IOSR Journal of Dental and Medical Sciences (IOSR-JDMS)
e-ISSN: 2279-0853, p-ISSN: 2279-0861.Volume 24, Issue 11 Ser. 5 (November. 2025), PP 01-07
www.iosrjournals.org

A Review on Motion Phantoms in Radiotherapy Treatment Planning

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Abstract:
Phantoms are essential in radiotherapy for quality assurance, patient-specific dose verification, and training by mimicking human tissue to measure and optimize radiation doses, ensuring safe and effective treatment. They allow for testing treatment planning systems, machine calibration, and validating treatment delivery methods before they are used on real patients. In both diagnostic and therapeutic applications, there are issues related to patient or organ motion. Motion can degrade image quality or interfere with the delivery of the desired dose distribution. Published articles related motion phantom in Radiotherapy between 2006 to 2024 are analysis and summarized tabulated.

Key words: *Motion Phantom, Radiation Therapy, Organ motion, Dose measurement*

Date of Submission: 11-11-2025 Date of Acceptance: 23-11-2025

I. INTRODUCTION

Phantom investigations are important in radiotherapy for several key reasons: they verify the accuracy of treatment plans by simulating patient anatomy and tissue properties, they ensure the quality and safety of treatment machines through rigorous testing, they provide a crucial controlled environment for research and development of new technologies, and they serve as a vital tool for training medical professionals. By using phantoms, clinicians can confirm that radiation doses are delivered precisely to the tumor while minimizing harm to surrounding healthy tissues. By providing a controllable and reproducible environment, phantoms help advance radiotherapy research and training, ultimately improving patient outcomes.

Why Phantoms Are Important

- Dose Verification and Treatment Planning:
  Phantoms are used to measure and confirm the radiation dose delivered to target areas. They mimic the radiological properties and anatomical complexity of human tissues, allowing for precise dose distribution checks and validation of treatment plans before they are applied to patients.
- Quality Assurance (QA) and Machine Performance:
  Phantoms enable routine quality assurance testing of treatment machines, like linear accelerators, to ensure they perform safely and accurately. This includes checking the consistency of the radiation beam and the overall performance of the machine.
- Research and Development:
  Phantoms provide a standardized and reproducible platform for testing new imaging techniques, radiation delivery methods, and treatment planning software. This allows for systematic comparisons and helps advance the field of radiotherapy.

- Patient-Specific Verification:
  While standard phantoms are useful, researchers and clinicians are developing individualized phantoms. These can be tailored to a specific patient's anatomy and potential complications like implants, allowing for highly personalized dose verification.
- Training and Skill Development:
  Phantoms are indispensable training tools, providing a realistic setting for medical professionals—including radiation oncologists, physicists, and technicians—to practice and refine their skills in a safe and controlled environment before working with patients.
- Addressing Anatomical Complexities:
  Phantoms can be designed to incorporate the heterogeneities found in the human body, such as different tissues, bone, and air cavities. This is vital for understanding and mitigating how these variations affect radiation dose distribution.

- Treatment Plan Validation:
  Phantoms help ensure that the planned radiation dose distribution matches the actual delivered dose, a critical factor for effective patient treatment.

In both diagnostic and therapeutic applications of medical radiation, there are issues related to patient or organ motion. Motion can degrade image quality or interfere with the delivery of the desired dose distribution. In either case, phantoms are used to explore the issues related to motion before the procedure is applied to the patient. There is a variety of motion phantoms commercially available to address quality control and research needs. Furthermore, motion phantoms have been constructed for use in more specialized investigations. It would be impossible to discuss in any depth the limitless options and varieties of motion phantoms that have been conceived and used.

Tumor motion can occur during intrafraction and interfraction treatment. Imaging motion phantoms are often custom designed to improve the use of four-dimensional computed tomography (4DCT). Motion phantoms can be used in many other medical applications such as cardiac surgery to improve robotic-assisted surgery. Many studies can now be accomplished with only a computer simulation, highly advanced anthropomorphic phantoms that also include cardiorespiratory motion.

