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Research Article

Comparative Analysis of Respiratory Monitoring Systems in Radiotherapy: Benchmarking RPM4D and DL4D Using a Novel Mobile Phantom

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Abstract:

Respiratory monitoring systems are equipped with additional hardware such as cameras. However, one of the most developments is equipment for deviceless computed tomography (CT), that can monitor the patient's respiratory phases and produce four-dimensional (4D) images without additional equipment. We investigated the determination of changes in target volume and critical structures in 4D images obtained with additional hardware (Real-Time Positioning Management System, RPM4D) and without additional hardware (Deviceless System, DL4D) from the CT. We evaluated their contribution to clinical use. Material and Methods: A mobile phantom was designed. Imaging was performed in the phantom under the same set-up conditions on both systems. The geometric discrepancy of gross tumour volume (GTV) and organs at risk(OAR) between RPM4D and DL4D images were evaluated. The assessment was based on the Dice similarity coefficient (DSC) and center of mass shift (COM) using both scanning protocols. The DSC for the right lung was 0.98, left lung 0.99, and tumour volume 0.92. Left and right lung displacement was up to 0.07 cm. It can be concluded thespatial overlaps were similar for both systems.

1. Introduction

Unintentional organ movement, such as respiration, during inter- and intra-fraction radiation procedures causes errors in dose distribution by irradiating more vital organs and omitting tumour volume. To produce the ITV, tumour motion must be accounted for by including an internal margin (IM) around the clinical target volume, as recommended by the International Commission on Radiation Units and Measurements [1]. (CTV). The purpose of treatment planning in radiotherapy is to correctly determine the location of the tumour and OARs. The primary aim of the treatment planning is sparing OARs while delivering the dose prescribed by the radiation oncologist to the tumour or target volume itself. However, tumours and organs move due to respiration or other physiologic changes such as gas and urine. Thoracic and abdominal regions, on the other hand, have the greatest motion due to respiration, which plays an important role in the location of tumours and critical organs. Thoracic and abdominal radiation processes [2,3] rely heavily on the management of respiratory movement. To this end, one of the most important developments is the use of four-dimensional Computed Tomography (4D CT) simulator devices. The CT simulator device simultaneously acquires a sufficient number of images containing respiratory cycle phases with a graphical record of respiratory movement to generate volumetric image data. It converts the images to the respiratory cycle graph for the different phases afterward. Images are used to identify tumour/normal organ movement. Respiratory monitoring systems used to obtain the respiratory signal in the CT simulator device are usually externally equipped [3,4].

These systems monitor respiratory movement by external equipment such as surface movement in the abdomen or chest wall (e.g., RPM) or pressure change in the abdominal belt (e.g., Anzai) [4]. The RPM system is an externally equipped system that works synchronously with the CT simulator device. The system consists of different components such as an RPM camera, 6-point marker block, optical tracking software, and additional computer hardware. Deviceless 4D CT devices are one of the latest developments in this field, which can capture patients' breathing phases and thus create 4D images without the need for any extra equipment such as an RPM camera. This study aimed to determine the changes in the target volume, critical structures in 4D images obtained from a CT device with additional hardware (RPM4D) and without additional equipment (DL4D) and com-pare both systems. We investigated the contribution of this deviceless 4D imaging to clinical practice. For this purpose, two systems in the clinical routine were evaluated using the DSC using a homemade phantom.

2. Material and Methods

2.1 Homemade Mobile Phantom

A homemade mobile phantom was developed to evaluate the differences in the organ images transferred with RPM4D and DL4D techniques and whether there was a contour change.

Polymethyl methacrylate (PMMA) was chosen as the phantom material because it is tissue equivalent. The material is 18.5 cm thick and shaped by CNC cutting to resemble the human body. To imitate the lung, two cylindrical holes were drilled into the phantom and Styrofoam material equivalent to the air density was placed (Figure1).

