Review paper

A review of brachytherapy physical phantoms developed over the last 20 years: clinical purpose and future requirements

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Abstract

Within the brachytherapy community, many phantoms are constructed in-house, and less commercial development is observed as compared to the field of external beam. Computational or virtual phantom design has seen considerable growth; however, physical phantoms are beneficial for brachytherapy, in which quality is dependent on physical processes, such as accuracy of source placement. Focusing on the design of physical phantoms, this review paper presents a summary of brachytherapy specific phantoms in published journal articles over the last twenty years (January 1, 2000 – December 31, 2019). The papers were analyzed and tabulated by their primary clinical purpose, which was deduced from their associated publications.

A substantial body of work has been published on phantom designs from the brachytherapy community, but a standardized method of reporting technical aspects of the phantoms is lacking. In-house phantom development demonstrates an increasing interest in magnetic resonance (MR) tissue mimicking materials, which is not yet reflected in commercial phantoms available for brachytherapy. The evaluation of phantom design provides insight into the way, in which brachytherapy practice has changed over time, and demonstrates the customised and broad nature of treatments offered.

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Key words: brachytherapy, phantoms, test object.

Purpose

This aim of this review paper was to present information on brachytherapy phantoms developed over the last 20 years. It offers a starting point for designing new phantoms, and a source of information on existing phantoms.

A phantom, sometimes called as "test-object", can be defined according to MeSH (medical subject headings thesaurus, produced by the National Library of Medicine) as a device or object used to enhance imaging techniques or for measuring radiation to evaluate performance, often with properties similar to human tissue [1]. A phantom may be designed to test image quality, check geometric accuracy of the radiation source positions, measure radiation dose, or mimic tissue mechanics.

While considerable growth in the range and quantity of commercial phantoms available for the verification of complex external beam radiotherapy techniques has been seen in the last two decades, the same cannot be said for brachytherapy applications [2]. This could be due to a variety of techniques used within the brachytherapy field worldwide, making it difficult to design generic phantoms, or to a smaller size of brachytherapy commercial market, as compared to external beam. However, there is a vast amount of in-house designed phantoms to achieve pre-defined specific endpoints, created by clinical and research groups.

Lack of choice in commercially available phantoms leads clinical physicists and researchers to either obtain and replicate already existing non-commercial designs, or to design and manufacture new phantoms. The first necessary step before starting designing is to perform a literature search, and to the best of our knowledge, such a review has not been published. There is a sub-section on ultrasound phantoms within a review of recommendations on quality assurance of ultrasound systems used for guidance in prostate brachytherapy [3]. Also, there are brachytherapy evaluations and external beam audits, containing sub-sections on phantoms by Palmer [4] and Pasler [5] for brachytherapy and advanced radiotherapy, respectively. In 2014, Xu *et al*. reviewed a rapidly growing field of computational phantom development [6].

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However, virtual phantoms could only be complementary to physical phantoms for brachytherapy, in which quality was dependent on physical processes, such as accuracy of source placement.

This literature review focuses solely on physical phantoms for brachytherapy. The remaining sections of this paper include methodology, results (tabulated overview of phantoms, followed by sections on phantom size/material, phantoms with integrated radiation dosimeters, and commercially available phantoms), discussion with consideration of the future direction of brachytherapy phantoms, conclusions, and references.

Methodology

Phantoms included in this evaluation were ascertained from a systematic literature review. The electronic databases PubMed and ScienceDirect were searched for: 1. Brachytherapy [Title] AND Phantom [Title]; 2. Brachytherapy [Title] AND Test Object [All Fields]; 3. Brachytherapy [Title] AND (electromagnetic OR EM) [Title] AND Phantom [Title/Abstract]; 4. Brachytherapy [Title] AND Anthropomorphic [Title]. Both searches were time-limited including papers published between January 1, 2000 and December 31, 2019, full journal paper only, and those published in English. The aim of this literature review focused on the design of physical phantoms and sealed brachytherapy sources. Therefore, unsophisticated phantoms, requiring no manufacturing (e.g., water bath or simple stack of solid materials), phantoms not described in detail, virtual/computational phantoms, electronic brachytherapy, thermal brachytherapy, patient-specific phantoms, unsealed sources, and phantoms for imaging quality tests only, with no specific brachytherapy purpose, were excluded from the study. Duplications were removed.

Literature review results

Key properties of the phantoms found in this literature review are presented in Tables 1-7, along with the reference to the paper, from which the information was extracted [7-129]. Within these tables, the phantoms are grouped by their primary clinical purpose, deduced from their associated publications.