Treatment Sites Affected by Motion

While lung and prostate treatments are the most prominent examples of sites that are susceptible to motion complications, several other treatment sites also undergo motion. For many of these other sites, the mechanisms are the same as for prostate motion (often caused by bowel movements) or lung motion (caused by respiration). In lung, there are several sites that move with respiration, such as the liver, the kidneys, and the pancreas. The same respiratory motion waveform that is used for lung motion likely applies to these sites also, but the amplitude of motion and hysteresis will differ.

II. LITERATURE REVIEW

A detailed literature survey related to the motion phantom was carried out in this review. The survey strategy for this particular review was a comprehensive literature search in the popular databases such as PubMed and Google Scholar under the key words “Motion Management'', “Radiotherapy”, “Lung cancer”, and “Breast cancer”. In addition to the database searches, the available data on the internet from international organizations were also included in the study. The search of literature was limited to the journal articles that were written in English and published between 2006 to 2024. The titles and abstracts of potential articles were reviewed and the full manuscripts of eligible publications were retrieved. The articles were analyzed and classified as year of published, phantom type, aim, assessment method, and results.

The detailed search in Pubmed and Google scholar resulted in 815 articles (509 from Pubmed and 306 from Google scholar). 326 articles were remained after removing 489 duplicates by scanning the titles. 134 articles which were based on RT and 109 articles which does not relate to motion phantom were removed and finally, 25 articles were considered for the review.

