The CIRS Dynamic Thorax Phantom: A Publication Review

By Starr-Wilmot Howard
College of William and Mary
March 25, 2022

Introduction

Computerized Imaging Reference Systems, Inc.'s, model 008A Dynamic Thorax phantom was introduced to the radiation therapy market in 2004 for testing new motion management techniques that ensure precise delivery of radiation dose to a tumor while sparing surrounding healthy tissue. This first-ever commercial motion phantom for radiation therapy produces repeatable 3-D target motion in a tissue equivalent phantom that can replicate the breathing motion of a patient. The body of the phantom represents a typical human thorax in shape, proportion, and composition. The lung equivalent rod contains a spherical target that can accept various dosimeters (ion chambers, TLDs, or film). This rod is inserted into the lung equivalent lobe of the phantom, and it is connected to a motion actuator box which applies a 3D motion to the target moving insert through linear translation and rotation of the lung equivalent rod. More information about the phantom can be found at https://www.cirsinc.com/products/radiation-therapy/dynamic-thorax-motion-phantom/.

Since its introduction, the model 008A has become an essential tool for the medical physics community to test image quality in 4D computerized tomography systems used for treatment simulation (as well as for diagnostic applications), to verify radiation dose delivery as part of quality assurance programs for radiation therapy, and to test new radiotherapy devices and protocols that incorporate motion management functions. This review paper provides an overview of published research using this phantom in each of these three areas.

Methods:

A Google Scholar search on the terms "Computerized Imaging Reference Systems" and "CIRS" provided periodic alerts on new papers published featuring CIRS phantoms. The papers were reviewed and filtered to include any papers featuring the model 008A Dynamic Thorax Phantom. These papers were then reviewed and categorized into the following three main application areas for the phantom: dose verification, 4DCT Image Quality, testing new deceives or protocols.

Results:

Dose Verification: A key application of the model 008A is to verify that radiation dose has been delivered according to the treatment plan, as the success of radiation therapy is dependent on maximizing tumor cell death and minimizing normal tissue toxicity. Tumor control increases with the delivery of appropriate radiation doses to the target area.

The researchers at the department of Radiation Oncology at the GROW School for Oncology at Maastricht University Medical Centre in Maastricht, Netherlands used model 008A and another, homogeneous phantom to verify treatment doses delivered during stereotactic body radiotherapy (SBRT) dose using Acuros® dose calculation software. The team found that the heterogeneous features of model 008A allow for more dose verification measurements than the water-equivalent homogeneous phantom (Octavius 4D). Seven patient treatment plans were tested on spherical, water-equivalent tumors ranging in size from 3 cm diameter down to 0.5 cm diameter on both the model 008A and on Octavius 4D. The team found that current verification methods using homogeneous phantoms are not adequate for lung tumors with diameters below 0.75 cm diameter. For that reason, the team recommends the use of an anthropomorphic lung phantom like model 008A with a soft tissue equivalent material target that matches clinical tumor size as closely as possible when performing dose verification measurements.

Researchers at Cliniques Universities, Saint-Luc, radiology department in Brussels Belgium, set out to uncover how to better account for breathing-induced motion when planning target margins and clinical target volumes. Different gating strategies were tested, including mid-position, mid-ventilation, a hybrid of MidV-MidP, and MidV-CT. After treating 45 lung lesions with stereotactic radiotherapy, they were confidently able to report a successful implementation of pseudo-mid solution without its inherent drawbacks. Prior to conducting this patient study, the team used the model 008A to help validate the scripts used to manage dose delivery

Researchers at the Henry Ford Health System Department of Radiation Oncology in Detroit Michigan used model 008A to compare the accuracy of internal target volume contours performed on 4D CT and daily 4D cone-beam CT (4D CB CT) simulation images used for dose planning during SBRT. The team concluded that 4D cone-beam CT's have great potential for accurately evaluating the extent of the tumor motion before dose treatment, but that reduced image quality hampers the ability to accurately delineate target volumes.

The Department of Physics at the Karunya Institute of Technology and Sciences in Coimbatore, India set out to determine how well helical TomoTherapy accounts for patient movement when delivering treatment doses. The model 008A was used to simulate patient treatments for end-to-end verification tests, and the team concluded that the internal target volume-based approach (ITV) when using helical TomoTherapy is ideal for shallow breathing circumstances, especially when the tumors were confined to 5mm in the S-I and 3mm in the L-R and A-P directions.