The following results sections cover phantom size/materials, phantoms with integrated dosimeters, and commercially available phantoms.

Phantom size/material

Suitable choices for phantom size/material and dosimetry were demonstrated for ^{192}Ir [130,131] and additional brachytherapy sources, such as ^{103}Pd, ^{131}Cs, ^{125}I, ^{169}Yb, ^{192}Ir, ^{137}Cs, and ^{60}Co [132]. According to the latter study, for these sources, only plastic water LR (CIRS, Norfolk, USA) has a deviation of less than 3% when comparing absorbed dose in the phantom material versus absorbed dose in water. While considering only high-dose-rate (HDR) sources, most commercially available phantom materials meet the evaluation criteria that absorbed dose to phantom versus absorbed dose to water must agree within 3%. It is important to note that these conclusions consider only fixed phantom sizes and measurement distances from the source. For example, Sina *et al*. concluded that for ^{192}Ir, a PMMA phantom of radius larger than 10 cm should be used with water equivalent to 1% [133]. Table 1 shows phantoms that are used for source measurements or dosimeter evaluation, in which the materials applied are largely restricted to solid water, plastic water, and PMMA. This is also true for the phantoms used in the dosimetric audits listed in Table 2 [34,35,36,37]. These solid materials can be machined to ensure precise geometric placement of applicators and detectors, which are particularly important in brachytherapy because of high-dose gradients. PMMA was used in one third of the phantoms identified in this review. In addition to favorable dosimetric characteristics, PMMA phantoms proved to be inexpensive, relatively easy to shape, and robust enough for its purpose. A much wider variety of materials were used in phantoms imitating the aspects of human anatomy or tissues (Table 3) as well as in phantoms designed for dose verification measurements, *in vivo* dosimetry, and secondary cancer incidence risks.

Paraffin wax can be easily molded to the required anthropomorphic shape and it has close to water properties, with an atomic number of 6.82 and a density of 0.9 g/cm^3. It is used in breast, esophageal, gynecological, and endoluminal brachytherapy phantoms, primarily for a dose verification [43,44,45,46]. These phantoms are not designed for imaging purposes. Polystyrene is a low-cost option, with light weight, which can be cut into simple shapes, and it has been used in breast phantoms [32,112] for quality control of interstitial implants and treatment planning optimization. Polystyrene was suitable for these interstitial techniques because the needles could be easily pushed through the material without the need for machining. Modelling clay and PVC have also been used as moldable materials.

Gelatin is a cheap and easy way of making a soft tissue substitute, where Young's modulus can be adjusted simply by increasing or decreasing the concentration of gelatin in water. A common alternative to gelatin is agar (also known as "agar-agar") or agarose, a purified form of agar. This may be preferable to gelatin, where the phantom is required for magnetic resonance (MR) imaging, in which varying concentration of agar changes in the T2 relaxation properties, making it possible to match different tissue types. De Brabandere *et al*. described good agreement of MR and computed tomography (CT) imaging characteristics between prostate and their agar prostate phantom [99]. Additionally, agar has been used in combination with glycerol and cellulose particles, where the aim was to mimic the characteristics of prostate tissue on ultrasound (US) [101,102]. Soliman *et al*. described a solution of manganese chloride II ($MnCl_2$) and copper sulfate ($CuSO_4$) to simulate the T1/T2 relaxation times of female pelvis [75].

In publications reviewed in this paper, a 3D printing (rapid prototyping) was first mentioned in 2012 when Ryu *et al*. utilized rapid prototyping to manufacture

Table 1. Phantom properties for source measurement/characterisation and dose verification

Clinical investigation purpose	Reference	Publication year	Radioisotope					Materials				Detector						Body site			Anthropomorphic? (Y/N)	Commercial phantom?
			^{125}I	^{60}Co	^{192}Ir	^{103}Pd	Other	Plastic water	Solid water	Perspex	Other	TLDs	Gafchromic film	Ionisation chamber	MOSFET	Gel	Other	Prostate	Gyne	Other		
Source measurements/characterization	[7]	2014		X	X					X				X								Kr[1]
	[8]	2000	X	X				X				X										
	[9]	2001			X					X		X										
	[10]	2002				X			X			X										
	[11]	2008				X				X		X										
	[12]	2009					48V			X	Ni[2]	X								RA[3]		
	[13,14]	2000	X						X			X										
	[15]	2011					^{106}Ru	X		X			X								Y	
	[16]	2013	X							X					X							
	[17]	2014																X				
	[18]	2013				X				X		X								Oc[4]	Y	
	[19]	2008	X				^{131}Cs						X									
	[20]	2012			X					X			X	X								
Dosimeter evaluation	[21]	2011			X					X		X	X									
	[22]	2019		X						X					X							
	[23]	2006			X						GI[5]					X						
	[24]	2011			X						PS[6]					X						
	[25]	2014			X					X							GaN					
	[26]	2015		X	X					X							GaN					
	[27]	2011	X			X				X		X					µDi[7]					
	[28]	2007					^{90}Sr/^{90}Y			X		X								X		