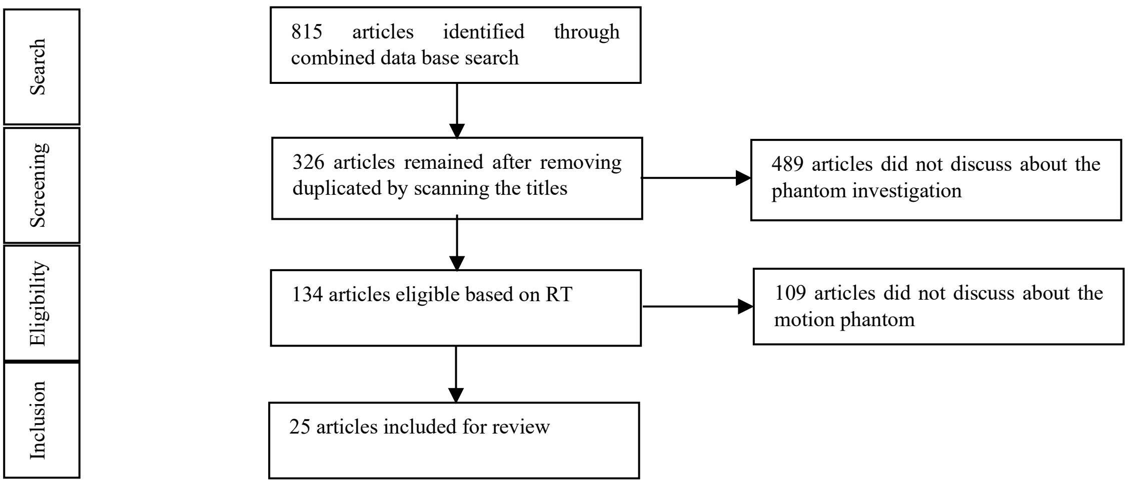

Figure 1: Flow chart of the review process

Table 1: Summary of the Motion Phantom survey data for Radiotherapy

Reference	Year	Phantom Type	Aim	Assessment method	Results
[01]	2006	Motion phantom	Determine the dosimetric effects of motion upon actual Helical tomotherapy treatment delivery, phantom film dosimetry measurements under static and moving conditions.	Dynamic static phantom doses compared to phantom doses in terms of axial dose profiles, cumulative DVH, percentage of CTV receiving the prescription dose and the minimum dose received by 95% of the CTV.	The larger motion amplitude resulted in more under-dosing at the ends of the CTV in the axis of motion, CTV dose coverage is not significantly dependent on machine and phantom motion periods.
[02]	2006	Breathing phantom with deforming lungs	Investigate and quantify the contribution of organ and tumour motion to the degradation of planned dose distributions during radiotherapy to the breathing lung	3DCRT fractions with different starting phases and IMRT plans delivered to the phantom and compared to a static and at the end-expiration position.	Bigger amplitudes of motion resulted in a higher degree of dose blurring, Severe underdosages observed when deliberately selecting the PTV wrongly, their extent being correlated with the degree of margin error.
[03]	2009	One-dimensional moving phantom.	Impact of motion velocity that may cause motion artifacts on TVs using a one-dimensional moving phantom.	Reflective marker position recorded by the RPM, maximum motion velocity for each phase bin, each volume, size and the motion range of TV in the CC direction were measured.	The motion artifacts substantially reduced when the phantom moved longitudinally at low motion velocity during 4D CT image acquisition
[04]	2010	4D Motion Phantom	Potential alternative scenario for accurate dose-painting delivery at 1 cm beam width with helical tomotherapy in the presence of 1 cm, 3D, intra-fraction respiratory motion, without any active motion management.	A model dose-painting experiment was planned and delivered to the average position with three spherical PTV levels to approximate dose painting to compensate for hypothetical hypoxia in a model lung tumor.	The dose uncertainty in the purposeful absence of motion management and in the absence of large, low frequency drifts or randomness in the breathing displacement yields very favorable results, only small blurring observed instead of interference effects.
[05]	2010	Deformable lung phantom	Simulate patient breathing motion and to evaluate a deformable image registration algorithm.	Verification of intensity-based 3D deformable registration based on the peak exhale and peak inhale breathing phases.	The registration differences ranged from 0.60 mm to 1.11 mm and accuracy was determined according to inner target deformation.
[06]	2011	Breast radiotherapy dynamic phantom	Quantifies changes in delivered dose due to respiratory motion for breast radiotherapy planning techniques	Dose distributions measured using films inserted through slits in the axial and sagittal planes between static and moving deliveries.	Delivered dose to the moving phantom within 5% of that to the static phantom, measurement accuracy ±3%. The homogeneity index significantly decreased only for the 2 cm motion end-exhale set-up and improved posterior breast coverage.
[07]	2011	Robot driven phantom	Investigate the influence of intrafractional tumor motion to the accumulated (absorbed) dose.	Different motion scenarios and compensation techniques on image acquisition, dose calculation, and dose measurement realized.	Reduction of dose at the periphery of the target, necessary safety margins to compensate for dose reduction was smaller, optimized margins was used instead of the standard ITV
[08]	2012	Programmable motion phantom	Reproducing patient respiratory motion in one dimension in both the AP and SI directions, providing controllable breath-hold and sinusoidal patterns for the testing of radiotherapy gating systems.	Sinusoidal and breath-hold patterns simulated with the motion platform and recorded with the RPM system to verify the systems potential for routine quality assurance of commercial radiotherapy gating systems.	Good correlation between replicated and actual patient data (*P* 0.003), Mean differences between the location of maxima in replicated and patient data-sets 0.034 cm with the corresponding minima mean equal to 0.010 cm.
[09]	2012	A breathing thorax phantom with independently programmable 6D tumour motion	Irradiation of moving targets using a scanned ion beam can cause clinically intolerable under- and overdosages within the target volume due to the interplay effect.	Commercial motion detection systems used to control the 4D treatment delivery and to generate data for 4D dose calculation.	Phantom's properties, measurements addressing reproducibility, stability, temporal behavior and performance of dedicated breathing pattern were performed
[10]	2015	Deformable, programmable lung motion phantom	Construction and experimental testing of an externally and internally deformable, programmable lung phantom in order to create a closer	Validating the geometric accuracy of the surface photogrammetry system and image registration tool, quantifying the geometric	Phantom correctly reproduced sinusoidal and patient-derived motion, realistic respiratory motion-related effects

