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ORIGINAL ARTICLE

Technical evaluation of a laser-based optical surface scanning system for prospective and retrospective breathing adapted computed tomography

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ABSTRACT

Background. For breathing adapted radiotherapy, the same motion monitoring system can be used for imaging and triggering of the accelerator.

Purpose. To evaluate a new technique for prospective gated computed tomography (CT) and four-dimensional CT (4DCT) using a laser based surface scanning system (Sentinel™, C-RAD, Uppsala, Sweden). The system was compared to the AZ-733V respiratory gating system (Anzai Medical, Tokyo, Japan) and the Real-Time Position Management System (RPM™) (Varian Medical Systems, Palo Alto, CA, USA).

Material and methods. Temporal accuracy was evaluated using a moving phantom programmed to move a platform along trajectories following a $\sin^6(\omega t)$ function with amplitudes from 6 to 20 mm and periods from 2 to 5 s during 120 s while the motion was recorded. The recorded data was Fourier transformed and the peak area at the fundamental and harmonic frequencies compared to data generated using the same sinusoidal function. For verification of the 4DCT reconstruction process, the phantom was programmed to move along a sinusoidal trajectory. Ten phase series were reconstructed. The distance from the couch to the platform was measured in each image. By fitting the function $\sin(\omega t\text{-}\varphi)$ to the values measured in the images corresponding to each slice, the phase of each image was verified.

Results and conclusion. In the recorded data, the peak area at the fundamental frequency covered on average $104 \pm 4\%$, $102 \pm 4\%$ and $91 \pm 27\%$ of the peak area in the generated data for the Sentinel™, RPM™ and AZ-733V systems, respectively. All systems managed to resolve both harmonic frequencies. The second experiment showed that all images were sorted into the correct series using breathing data recorded by each system. The systems generated very similar results, however, it is preferable to use the same system both for imaging and treatment.

In external beam radiotherapy, there are several motion management strategies for mitigating the increased uncertainties of dose distribution due to breathing induced organ motion. Respiratory gating and tracking are two such techniques. In respiratory gating, the irradiation only occurs during a limited part of the respiratory cycle. The accelerator is triggered by an external system monitoring the patient's respiration. For the planning of a gated treatment, computed tomography (CT) images acquired during the same phase of the respiratory cycle as when the radiation will be delivered is used [1]. The same gating technique is used during the CT scan. The response time and the temporal accuracy of the motion monitoring system are of fundamental importance in gating.

Another breathing adapted CT imaging technique used in radiotherapy treatment planning is four-dimensional CT (4DCT) [2,3]. The technique gives information about the motions of the internal organs during the respiratory cycle. The patient's breathing motion is recorded by an external monitoring system during a 4DCT scan. Images are thereafter reconstructed from raw data acquired during specific

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phase intervals. Several motion monitoring systems based on different techniques, e.g. pressure sensors, optical tracking of external markers or surface scanning are commercially available.

The aim of this study is to evaluate a new optical surface scanning system used as a motion monitoring system for breathing adapted imaging. For comparison, two systems already in clinical use are included in the study.

Material and methods

Motion monitoring systems

Sentinel$^{\mathrm{TM}}$ (C-RAD Positioning, Uppsala, Sweden) is a laser-based surface scanning system. A laser beam is swept over the patient's chest and the scattered light is captured by a complementary metal-oxide semiconductor (CMOS) camera. The unit containing the laser and the camera is mounted in the ceiling above the foot end of the CT couch, as demonstrated in Figure 1. Previous studies have presented evaluations of the accuracy of patient positioning and setup correction for the system [4–9].

The patient is scanned using the laser beam to register the surface of interest before the CT scan. For gating purposes, a point on the patient's chest is used to track the breathing motion during the CT scan. Since the couch moves into the CT gantry during the scan and the Sentinel™ unit is mounted in the ceiling, the laser must constantly be redirected based on the couch's current position in order to follow the point on the patient's chest where the amplitude is measured. The couch position is measured using a wire actuated encoder connected to the couch.

The baseline of the breathing curve will, depending on the mass placed on the couch, either rise or fall during the scan causing the triggering to occur later or earlier in the respiratory cycle. During the calibration of the Sentinel™ system, weights (~30 kg plastic slabs) were placed on the head end of the couch. The same weights were applied during the experiment.

The Real-Time Position Management (RPM™) System (Varian Medical Systems, Palo Alto, CA, USA) consists of an infrared light source and a camera directed at the patient. The unit is mounted on the foot end of the CT couch. A plastic box with reflecting markers placed on the patient's chest is used to trace the patient's breathing motion.