A group of researchers from the Department of Oncology at Stanford University and University of California San Francisco, investigated the impact of the CT protocol and in-room techniques on Cyberknife tracking accuracy by performing end-to-end tests of radiotherapy treatments using the model 008A. Tracking was implemented using a low-dose protocol, which reinforced that idea that CT protocol should be set by the target contouring needs. It further found that high tracking accuracy was achieved through in-room x-ray imaging techniques which produces the highest of quality images.

4D CT Image Quality: Four-dimensional computerized tomography (4DCT), in which multiple CT images at taken at specific positions and times of breathing cycle over a few breathing cycles and then stitched together to create a cine (movie-like) CT series, is required for stereotactic ablative body radiotherapy (SABR) of mobile targets to account for tumor motion during treatment planning and delivery. Assessing the quality of 4D CT image quality reconstruction, both for radiation therapy treatment planning and diagnostic applications, is another key use of the model 008A.

Researchers from the Department of Medical Physics at BC Cancer and the Physics Department in Vancouver BC Canada used the model 008A to develop a procedure for minimizing 4D CT reconstruction size. As part this work, they quantified the effect of anterior-posterior motion artifacts on known object reconstruction for periodic and irregular breathing pattern, and offered a treatment planning suggestion for target sizes below minimum threshold. Testing of image quality was performed on both the model 008A and a rod phantom constructed by the team by obtaining 4DCT images with the phantoms moving in the AP direction using sinusoidal and irregular breathing traces. The 4D CT images were obtained using a GE Lightspeed RT16 CT scanner in cine mode (120 kV, 145 mA, 2.5 mm slice thickness, 20 mm collimation) and Varian Real-Time Position Management (RPM) software. The examination of the rod width, under sinusoidal motion, found it was best represented during the inhale and exhale phases for all periods and ranges of motion. These researchers were able to uncover a new procedure for computed tomography simulation and implemented a SBRT program to determine the lowest target size that can be reliably reconstructed.

The research group at the Department of Computational Neuroscience, at the University Medical Center Hamburg-Eppendorf in Hamburg Germany investigated a new method to help improve image quality. They wanted to further understand if a deep-learning framework could boost image quality of 4D CBCT image data in addition to any cone-beam CT reconstruction approach and clinical 4D CBCT workflow. Unlike current approaches, this method does not require patient specific knowledge about anatomy or motion characteristics. They hypothesized that the residual dense network (RDN) identifies the appearance of the streaking artifacts that are common for 4D CBCT phase imaging. After training, the RDN can be applied to the 4D CBCT phase images to enhance the image quality without affecting the contained temporal and motion approach. In the end, they found that this new approach significantly boosts 4D CBCT image quality as well as improved DIR and motion field consistency. The group supplemented work on patient images of lung and liver tumors with a phantom study using the model 008A. This phantom study allowed them to assess image quality of the 30-mm spherical insert for different motion profiles. In their protocol, an $A*\cos^4(\omega t)$ motion profile was used, where the amplitude of motion A was set to 20 mm and the frequency ω was changed to produce different degrees of motion artifact.

In another effort to reduce motion-induced artifacts from 4D CT images, researchers at multiple locations (ACRF Image X Institute, Faculty of Medicine and Health, The University of Sydney, Australia, Blacktown Cancer and Haematology Centre, in West Sydney, Australia, and the Institute of Medical Physics, School of Physics, The University of Sydney) developed a Respiratory Adaptive Computed Tomography (REACT) procedure. The model 008A was used to test the first implementation of this software on a clinical system that included a Varian Real-Time Position Management (RPM) system for implementing respiratory gating and the Siemens Somatom CT scanner. During this testing, breathing profiles from 13 patients were imported into the 008A motion controller to simulate a patient-realistic breathing pattern. CT images of the phantom obtained with the REACT system were compared to conventional 4D CT images, and to ground-truth static-phantom images for absolute geometric differences within the region-of-interest.

A different team of researchers at the Department of Computational Neuroscience, at the University Medical Center Hamburg-Eppendorf in Hamburg Germany set out to diminish the impact of motion artifacts caused by breathing irregularities during data collection. To resolve this issue, they investigated the possibility of online respiratory signal analysis and signal-guided CT tube control. The Intelligent 4D CT (i4DCT) was used on the Siemens SOMATOM platform. The 4D CT measurements were then performed using the model 008A, and the motion curves were programmed to gradually change from regular to very irregular. Through this work, they were able to validate the utility of i4DCT prior to clinical implementation.