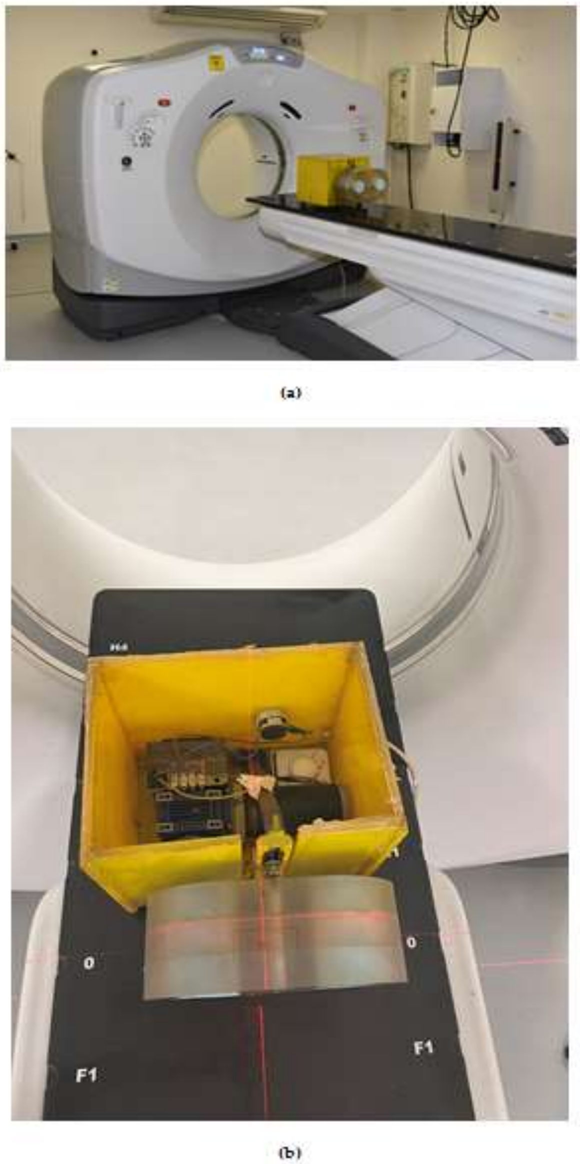

Figure 1. *(a) 4D CT device and (b) homemade phantom*

After the PMMA piece was formed, a motor was attached to the back of the phantom using a fixture attached to the PMMA block to move the phantom. The tissue and air equivalence of the material densities used was controlled over the Hounsfield Unit value in CT scanning. The CT number linearity is also evaluated using Catphan 600 Phantom (The Phan-tom Laboratory, Salem, NY, USA).
The manufacturer estimated HU values in accordance with the Catphan data sheet supplied by the producer is - 1000 for air and + 120 for acrylic. For the respective objects in our study, HU values obtained for air and tissue materials are - 970 and + 126 HU. In addition, a space was created in the phantom centre to make measurements with an ion-chamber. This phantom also permits dosimetry and non-dosimetry tests on radiotherapy devices. A 5.1 cc tumour structure in the right lung on the phantom was formed with playdough and placed in the lung design. Other technical specifications of the phantom are given in Table 1.

Table 1. *Technical properties of homemade mobile phantom*

Structure	COM-x	COM-y	COM-z	DSC
GTV RPM 4D/ DL4D	0.01	0.05	-0.03	0.93
Llung RPM 4D/ DL4D	0	0.03	-0.02	0.98
Rlung RPM 4D/ DL4D	0.01	0.07	0.02	0.98