[1]Kreiger, [2]Nitinol, [3]Renal Artery, [4]Ocular, [5]Glass, [6]Polystyrene, [7]Micro diodes

Table 2. Phantom properties for dose optimisation and audit

Clinical investigation purpose	Reference	Publication year	Phantom name	Radioisotope					Materials				Detector				Body site			Imaging			Commercial phantom	Anthropomorphic? (Y/N)
				^{125}I	^{60}Co	^{192}Ir	^{103}Pd	^{137}Cs	Polystyrene	Gelatin	Perspex	Other	TLDs	Gafchromic film	Ionisation chamber	Alanine	Prostate	Gyne	Other	MRI	CT	Other		
Dose optimization	[29]	2018		X								Z[1]					X			X	X	US[2]	C53[3]	Y
	[30]	2004		X			X		X				X											
	[31]	2005								X							X							
	[32]	2005				X			X				X	X					Br[4]					
	[33]	2012										AG[5]					X			X	X			Y
Audit	[34]	2006	Baltas								X	ROM[6]									X	X-ray		
	[35]	2001				X		X			X				X									
	[36]	2007			X	X					X		X											
	[37]	2013	BRAD		X	X					X	SW[7]		X				X						
	[38]	2017			X	X					X	SW[7]				X		X						

[1]Zerdine, [2]UltraSound, [3]CIRS prostate phantom, [4]Breast, [5]Agrose gel, [6]Radio opaque markers, [7]Solid Water

a negative mould for their agar prostate phantom [33]. The concept of 3D printing moulds was also utilized by Nattagh *et al*. [126] to manufacture a uterus and vagina for their insertion and suturing phantom intended for gynecological brachytherapy training. In 2015, an artificial bladder was directly printed with polylactic acid (PAA) to investigate bladder dose during gynecological brachytherapy [54]. The authors investigated the mass attenuation coefficient of ^{192}Ir for PAA and soft tissue, concluding equivalent behavior in the energy region of interest. Lugez *et al*. [86] employed rapid prototyping with a resolution of 0.25 mm to manufacture a phantom consisting of seven HDR prostate brachytherapy grids linked together, with a slot for an EM sensor. This allowed to evaluate the accuracy of tracking catheter paths. In 2019, PAA was used again as a 3D printing material by Leong *et al*. [110] in their liquid-based single phantom solution for TG128 brachytherapy ultrasound QA [134].

Phantoms with integrated radiation detectors

Less than half of the articles reviewed referred to phantoms designed specifically for the measurement of radiation. Thermoluminescent dosimeters (TLDs) were the only dosimeters that have been used throughout the period of this review. It was not until 2008, that the use of Gafchromic film in brachytherapy phantoms became more consistent, and dosimetric techniques were established (Tables 1-3 and 6). It is common to see phantoms designed for both TLD's and Gafchromic film, where one acts as verification or gold-standard for the other (Tables 1-3), particularly in the initial evaluation and characterization stage of a new dosimeter.

Seven publications of phantoms designed for source characterization with TLDs had referred to an earlier design of Meigooni *et al*. [135]. The arrangement of TLDs was chosen to minimize interchip effects, and solid water was selected for water equivalence. Full scatter conditions were met by ensuring at least 10 cm of solid water between any TLD and the exterior of a phantom. Measurements were performed and recorded following the AAPM TG43 recommendations [136,137,138].

First indication of brachytherapy phantoms using MOSFET's (metal-oxide-semiconductor field-effect transistor) for radiation measurements were found in a 2009 reference [58]. MOSFETs are advantageous for *in vivo* measurements because their small size and cable assembly allows for needles and catheters insertion, and hence their use in an assessment of prostate, gynecological, and head and neck techniques (Table 3). One of the characteristics of MOSFET showed in the measurements of low-dose-rate (LDR) prostate brachytherapy by Bloemen van Gurp *et al*. was the angular dependence in a PMMA phantom, which they found to be up to 3.1% (±0.51%) [58]. To overcome this phenomenon, Gambarini *et al*. proposed the technique of coupling two MOSFET face-to-face detectors in their phantom [59].