<u>Testing New Devices and Protocols:</u> Other new developments in radiation therapy, primarily centered around technique designed to measure patient motion and adaptive

dose delivery in response to that motion, have been tested using the model 008A. The sections below highlight this work.

Researchers of the Department of Health Sciences at the University of Kumamoto University in Kumamoto Japan, the Kohura Memorial Hospital, and the National Hospital Organization Kyushu Medical Center investigated how the magnetic fields of an MRI scanner could affect dose delivery during to VMAT procedures performed in an MR-linac. In this experiment, the group took CT images of the phantom at 3 different tumor diameters, which were then converted to voxel-based phantoms with 3 different lung densities for use in Monte Carlo dose calculation. VMAT treatment plans without the influence of a 1 Tesla magnetic field were performed using Varian's Ecplise® treatment planning system, while plans made with a magnetic field were performed using the Beamnrc and DOSXYZnrc user codes from the EGSnrc system. (Fields of 0T, 0.5 T and 1 T were used in these simulations.) The group then assessed the dose distributions, dose differences, dose volume histograms, and dose volume indices of the two calculations to determine the effect of the magnetic field on dose. The group found that MR-Linac's with a magnetic field over 1T can increase the dose delivered to a lung tumor; for a 1 cm tumor, the minimum dose delivered to 95% of the planning volume increased by 14%.

The research scientists of the Department of Radiation Oncology, at the Stanford School of Medicine, and the San Francisco (UCSF) Comprehensive Cancer Centre, set out to resolve effective radiation dose to a heavy upper abdomen thorax movement. They designed an alternative surrogate motion management device, made from the onboard Apple iOS hardware. It helps provide patients with visual coaching with the potential to improve the reproducibility of breathing as well as improve patient compliance and reduce treatment delivery time. The iOS application, paired with the *Instant Respiratory Feedback* (IRF) system, was developed in Swift (Apple Inc., Cupertino, CA) using the Core-Motion library and implemented as an Apple iPhone® device. The experimental setup includes an iPhone, a three-dimensional printed arm, and a radiolucent projector screen system for feedback. The model 008A helped them to identify that the application provided them with real-time respiratory motion. They developed a system that provided comparable signal traces to a commercially available system and offered an alternative to traditional respiratory motion monitoring. The model 008A was used to evaluate the accuracy of IRF systems RPM.

The researchers of two institutions Research Center for Charged Particle Therapy, National Institute of Radiological Sciences, Chiba and The Technology Research Laboratory, Shimadzu Corporation, Kyoto, Japan propose a different approach to real-time markerless tracking. They suggested using patient-specific deep learning (DL) and using a personalized data generation strategy. They designed a lung tracking lung tumor for radiation therapy using a neural network for each phantom's individually calibrated lesion by using multiple digitally reconstructed radiographs (DRRs) generated from each phantom's treatment planning 4D-CT. From this design they were able to conclude they did find an effective alternative and stereotactic lung radiotherapy based on patient-specific DL with personalized data generation with digital phantom and epoxy phantom studies is feasible. The idea of this work is, rather than image a patient in real time during treatment, they only need to monitoring the motion of the patient using a laser sensor. That motion data is feed into the AI tool ("multi-modality Deep Learning") that generates a digital image (DRR) of the moving patient. This technique was tested on the 008A using a variety of tumor motion patterns.

Similarly, the researchers at the Quanzhou Institute of Equipment Manufacturing, Fujian Medical University Union Hospital, in Fuzhou, China and the School of Mechanical Engineering and Automation in Shenzhen, China used 008A to test a new method for adjusting the tumor targeting of linear accelerator using position data obtained from three permanent magnets markers implanted around the tumor site by a puncture knife. For verification tests performed on the model 008A, these markers were placed around a modified tumor insert prior to performing a simulated treatment in which radiation dose was wirelessly adjusted in real-time.

Discussion/Conclusion:

As mentioned above these articles reiterate the various capabilities and uses of the model 008A phantom (dose verification, 4D CT Image Quality, and Testing New Devices/Developing New Protocols). The model 008A has been found to produce quality images, provide more appropriate studies data than their homogenous counterparts, and provide good support for dosimetry applications. This device is truly improving the way we look at tumors and treat them, it helps ensure human patients are receiving the adequate treatment they deserve. Paving a new way of medicine.