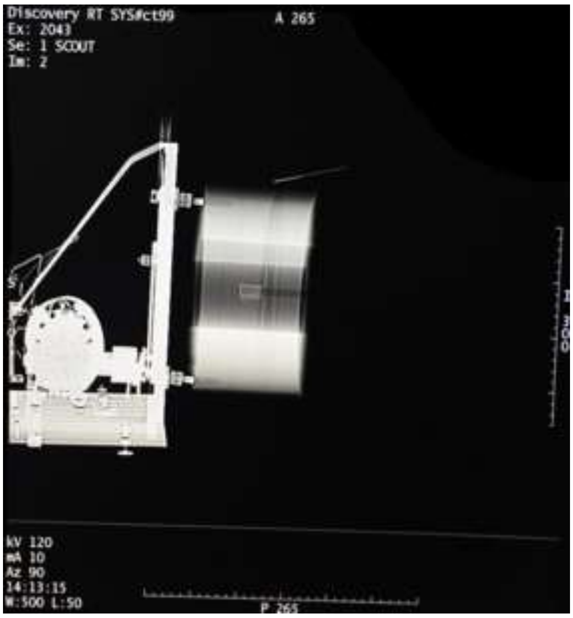

Figure 2. *CT scan of homemade phantom*

2.2 Phantom Scan Process

Two different acquisition protocols for tracking respiratory motion, RPM4D and DL4D were used from the 4DCT Discovery RT model (GE Medical Systems, Chicago, USA). Imaging was performed with GE CT using together RPM system while the mobile phantom was in motion (see Figure 2).
After applying the camera calibration procedure for the RPM application, a 6-point marker block was placed on the homemade phantom and its location was determined with the RPM camera. For the deviceless application, the marker block was removed, and a lead wire (approximately 5 cm long) was placed in the same place, and imaging was performed without using an external camera (see Figure 3).

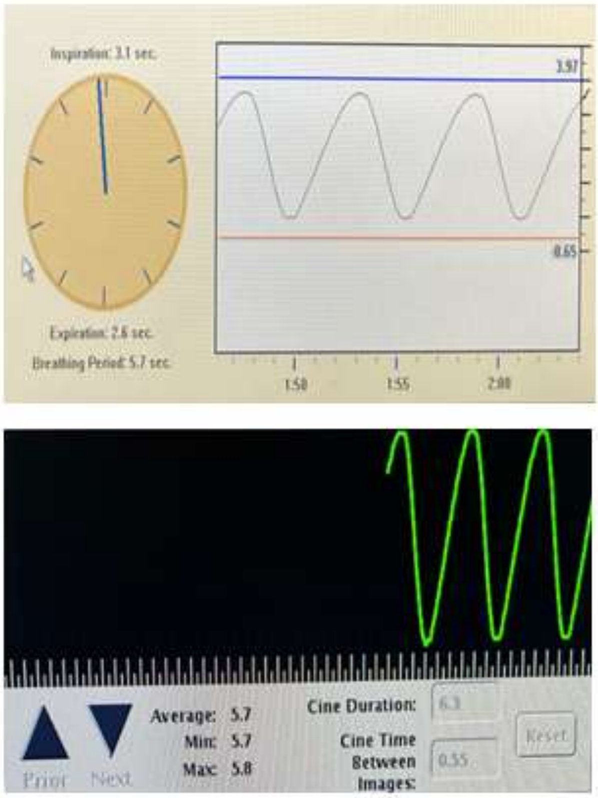

Figure 3. *Schematic representation of the imaging process*

Each image that was reconstructed was divided into ten parts. Advantage 4D was used to generate Maximum Intensity Projection (MIP) and Average Intensity Projection (AIP) pic-tures from the raw data set of the 4DCT scan for 10 phases.

2.3 Image Contouring Process

The tumour volumes and lungs were delineated on the Velocity software V4.0 by a radiation oncologist. The MIP images were used as a basic image for tumour delineation. The contours were fused to the

AIP image. In AIP using the mean attenuation data, lung structures were contoured by the same radiation oncologist on the images of both systems (Figure 4).

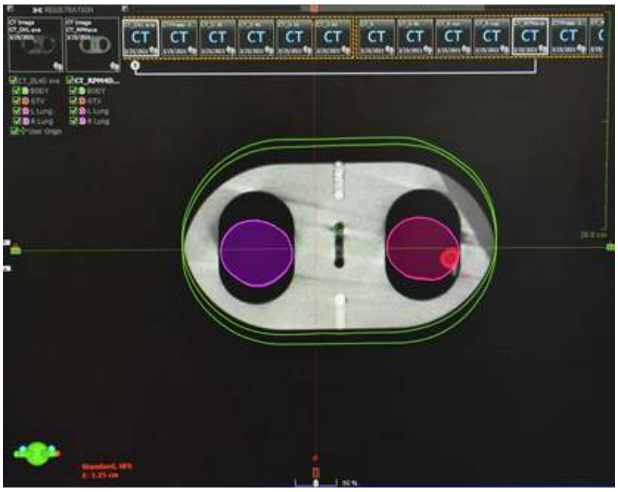

Figure 4. *Structures of the homemade mobile phantom on contouring image*

The rigid image registration and statistical evaluation were performed on the Varian Eclipse TPS (Varian Medical Systems, Palo Alto, CA).