The AZ-733V respiratory gating system (Anzai Medical, Tokyo, Japan) consists of an elastic belt strapped over the patient's chest. A load cell inside the belt measures the pressure over the chest during the respiratory cycle.

The Sentinel™ and RPM™ systems both measure how a point on the patient's chest moves in space, while the AZ-733V system measures how the belt stretches. The shape of the recorded breathing pattern may therefore be different between the systems.

Temporal accuracy

A moving phantom simulating a respiratory motion was constructed. The devise could be programmed to move a plane platform, parallel to the CT couch. The moving phantom was constructed using the Hexamotion 6D moving platform (ScandiDos, Uppsala, Sweden) by replacing the Delta4 detector with a plastic platform, as demonstrated in Figure 2. The phantom was programmed with 10 trajectories following a sinusoidal function to the power of six [$A \cdot \sin^6(\omega t)$] with different frequencies (ω) and amplitudes (A). The platform was moved in the vertical direction. Five of the trajectories had a 2 s period

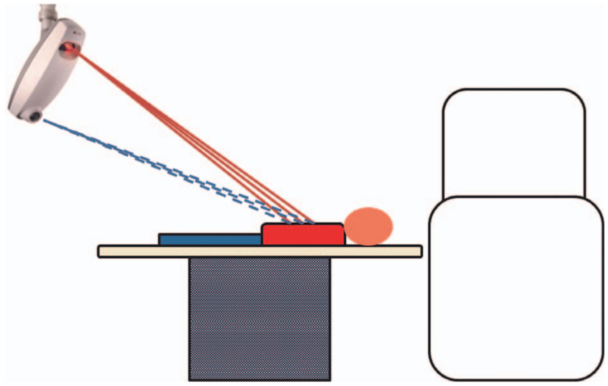

Figure 1. The Sentinel$^{\mathrm{TM}}$ unit mounted in the ceiling above the foot end of the CT couch. The solid lines illustrate the laser beam sweeping over the patient and the dashed lines illustrate the scattered light registered by the camera.

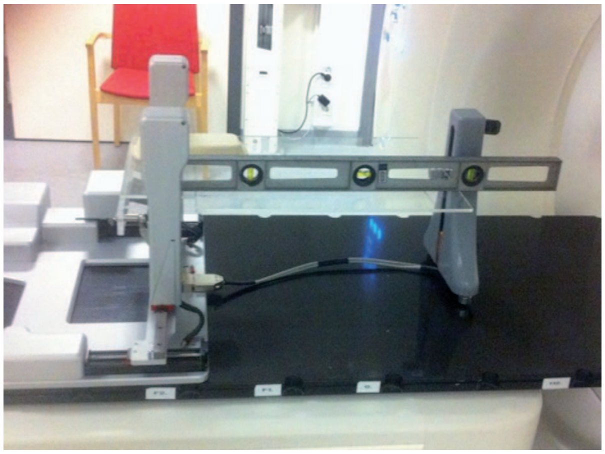

Figure 2. The platform made of transparent plastic mounted on the Hexamotion phantom.

and 1.67, 3.33, 5, 6.67 and 10 mm amplitude, respectively. The other had a 5 s period and 1.67, 3.33, 5, 6.67 and 10 mm amplitude, respectively. For the AZ-733V system, only the 1.67 mm and 5 mm trajectories were used. The method was adopted from Kauweloa et al. [10] who used it to evaluate the RPM™ and GateCT™ (VisionRT, London, UK) systems.

For the experiments with the RPM™ and Sentinel™ systems, the reflector box and a sheet of cardboard were placed on the platform to be traced by each system, respectively. For the AZ-733V system, the belt was strapped around the platform and a metal plate placed on the couch. The belt was tightened hard enough to put pressure on the load cell even at the lowest amplitudes.

The motion of the phantom was recorded during 120 s using each monitoring system. The recorded data were analyzed using an in-house written script (Python 2.7). The recorded data was Fourier transformed. Since the platform trajectory followed a $\sin^6(\omega t)$ function, the fundamental frequency and two harmonic frequencies should be seen as peaks in the Fourier spectra.

To compare the recorded data to the trajectories programmed in the phantom, new arrays corresponding to 120 seconds of breathing data were generated for each system using the same phantom settings. Since the sampling frequencies were 40 Hz, 25 Hz and 11 Hz for the AZ-733V, RPM™ and Sentinel™ systems, respectively, separate series had to be generated for each system. A small inaccuracy in the phantom motion frequency was corrected for by slightly change the period in the generated data.

Kauweloa et al. [10] used the Pearson product moment correlation test to compare the whole sets of recorded and generated data. In this study, however, the ratio between the areas under the peaks at the fundamental and harmonic frequencies was compared. The choice of analyze method will be explained in the discussion section.