			approximation of respiratory motion	error due to irregular motion in 4DCT.	while 4DCT can be used to localize internal markers for sinusoidal motion with reasonable accuracy.
[11]	2015	Dynamic motion phantom	Estimation and mitigation of errors due to respiratory motion in radiotherapy of lung cancer by PET/CT guidance	Target volumes estimated by SUV thresholds, non-uniform dose painting plans using volumetrically modulated arc therapy were optimized for fixed normal lung and spinal cord objectives and variable PET-based target objectives.	Estimated errors relative to the static ground truth condition for T/B_{mean} ratios, target volumes, planned equivalent uniform target doses, and 2%-2 mm gamma delivery passing rates.
[12]	2016	Anthropomorphic lung phantom	Compare the latest respiratory motion-management strategies, namely the ITV concept, MidV principle, respiratory gating and dynamic couch tracking.	Dose distributions used to calculate D_{mean}, changes in homogeneity indices, gamma agreement, and $A_{>Dmin}$.	All techniques achieved good tumor coverage ($A_{>Dmin} > 99.0\%$) and minor changes in D_{mean} (±3.2%). For lung, heart and spinal cord, significant dose differences between the four techniques were found ($p < 0.05$), with lowest doses for gating and tracking strategies.
[13]	2016	Anthropomorphic dynamic lung phantom	Validation of clinical workflows in adaptive radiation therapy, which combines a dynamic ex vivo porcine lung phantom and 3D polymer gel dosimetry.	Dose delivery under static and dynamic conditions of the phantom with and without motion compensation by beam gating.	Set up with the dynamic and anthropomorphic lung phantom together with 3D-gel dosimetry provides a valuable and versatile tool for geometrical and dosimetrical validation of motion compensated treatment concepts in adaptive radiotherapy
[14]	2017	Anthropomorphic breathing phantom of the thorax	Motion-induced range changes and incorrectly placed dose spots strongly affect the quality of PBS proton therapy	Comprehensive commissioning tests to evaluate the mechanical performance of the phantom, visibility on CT and MRI and its feasibility for dosimetric validation of 4D proton treatments.	Phantom is suitable for imaging and dosimetric studies in a thoracic geometry closely-matched to lung cancer patients under realistic motion conditions
[15]	2017	Respiratory motion lung-phantom with custom-designed	Describe the first end-to-end dosimetry audit for non-SABR lung treatments, measuring dose accumulation in a moving target, and assessing adequacy of target dose coverage	Dose was measured with radiochromic film, employing triple-channel dosimetry and uncertainty reduction of phantom static and moving at treatment delivery.	Planned and static-phantom results were seen (mean gamma pass 98.7% at 3% 2 mm), Dose blurring was evident in the moving-phantom measurements (mean gamma pass 88.2% at 3% 2 mm).
[16]	2017	Radiotherapy motion phantom	Design and build a motion phantom accurately reproduce the breathing motion of patients to enable end-to-end gating system quality control of various gating systems as well as patient specific quality assurance.	The phantom programmed and evaluated with patient data and with a square wave signal to be tracked with a motion monitoring system.	The comparison of patient curve data showed a mean error value of −0.09 mm with a standard deviation of 0.24 mm and a mean absolute error of 0.29 mm.
[17]	2017	Advanced Deformable Phantom	Quantitatively analyze the effects of tumor size and motion between 3D and 4D dose	Accuracy of the phantom diaphragm motion was assessed by comparing measured motion with predicted motion, the correlation between the diaphragm and tumor motions was calculated.	The accuracy of phantom diaphragm motion was better than 1 mm, tumor motion was larger in the 10 cm^3 tumor than in the 90 cm^3 tumor, range of difference between the tumor set-up positions was 0 to 0.45 cm.
[18]	2018	Anthropomorphic thorax phantom	Overcome Motion correction methods by patient motion during medical imaging.	Phantom allows to simulate various types of cardio-respiratory motions inside a human-like thorax, including inflatable lungs, beating left ventricular myocardium, respiration-induced motion of the left ventricle, moving lung lesions, and moving coronary artery plaques	The constructed phantom can perform studies in PET, SPECT and CT, and also inside an MRI system.