2.4 DSC Analysis

In this study, DSC and shifts in the x–y-z axes were calculated to evaluate segmentation performance for both lungs. The geometric comparison was made by measuring the volume change in cc, using the DSC, and calculating the center of mass displacement in the Eclipse statistics tool. The geometric comparison was made with two methods; one used by measuring the volume change in cc using the DSC, and second using the Eclipse statistics tool that calculated the center of mass displacement. The DSC is a statistical validation metric used to evaluate both the reproducibility of manual segmentations and the performance of spatial overlap accuracy of CT images over the intersection of overlapping volumes [5,6]. It is calculated by multiplying two by the area of overlap (i.e., inter-section area) divided by the total number of pixels (i.e., union area). In this study, the formula (1) given below was used as the Dice similarity constant [7,8].

$$DSC=2(A+B)/[n(A)+n(B)] \quad (1)$$

In the formula, while the numerator represents the number of voxels at the intersection of A and B structures; the denominator represents the average number of voxels in structures A and B. The DSC value ranges between 0 and 1. While the DSC value goes to-wards 0, the non-overlapping and mismatch of the contoured structures indicate that there is no spatial overlap; A value of 1 indicates full overlap in the two contoured structures. Meanwhile, dice similarity for both techniques is close to 1 (see Table 2 and Table 3).

Table 2. *Dice similarity coefficient (DSC) and the distance between the Centers of mass (COMs) of structures*

Dimensions	29.5x 19.5x 11.5 cm3
Average Weight	30 kg
Breath Period	5.6 seconds
Breath Wavelength	5.6 cm
Velocity	1 cm/ second

Table 3. *Volume and volume change of the structures.*

Structure Volume	**Volume (cc)**	**Volume Change (cc)**
GTV (DL4D)	5.10	-0.1
GTV (RPM4D)	4.90	
Llung (DL4D)	398	-0.3
Llung (RPM4D)	397.8	
Rlung (DL4D)	369.9	-5.5
Rlung (RPM4D)	391.4	

3. Results and Discussions

The contoured image volume values obtained from the two acquisition protocols for tracking respiratory motion, RPM4D, and DL4, were measured for the right and left lung. In this study, DSC for the right lung (391.4 cc) was 0.98; 0.99 for the left lung (397.8 cc), and 0.92 for the tumor volume. In addition, while the shifts in the x-y-z axes were- 0.01 cm, - 0.03 cm, and 0.0 cm for the right lung, respectively, the corresponding shift amounts were 0.0, 0.01 and 0.02 cm for the left lung, and 0.0, - 0.02, 0.03 for the tumour volume, respectively (see Figure 5).

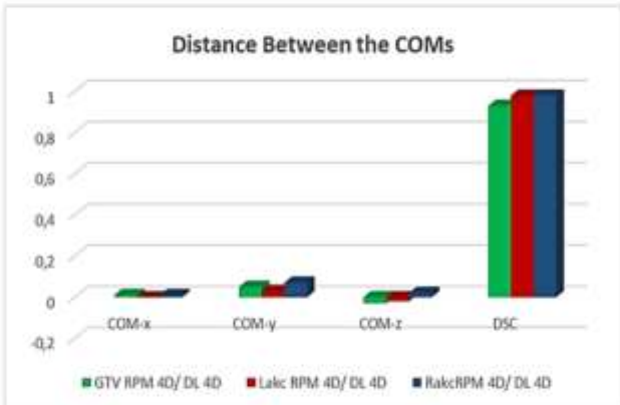

Figure 5. *The graphs show the Dice similarity coefficient (DSC) and the distance between the Centers of mass (COMs) of structures.*

Unintentional organ movement such as respiratory movement during inter and intra-fraction radiotherapy processes introduces mistakes in dose delivery by irradiating more of the critical organs and missing tumour volume. According to the International Commission on Radiation Units and Measurements [1], tumour mobility must be accounted for when creating the internal target volume (ITV) by adding an internal margin (IM) around the clinical target volume (CTV). Nevertheless, there are limitations to this suggestion. For tumours with significant respiratory motion, the inclusion of varied geometric boundaries increases the risk of problems by irradiating a wide volume of essential organ tissue. The AAPM (American Association of Physicists in Medicine) report numbered TG -76 suggested a technique for the management of respiratory movement, in case of tumour movement; 5 mm in any direction, or if important normal tissue preservation is obtained by the technique used in the management of respiratory movement [1]. It has been shown that the correlation between the use of external equipment and internal organ movement during free breathing is good [9-13].