The peaks were defined as the values corresponding to the peak frequency ± 0.1 Hz for the trajectories with a 2 s period and ± 0.05 Hz for the trajectories with a 5 s period. The same intervals of indices were used in the recorded and in the generated data series. An example of a 0.5 Hz trajectory recorded by the Sentinel™ system is demonstrated in Figure 3.

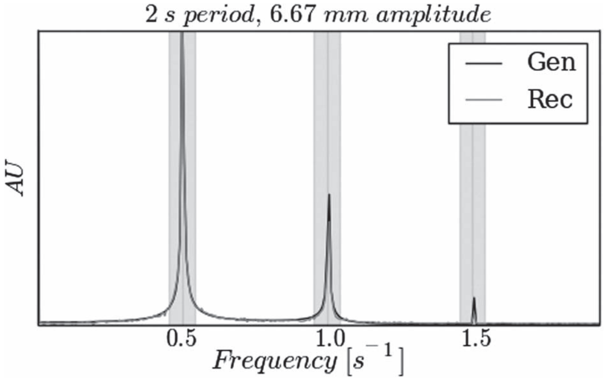
2 s period, 6.67 mm amplitude

Figure 3. Fourier spectra of recorded and generated data. Shaded regions defines the peaks.

4DCT reconstruction accuracy

For the second experiment, the moving phantom was programmed with three trajectories following a $\sin(\omega t)$ function. Two of the trajectories had a 5 s period and 6 and 10 mm peak to peak amplitude, respectively, and the third a 10 s period and 20 mm peak to peak amplitude.

The phantom was placed on the CT couch and the platform adjusted to be horizontal using a spirit-level. Since the edges of the plastic platform could not accurately be outlined in the CT images, an aluminum rod ($500 \times 30 \times 15$ mm^3) was placed on the platform, parallel to the couch.

The experiments were conducted at two sites, at the first with the RPM™ and Sentinel™ systems and at the second with the AZ-733V system. The same CT scanner (Siemens Somatom AS+) was used but with different software versions (2011A at site 1 and 2012B at site 2).

4DCT studies were performed using each system. Images were reconstructed using phase sorting into 10 series (0%, 10%… 90%) of 512×512 pixel matrixes. The slice thickness was 3 mm and the pixel spacing 0.98×0.98 mm^2.

The image series were analyzed using an in-house written script (Python 2.7) where the distance between the CT couch and the upper surface of the aluminum rod was measured in every reconstructed image as demonstrated in Figure 4. The upper surface was defined as the first pixel in a pixel column running through the rod with a pixel value higher than 2000 Hounsfield units.

Since the rod, at all times, was moving parallel to the couch, the distance between the rod and the couch should, within each phase series, be constant. It also implies that the distances (platform amplitude) measured in the 10 images corresponding to the same slice could be predicted using equation:

$$A_i = A \cdot \sin(x - \varphi) + A_0,$$

where A_i is the distance between the aluminum rod and the couch in the series i, A is the amplitude of the trajectory, x is an array of numbers ranging from 0 to $0.9 \cdot 2\pi$ radians in 10 steps, φ is the phase shift,

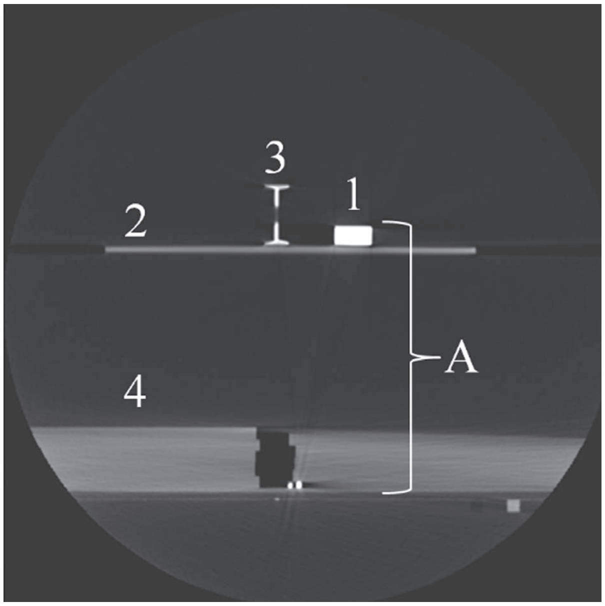

Figure 4. CT-image of the phantom. Amplitude (A) was defined as the distance between the upper surface of the aluminum rod (1) placed on the moving platform (2) and the couch. The dense structure in the middle of the platform is a spirit-level (3) used for adjusting the platform. Plastic slabs (4) were placed on the couch to prevent couch from bending.

and A_0 is the mean distance between the couch and the aluminum rod. The same equation was used to produce the phantom trajectories. The sine curve was fitted to the 10 amplitude values using the Levenburg-Marquardt algorithm for least square optimization.