[19]	2018	Moving phantom	Investigate the dosimetric impact of hysteresis on lung cancer tomotherapy	Measurements using Map Check with an XY 4D motion simulation with sinusoidal motions in the SI and left–right orientations.	Dose difference analysis of each hysteresis vs. static state mostly indicated that the passing rate differed between structures, both analyses showed the Dose difference distribution changed with hysteresis.
[20]	2019	Affordable custom phantom	In order to reduce tumour motion uncertainties due to breathing	The measured beam on/off, correlated to the known positions of the phantom is compared to the gate window for RPM.	The measured time delay for sinusoidal movements with a period of 7.50 s and 3.75 s, and for three patient breathing traces.
[21]	2020	Dynamic thorax phantom	Calibration a mechanical system of In-house Dynamic Thorax Phantom used as a dosimetry on the Radiotherapy RPM technique.	Calibration of mechanical system by finding out the number of counts needed each direction for rotational system	Mechanical system between the actual readings compared with the system specification is 0.0% and < 1% for the measurement testing.
[22]	2021	Motion phantom	Effect of respiration-induced lung tumor displacement on dose delivery in IMRT-SBRT, VMAT-SBRT, and HT-SBRT.	Ionization chamber and radiochromic films used to measure the point dose at the tumor center and the dose profiles and compared with the calculated doses to verify the accuracy of the dose delivered to the lung tumor.	The HT-SBRT plans showed better CI and HI than IMRT SBRT and VMAT-SBRT plans for all respiratory amplitudes, all film results showed an adequate treatment dose coverage in the lung tumor at different respiratory amplitudes.
[23]	2023	In-house Moving Phantom	Skin dose by using optically stimulated luminescence on an in-house moving phantom for breast cancer treatment in tomotherapy.	Impact of respiratory motion on skin dose between static and dynamic phantom's conditions was evaluated.	Skin dose reduced to 84.1% and 78.9% for dynamic conditions, treatment plans without skin flash or virtual bolus showed significant skin dose differences under static and dynamic conditions by 4.83% and 9.43%.
[24]	2024	Dynamic anthropomorphic thorax phantom	Create a dynamic phantom designed for quality assurance and to replicate a patient's size, anatomy, and tissue density.	The extent of respiratory motion quantified using a 4DCT scan, end- to-end tests conducted to evaluate two motion management techniques for lung SBRT.	Left lung tumor displaced ± 7 mm SI and AP, end-to-end testing showed an excellent agreement between the measured and the calculated dose for ion chamber and film dosimetry.
[25]	2024	Dynamic anthropomorphic thorax phantom	Create a dynamic phantom designed for quality assurance and to replicate a patient's size, anatomy, and tissue density.	Respiratory motion quantified using a 4DCT scan, evaluate two motion management techniques for lung SBRT for End-to-end tests.	The end-to-end testing showed an excellent agreement between the measured and the calculated dose for ion chamber and film dosimetry.

