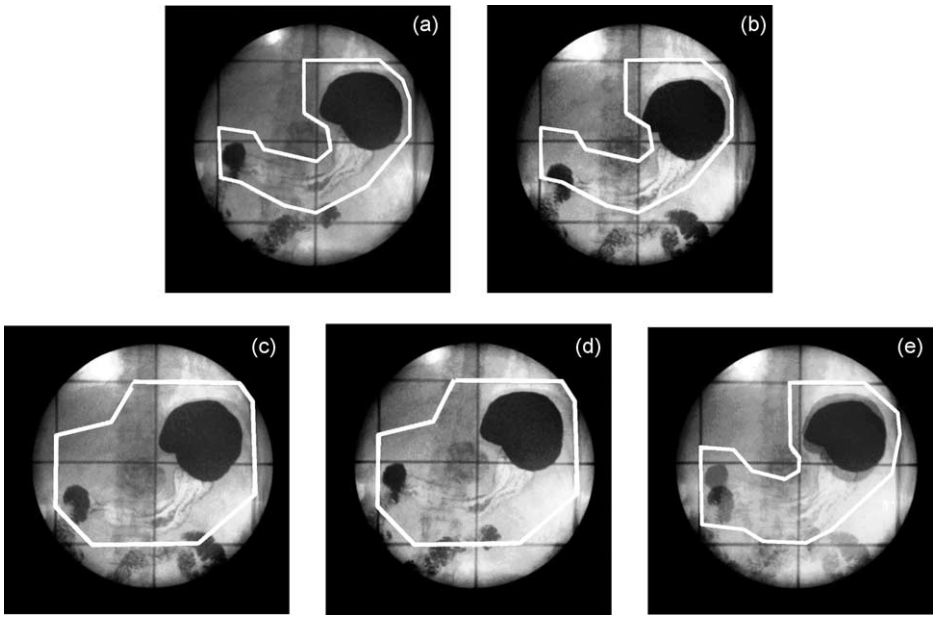

Fig. 3. Examples for the field conformation for the irradiation of the stomach in a case of malt lymphoma. The ideal conformation (a) does not take into account the physiologic motion, provoking incorrect irradiation of the stomach (b). Classical irradiation fields for a malt lymphoma preserve security limits enough to include organ motion (c, d). Final conformed field on a Gray scale PDF image, in which physiological motion has been considered (e).

avoided, without affecting the correct irradiation of the tumour.

4. Discussion

When focusing on the task of characterizing the extent of periodic movements, paying special attention to those induced by breathing, there are two tendencies proposing practical solutions. Some authors observe a diminishing CT image quality due to patient breathing [1,2,17] and consequently propose the acquisition of CT images in synchronization with breathing. In this way, internal contours can be precisely defined in both extremes of their movement (inhalation and exhalation), allowing to define an 'effective' area of the PTV in each slice, similar to the actual area occupied by the moving organ during free breathing [2]. To do this, the slice acquisition time must be very short. In fact, respiratory movement is a quasi-periodic movement, with a variable amplitude and frequency [17,18], which makes the static CT acquisition difficult. Moreover, this kind of fast-static image acquisition can lead to errors in the correct determination of external organs contours since in the antero-posterior sense, the expansion of the chest while breathing can provoke variations in the beam external contours of 1 cm or more and can even change the lung density in a 28% [8]. Finally, the patient irradiation can only be performed in the same conditions as the image acquisition if an active breathing control (ABC) system is available as those described by Wong et al. [20] or Kubo et al. [12]. On the other hand, another group of authors propose to take the organ movement into account in the calculation instead of temporally halting them. Some studies [3,7,13,16,18] propose the evaluation of the error which can be made in the determination of the CTV due to movement and—together with other errors—the design of strategies to define security margins around the CTV, thus constructing an area of 'controlled uncertainty'. This solution is not easy to handle, since the movement amplitude can greatly vary among patients [4] and depends on various factors such as tumour localization, its fixation to adjacent structures, lung capacity, immobilization of the patient and his/her anxiety status [14].

In a classical treatment planning, this mobile irradiation volume is determined de visu with the fluoroscopy of a RT simulator, and generally no graphical documentation of the extent of such movement can be kept. Beam conformation is designed over static radiographs with no possibility of quantifying the extent of alleged movements. When the determination of the irradiation volumes is done virtually with a 3D patient reconstruction, the movement cannot be easily taken into account previous to the treatment, but it can be estimated by repeating image series along the treatment and redefining it when necessary [14]. In both cases, it is necessary to assign security margins of an arbitrary size and shape, big enough to ensure that the CTV is to be adequately irradiated despite any physiological movement. This practice generates irradiation volumes excessively big and therefore, tends to irradiate healthy tissue in excess. In the case of a virtual simulation, there is a contradiction between the accuracy gained with the use of sophisticated planning tools and the impossibility of accurately measuring the extent of physiologic movements which leads to the assignment of arbitrarily big margins.

In this paper, we have proposed and demonstrated a method for using a fluoroscopic sequence for CTV margins determination. After obtaining a fluoroscopic sequence, the most immediate and intuitive way of analysing it is using an interactive—multimedia style—visualization tool. The usual navigation buttons permit to move forward and backwards within the sequence until finding the spatial limits of the mobile structure under study. Nevertheless, this system is slow and takes too much time of specialized personnel (physicist or physician). The method proposed in this paper provides a means to automatically perform this procedure. This is a patient adaptive method and substitutes those one-dimensional functions semi-empirically obtained by other authors [13,16] from population studies.

The proposed analysis method allows physiological movements to be accurately included in the daily clinical practice. It is applicable to all organs periodic movements, e.g. breathing and cardiac movement, especially in chest and upper abdomen. Other different sources of movement in the same organ, e.g. peristaltic movement, cannot be distinguished with this system because their lack of periodicity.

This procedure is an alternative to respiration gating and active breath control. There is an emergence of very fast multi-slice CT technologies, for respiratory correlated CT, which will probably replace this method with time, but at the cost of complicating the treatment delivery. With the method developed in this paper, neither the planning routine (standard or virtual) nor the treatment are essentially modified, and the PDF is used to optimize the PTV margin.

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