If the sorting process had been correct, every phase series consists of one image from each slice.

The phase shift will depend on how the peaks and valleys in the breathing data are defined. If the first phase series corresponds to full inhalation, the phase shift should be close to $\pi/2$.

The definition of the 0% phase differed between the systems. The reason for this was the definition of the coordinate systems. This meant that the 0% phase series defined full exhalation for the Sentinel™ system and full inhalation for the RPM™ and AZ-733V systems.

Results

The results of the first experiment are presented in Table I. The mean peak area ratio at the fundamental frequency was closer to 1 for the Sentinel™ and RPM™ system than for the AZ-733V system. Despite the lower sampling frequency, both peaks at the harmonic frequencies were resolved by the Sentinel™ system.

The results of the second experiment are presented in Table II. The calculated phase shift was in all slices within interval less than one tenth of 2π radians around the mean value.

Table I. The ratio between area of the peak in the recorded and the generated breathing data at the fundamental frequency, first harmonic frequency and second harmonic frequency.

Trajectory	AZ-733V	RPM™	Sentinel™
2 s/1.67 mm	1.02, 0.64, 0.48	1.03, 0.68, 0.14	1.01, 0.58, 0.54
5s /1.67 mm	1.10, 0.63, 0.59	1.03, 0.58, 0,16	0.98, 0.34, 0.81
2 s/3.33 mm		1.02, 0.66, 0.46	1.05, 0.61, 0.53
5 s/3.33 mm		1.05, 0.64, 1.19	1.08, 0.70, 0.50
2 s/5 mm	1.01, 0.54, 0.54	1.04, 0.72, 0.30	1.11, 0.70, 0.65
5 s/5 mm	0.52, 0.41, 0.43	1.04, 0.71, 0.52	1.04, 0.76, 0.33
2 s/6.67 mm		0.99, 0.73, 0.38	1.01, 0.79, 0.68
5 s/6.67 mm		1.03, 0.74, 0.54	1.03, 0.79, 0.30
2 s/10 mm		0.92, 0.79, 0.53	0.98, 0.83, 1.28
5 s/10 mm		1.04, 0.70, 0.86	1.07, 0.83, 1.51

Discussion and conclusion

In the first experiment, recorded data were compared to data generated using the same equations used for programming the phantom. Since different sampling frequencies are used by the systems, fewer data points were recorded by the Sentinel™ system. Consequently, the same number of data points was not included in the peaks in the Fourier domain. Defining intervals in the different series introduced a source of uncertainty.

Kauweloa et al. used the Pearson product moment correlation test to compare the recorded and generated data. Using this method, no peaks have to be defined. However, if the moving platform is programmed with a simple sinusoidal function most of the data points will be close to zero in the Fourier domain. The Pearson correlation test is a parametric test and should be used when the data is normal distributed. In this study, differences between the peak areas in the generated and peak areas in the recorded data were compared instead.

All three systems managed to resolve the peak at the fundamental frequency and the peaks at the first and second harmonic frequencies, even in the low amplitude trajectories. The area of the peak at the fundamental frequency would be larger than the peak area in the generated data due to noise and inaccuracy of the phantom motion. Since the temporal

Table II. Mean phase shift (± 1 s.d.) calculated for the three systems and trajectories.

	Trajectory		
System	3 mm	5 mm	10 mm
AZ-733V	1.46 ± 0	1.47 ± 0	1.52 ± 0
RPM™	1.15 ± 0.17	1.20 ± 0.20	1.30 ± 0.01
Sentinel™	1.31 ± 0.17	1.43 ± 0.16	1.50 ± 0.05

resolutions of the systems were limited, the areas of the peaks at the harmonic frequencies were in general lower. This experiment showed that the systems are comparable good at detecting small changes in breathing amplitude.

Motion monitoring systems have previously been evaluated in clinical studies or by using various phantoms simulating respiratory motion where 4DCT reconstruction accuracy has been verified by measuring centroid position or volume of moving objects [11–13]. While evaluating the AZ-733V and GateCT™ systems (VisionRT, London, UK), Vasquez et al. [14] found that images would be sorted into the wrong phase series if the sampling rate defined in the header of the breathing data file was incorrect. The same error was found in the breathing data file from the Sentinel™ system. The error will cause the phase shift of the images in a series to increase or decrease along the longitudinal axis and might not be detected if only images at one slice are analyzed. Vasquez et al. [14] clearly demonstrated the need for testing new equipment thoroughly.