[ITV-internal target volume, DVH-dose volume histograms, CTV-clinical target volume, SABR-stereotactic ablative body radiotherapy, PTV-planning target volume, AP- anterior–posterior, SI- superior–inferior, RPM-real-time position management, 4DCT- 4-dimensional Computer Tomography, SBRT- stereotactic body radiotherapy, ITV- Internal Target volume, D_{mean}- mean doses, $A_{>Dmin}$- areas covered by the planned minimum dose, PET- Positron emission tomography, SAF- specific absorbed fractions, ^{18}F-FDG- ^{18}F-fluorodeoxyglucose, CT- computer tomography, SUV- standardized uptake value, T/B_{mean}- mean target-to-background, PBS- pencil-beam-scanned, MRI- magnetic resonance imaging, PAGAT- polyacrylamide gelatin gel fabricated at atmospheric conditions, TV- target volumes, CC- cranial-caudal, IMRT- intensity modulated radiotherapy, SBRT- stereotactic body radio therapy, IMRT- intensity-modulated radiation therapy, VMAT- volumetric modulated arc therapy, HT- helical tomotherapy, CI- conformity index, HI- homogeneity index]

III. METHODS AND MATERIALS

There are different commercially available phantoms and moderated phantoms are used to for various purposes in radiotherapy. Depending on the intended use of the phantom, a motion phantom must satisfy certain mechanical specifications. Mechanical requirements of a motion phantom for different applications and the specifications of select commercial and custom motion phantoms are discussed in this section.

Types of Phantoms

- Anthropomorphic Phantoms**:** These resemble human anatomy and are used for accurate dose measurements and verification. Most of anthropomorphic phantoms are normally designed and made to closely resemble the shape and size of the human body, whether male, female, adult or child.

- Tissue-Equivalent Phantoms**:** Made from materials that simulate the interaction of ionizing radiation with human tissue.
- Solid Phantoms**:** Easy to use and preferrable for situations requiring precise depth positioning and surface dose measurements.
- Water-Filled Phantoms**:** Offer an economical method for calibrating stereotactic beams.
- Computational Phantoms**:** Digital models created with mathematical equations, used in Monte Carlo simulations to model dose distributions.

IV. DISCUSSION

Phantom is a physical device used in the radiological science for calibration of the detectors and therapy unit, quality assurance, treatment planning method for accuracy and to mimics the dose to the human body. Commonly phantoms are made of solid materials which are radiologically equivalent to human tissues. Because the human body consists mostly of water, homogenized water or plastic phantoms are widely used for the calibration of radiation detectors and treatment systems. anthropomorphic phantoms are more realistic and better represent the complex heterogeneity of the human body; they often consist of several tissue-equivalent materials that are moulded into shapes of organs or bones to represent part or all of the body. For the ease of placing tiny radiation dosimeters, some of the phantoms for dose measurements come in slices with cavities in locations that match with organs of interest. Commercially available phantoms only come in a limited number of body sizes and do not fully reflect the diversity of the human population. Computational phantoms include extensive details of the exterior and interior features of the human body such as the shape, volume, and mass of radiosensitive organs. Coupled with information for tissue density and chemical composition, a computational phantom allows to simulate radiation interactions and energy deposition patterns in the body accurately.

A motion phantom requires a motor and a translation device to make a more traditional type of phantom move relative to the laboratory frame for which the treatment is prepared. The motor can be as simple as a rotary motor with a cam shaft for simple harmonic motion. It is common to use Solid Water phantom or an anthropomorphic phantom with thermoluminescent dosimeter (TLD) chips or film (radiochromic or radiographic) embedded. The motion needs to be controlled by some type of control circuit, typically a computer, so the user can achieve a high level of accuracy in the amplitude, frequency, initial phase, and start and stop times of the motion. To create realistic motions with randomness or positional drifting due to low-frequency components, computer-programmable motors are preferable. The level of precision and accuracy required depends upon the expected dose distribution and the sensitivity of the final outcome to dose inaccuracies.

Another requirement of motion phantoms is the dimensional degrees of freedom: up to three orthogonal translations and three orthogonal rotations, all of which can potentially be modulated in time. Usually, only a subset of these degrees of freedom is required. Even a simple one-dimensional motion phantom is useful for motion sensitivity studies.

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