In 2006, Hurley *et al*. described a phantom design for dosimetry of HDR brachytherapy source using a normoxic high-resolution polymer gel dosimeter called "MAGIC" (methacrylic and ascorbic acid in gelatin initiated by cop-

Table 3. Phantom properties for dose verification measurements, *in vivo* dosimetry and secondary cancer

Clinical investigation purpose	Reference	Publication year	Radioisotope			Materials					Radiation detector				Body site				Commercial/modified commercial phantom?	Anthropomorphic (Y/N)
			^{60}Co	^{192}Ir	Other	Polystyrene	Perspex	Silicon	Paraffin wax	Other	TLDs	Gafchromic Film	MOSFET	Other	Prostate	Gyne	Breast	Other		
Dose verification measurements	[39]	2003		X				X			X						X		A[1]	
	[40]	2015		X						Plastilina™		X					X		R[2]	Y
	[41]	2002		X	^{90}Sr/^{32}P							X						EV[3]		
	[42]	2013		X				X		Poly-propelelne				FBX[4]		X				
	[43]	2031		X					X		X	X					X			
	[44]	2015		X					X	Bone/NaCl/wood	X							Oes[5]		Y
	[45]	2009		X					X		X	X						EV[3]		
	[46]	2013		X					X	Al[6]/cork						X		Oes[5]		Y
	[47]	2014		X		X				SW/high-Z[7] materials		X				X				
	[48]	2007		X			X			H_2O	X	X		IC[8]		X				
	[49]	2010		X			X					X		IC[8]		X				
	[50]	2016	X		^{137}Cs		X					X				X				
	[51]	2018		X						Superflab bolus			X		X			H&N[9]		
	[52]	2001			^{90}Sr									PS[10]				CV[11]		
	[53]	2013					X			Skull bone				M[12]				NP[13]		Y
	[54]	2015		X			X			PA[14]	X	X			X					
In vivo dosimetry	[55]	2009		X						SW				AS[15]	X				C53[16]	Y
	[56]	2018		X			X			H_2O		X				X				
	[57]	2019		X				X		Urethane						X				
	[58]	2009			^{125}I		X			Gelatin			X							Y
	[59]	2013		X						Gel			X		X					
	[60]	2014		X		X				High-Z[7] materials			X		X					
	[61]	2018		X		X							X			X				
Secondary cancer	[62]	2018		X						BG[17], MM[18], $BaSo_4$, $CuSo_4$	X	X					X		A[1]	Y
	[63]	2016		X			X							Glass rods		X			R[2]	Y

[1]Alderson phantom, [2]Rando phantom, [3]Endovascular, [4]Ferrous sulphate-benzoic acid-xylenol orange, [5]Oesophagus, [6]Aluminium, [7]Atomic number, [8]Ionisation chamber, [9]Head and neck, [10]Plastic scintillator, [11]Cardiovascular, [12]MAGIC dosimeter, [13]Nasopharynx, [14]Polyactic acid, [15]Alanine strand, [16]CIRS prostate phantom, [17]Ballistic gel, [18]Metamucil powder

Table 4. Phantom properties for catheter/applicator reconstruction and artifact detection

Clinical investigation purpose	Reference	Publication year	Materials						Body site					Imaging			Commercial phantom	Anthropomorphic?	EMT?
			Plastic water	Solid water	Perspex	Agarose gel	Zerdine	$CuSo_4$	Other	Prostate	Gyne	Breast	Other	MRI	CT	US	Other			
Catheter/applicator reconstruction and artifact detection	[64]	2014					X			X						X		C53[1]	Y	Y
	[65]	2013					X								X	X		C53[1]	Y	Y
	[66]	2012					X									X		C53[1]	Y	
	[67]	2018					X									X		C53[1]	Y	Y
	[68]	2017		X						X							FPI[2]			
	[69]	2010			X						X				X					
	[70,72,73]	2011			X			X			X				X					
	[71]	2013			X				Air/bone inserts		X			X	X		CBCT[3]		Y	
	[74]	2000							Wax/vaseline				Interstitial	X	X					
	[75]	2016							$MnCl_2$		X			X						
	[76]	2005									X				X					
	[77]	2003							Metal mano-site		X				X					
	[78]	2018			X						X				X				Y	
	[79]	2018							Z^4	X				X	X			C53[1]	Y	Y
	[80]	2011							Gelatin/latex	X						X				
	[81]	2002			X				18-FDG[5]		X				X		PET			
	[82]	2009				X		X			X			X						
	[83]	2000			X				Foam/CT contrast				Interstitial		X					Y
	[84]	2013		X						X										Y
	[85]	2014	X			X														Y
	[86]	2017							Plastic (3D print)	X										Y