While evaluating the breathing data files from the RPM™ system and the AZ-733V system, Otani et al. [15] found that the tags marking different phases in the data file defined by the two systems differed. The breathing pattern recorded by the AZ-733V system is not following the sine function. This will affect how the phase intervals are defined and thereby which phase each image corresponds to.

Using the long platform phantom design, the phase that each image corresponds to could be calculated, making it possible to verify that all the images had been sorted into the correct bin. The amplitude in the reconstructed images can either be measured directly in the software at the CT laboratory or after export using the method presented in this study.

The three systems generated very similar results. However, it could be concluded that, since the shape of the breathing pattern recorded by each system differs, and thereby the definition of the phase intervals, it is preferable to use the same system for imaging and treatment. Further, the Sentinel™ system require no part that is in direct contact with the patient (box, belt etc.) to produce a relevant breathing amplitude and this may be beneficial for some applications.

Declaration of interest: The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

References

[1] Keall P. 4-dimensional computed tomography imaging and treatment planning. Semin Radiat Oncol 2004;14: 81–90.

[2] Ford EC, Mageras GS, Yorke E, Ling CC. Respiration-correlated spiral CT: A method of measuring respiratory-induced anatomic motion for radiation treatment planning. Med Phys 2003;30:88–97.

[3] Vedam SS, Keall PJ, Kini VR, Mostafavi H, Shukla HP, Mohan R. Acquiring a four-dimensional computed tomography dataset using an external respiratory signal. Phys Med Biol 2003;48:45–62.

[4] Brahme A, Nyman P, Skatt B. 4D laser camera for accurate patient positioning, collision avoidance, image fusion and adaptive approaches during diagnostic and therapeutic procedures. Med Phy 2008;35:1670–81.

[5] Moser T, Fleischhacker S, Schubert K, Sroka-Perez G, Karger CP. Technical performance of a commercial laser surface scanning system for patient setup correction in radiotherapy. Phys Med 2011;27:224–32.

[6] Moser T, Habl G, Uhl M, Schubert K, Sroka-Perez G, Debus J, et al. Clinical evaluation of a laser surface scanning system in 120 patients for improving daily setup accuracy in fractionated radiation therapy. Int J Radiat Oncol Biol Phys 2013;85:846–53.

[7] Pallotta S, Marrazzo L, Ceroti M, Silli P, Bucciolini M. A phantom evaluation of Sentinel™, a commercial laser/camera surface imaging system for patient setup verification in radiotherapy. Med Phys 2012;39:706–12.

[8] Pallotta S, Simontacchi G, Marrazzo L, Ceroti M, Paiar F, Biti G, et al. Accuracy of a 3D lasercamera surface imaging system for setup verification of the pelvic and thoracic regions in radiotherapy treatments. Med Phys 2013;40:011710.

[9] Wikström K, Nilsson K, Isacsson U, Ahnesjö A. A comparison of patient position displacements from body surface laser scanning and cone beam CT bone registrations for radiotherapy of pelvic targets. Acta Oncol 2014;53: 268–77.

[10] Kauweloa KI, Ruan D, Park JC, Sandhu A, Kim GY, Pawlicki T, et al. GateCT™ surface tracking system for respiratory signal reconstruction in 4DCT imaging. Med Phys 2012;39:492–502.

[11] Lu W, Parikh PJ, Hubenschmidt JP, Bradley JD, Low DA. A comparison between amplitude sorting and phase-angle sorting using external respiratory measurement for 4D CT. Med Phys 2006;33:2964–74.

[12] Spadea MF, Baroni G, Gierga DP, Turcotte JC, Chen GT, Sharp GC. Evaluation and commissioning of a surface based system for respiratory sensing in 4D CT. J Appl Clin Med Phys 2011;12:3288.

[13] Wink N, Panknin C, Solberg TD. Phase versus amplitude sorting of 4D-CT data. J Appl Clin Med Phys 2006;7: 77–85.

[14] Vasquez AC, Runz A, Echner G, Sroka-Perez G, Karger CP. Comparison of two respiration monitoring systems for 4D imaging with a Siemens CT using a new dynamic breathing phantom. Phys Med Biol 2012;57:N131–43.

[15] Otani Y, Fukuda I, Tsukamoto N, Kumazaki Y, Sekine H, Imabayashi E, et al. A comparison of the respiratory signals acquired by different respiratory monitoring systems used in respiratory gated radiotherapy. Med Phys 2010;37: 6178–86.