References

Capaldi, D. P., Nano, T. F., Zhang, H., Skinner, L. B., & Xing, L. (2020). Technical note: Evaluation of audiovisual biofeedback smartphone application for respiratory monitoring in Radiation Oncology. *Medical Physics*, *47*(11), 5496–5504. https://doi.org/10.1002/mp.14484

Dai, H., Dong, L., Lv, B., Chen, Y., Song, S., & Su, S. (2021). Feasibility Study of permanent magnet-based tumor tracking technique for precise lung cancer radiotherapy. *IEEE Transactions on Instrumentation and Measurement*, *70*, 1–10. https://doi.org/10.1109/tim.2020.3039645

Dechambre, D., Vander Veken, L., Delor, A., Sterpin, E., Vanneste, F., & Geets, X. (2021). Feasibility of a TPS-integrated method to incorporate tumor motion in the margin recipe. *Medical Dosimetry*, *46*(3), 253–258. https://doi.org/10.1016/j.meddos.2021.02.002

Dumas, M., Laugeman, E., Sevak, P., Snyder, K. C., Mao, W., Chetty, I. J., Ajlouni, M., & Wen, N. (2020). Technical note: Comparison of the internal target volume (ITV) contours and dose calculations on 4DCT, average CBCT, and 4DCBCT imaging for Lung Stereotactic Body Radiation Therapy (SBRT). *Journal of Applied Clinical Medical Physics*, *21*(11), 288–294. https://doi.org/10.1002/acm2.13041

Holla, R., Khanna, D. K., & Narayanan, V. K. S. (2021). Dose delivery accuracy on helical tomotherapy for 4-Dimensional Tumor Motion — A phantom study. *Reports of Practical Oncology and Radiotherapy*. https://doi.org/10.5603/rpor.a2021.0068

Madesta, F., Sentker, T., Gauer, T., & Werner, R. (2020). Self-contained deep learning-based boosting of 4D cone-beam CT reconstruction. *Medical Physics*, *47*(11), 5619–5631. https://doi.org/10.1002/mp.14441

Morton, N., Sykes, J., Barber, J., Hofmann, C., Keall, P., & O'Brien, R. (2020). Reducing 4D CT imaging artifacts at the source: First experimental results from the respiratory adaptive computed tomography (REACT) system. *Physics in Medicine & Biology*, *65*(7), 075012. https://doi.org/10.1088/1361-6560/ab7abe

Nano, T. F., Capaldi, D. P., Yeung, T., Chuang, C. F., Wang, L., & Descovich, M. (2020). Technical note: Performance of cyberknife ® tracking using low-dose CT and KV Imaging. *Medical Physics*, *47*(12), 6163–6170. https://doi.org/10.1002/mp.14537

Ohno, T., Araki, F., Anami, N., Kubota, T., Yano, M., & Ito, S. (2020). Impact of lung density on isolated lung tumor dose in vmat using inline MR-linac. *Physica Medica*, *80*, 65–74. https://doi.org/10.1016/j.ejmp.2020.10.009

Sonier, M., Vangenderen, B., Visagie, D., Appeldoorn, C., Chiang, T. C. (A., Mathew, L., Reinsberg, S., Rose, J., & Ramaseshan, R. (2020). Commissioning a four-dimensional computed tomography simulator for minimum target size due to motion in the anterior–posterior direction: A procedure and treatment planning recommendations. *Journal of Applied Clinical Medical Physics*, *21*(9), 116–123. https://doi.org/10.1002/acm2.12980

Werner, R., Sentker, T., Madesta, F., Schwarz, A., Vornehm, M., Gauer, T., & Hofmann, C. (2020). Intelligent 4D CT sequence scanning (i4dct): First Scanner Prototype implementation and phantom measurements of automated breathing signal-guided 4D CT. *Medical Physics*, *47*(6), 2408–2412. https://doi.org/10.1002/mp.14106

Öllers, M. C., Swinnen, A. C. C., & Verhaegen, F. (2020, October 7). *Acuros® dose verification of ultrasmall lung lesions with EBT-XD film in a homogeneous and heterogeneous anthropomorphic phantom setup*. American Association of Physicists in Medicine (AAPM). Retrieved December 27, 2021, from https://aapm.onlinelibrary.wiley.com/doi/abs/10.1002/mp.14485?af=R