Therefore, the techniques used may vary depending on the clinical device park or clinical preference. However, all this equipment, with such advanced technologies, must be validated before these technologies are applied clinically, by means of physical phantoms as part of quality assurance programs [9,10]. Earlier studies show a good agreement between the external respiratory movement system and internal organ motion in respiratory gating treatment. There are many studies in the literature comparing RPM and Deviceless respiratory monitoring systems, but virtually all of these studies are patient-based. In general,the 4D deviceless method was developed for lung tumours, and it has been shown that it is not different from the Varian RPM system for thoracic radiotherapy in both our study and Sprouts (2017) with 35 cases. The evaluation was made for both the thoracic and abdominal regions. The comparisons were made with two reconstruction methods (RPM and 4D Deviceless) [2]. Moreover, in Yip (2020), external device-based 4DCT and anatomy-based deviceless 4DCT were compared in patients with lung tumours who underwent SBRT. Yip reported that the results were similar [14]. On the other hand, Holla et al. compared the influence of target movement on the reconstructed ITV for a device-based (DB) external surrogate system (Anzai belt system) and a Smart deviceless (DL) 4-dimensional (4D) system in a controlled phantom test. The outcomes showed that the DL method is an efficient technique of image sorting in 4D obtained for smaller target excursions [15]. The use of a 4D CT has benefits over a conventional CT because of the extra data on tumour and organ movement during a respiratory cycle. But the generation of the CT images is dissimilar in comparison to a conventional CT. For this reason, CT image creates a new quality assurance is requisite, controlling the recent properties and correlations of the extra types of equipment.

Block and Mewes (2009) have developed an extensive quality assurance process with respiratory motion phantom, which controls geometric dimension as well as the extension of the movement. They suggest performing these quality assurances with respiratory motion phantom monthly or later for all technical service operations. Furthermore, we are going to study research dosimetrically the usefulness of a quality assurance process with this handmade mobile model (phantom). There are several limitations of the current study. First, the phantom moves only on one axis-vertically, however tumours move in 4 - 6 axes. This might constrain the clinical applicability of the results. Second, the tumour was mounted at
the very peripheral site of the phantom, which may not reflect the movement of the tumours
in other localizations.

4. Conclusions

In respiratory-gated radiotherapy, there is a crucial potential to improve the irradiation of lung, breast, and liver that are impacted by respiratory motion. It is anticipated that an improvement in the conformity of irradiation fields would reduce the incidence of complications in organs at risk. In our study, two different scanning protocols were evaluated under the same conditions by imaging with a moving phantom, and the images were transferred to the TPS using the same method. Many metric systems can be used in image evaluation, and each has its own advantages and disadvantages. In this study, the DSC metric method was chosen to determine if contours overlapped. When the results were evaluated using the DSC method, it was found that the spatial overlaps between the two methods were similar and indistinguishable, and that both methods could be used for ITV determination. In conclusion, this study demonstrates that deviceless 4D CT systems, such as DL4D, offer a promising alternative to traditional external device-based systems like RPM4D in radiotherapy. Both systems exhibited comparable spatial accuracy, with minimal differences in tumor and organ volume detection. The ability of DL4D systems to capture respiratory phases without additional hardware could simplify radiotherapy workflows, reduce setup times, and improve patient comfort. Future studies should focus on addressing the limitations of the current study, such as the unidirectional motion of the phantom, and explore the potential for integrating DL4D systems into routine clinical practice. By reducing the reliance on external devices, DL4D systems could help streamline the treatment process, particularly in settings with high patient volumes. Further research is needed to fully assess the dosimetric implications of this technology and validate its efficacy across a broader range of clinical scenarios.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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