[1]CIRS prostate phantom, [2]Flat panel imager, [3]Cone Beam CT, [4]Atomic number, [5]18-Fluorodeoxyglucose

Table 5. Phantom details for LDR seed reconstruction and TPS commissioning/evaluation

Clinical investigation purpose	Reference	Publication year	Materials					Body site		Imaging				Commercial phantom?	Anthropomorphic? (Y/N)	EMT?
			Radio-isotope	Ag	Perspex	Zerdine	Other	Prostate	Breast	MRI	CT	US	Other			
LDR seed reconstruction	[87]	2019	^{125}I	X			X	X				X	γ-camera	C53[1]	Y	
	[88]	2003	X			X		X					X-ray	C53[1]	Y	
	[89]	2019	X	X				X		X						
	[90]	2018	X	X			NaCl	X		X						
	[91]	2012					PVC[2]	X		X	X	X			Y	
	[92]	2017	X		X			X				X	γ-camera	C53[1]	Y	
	[93]	2006		X			Turkey/chicken	X				X				
	[94]	2012					Delrin	X					C-arm			
	[95]	2009			X			X					OBI[3]			
	[96]	2007			X			X			X					
	[97]	2012					Si[4]/breast tissue/PM[5]		X		X		X-ray		Y	
	[98]	2006		X	X			X		X	X					
	[99]	2009					PG[6]/CP[7]	X				X	VA[8]		Y	
	[100]	2018						X			X	X		Vz[9]	Y	Y
	[101]	2007	X	X			GI[10]/CI[11]	X			X					
	[102]	2000		X			GI[10]/CI[11]	X			X	X				
TPS commissioning/evaluation	[103]	2004	X			X		X			X			C53[1]	Y	
	[104]	2007			X					X	X					
	[105]	2015				X	PVC[2]					X		C45[12]		

[1]CIRS prostate phantom, [2]Polyvinyl chloride, [3]On-board imaging, [4]Silicon, [5]Polymeric membrane, [6]Porcine gel, [7]Cadaver prostate, [8]Vibro-Acoustogrpahy, [9]Yezitronix, [10]Glycerol, [11]Cellulose, [12]CIRS brachytherapy QA phantom model 045B

Table 6. Phantom details for quality control/quality assurance

Clinical investigation purpose	Reference	Publication year	Phantom name	Radio-isotope		Materials			Body site		Imaging	Radioation detectors			Commercial phantom	Anthropomorphic? (Y/N)	EMT?
				^{192}Ir	Other	SW	Perspex	Other	Interstitial	GYN	Ultrasound	Plastic scintillator	Gafchromic film	Other			
Quality control/assurance	[106]	2006			$^{90}Sr/^{90}Y$/ ^{106}Ru	X	X					X	X		RMI/ PTW		
	[107,108]	2013	MAGIC	X		X								Diodes			
	[109]	2007	Multi-slit	X				LF[1]/PF[2]						DR[3]			
	[110]	2018					X	PAA/ NaCl			X						
	[111]	2002			^{137}Cs		X			X				IC[4]		Y	
	[112]	2001		X				PS[5]	X				X	TLDs			
	[113,114]	2016	DoRGaN	X						X				GaN[6]			
	[115]	2017	Quality cross check	X					X								Y

[1]Lead foil, [2]Plastic foil, [3]Digital radiography, [4]Ionisation chamber, [5]Polystyrene, [6]Gallium Nitrate

per) combined with high-resolution MRI for dose readout [23]. A variation of MAGIC, named "MAGICA" was used in a nasopharynx phantom design. It varies subtly from the MAGIC recipe by including 0.5% agarose in the mixture [53]. Fricke gel was used in a phantom design by Carrara *et al*. In their design, two polystyrene templates with a regular grid pattern were used to hold fifteen catheters in place. Five of these were source catheters and the other ten surrounding them catheters contained radiochromic tissue-equivalent Fricke gel. The structure was placed in water for backscatter [24].

In 2009, a research group from France published [139] the first of a series of papers on implantable real-time dosimetric probes, which used a semiconductor material GaN (gallium nitrate) as a radiation detector, coupled with an optical fiber for radioluminescence collection and transmission. From this work and from a part of the DoRGan research project, an instrumented phantom for QA in HDR brachytherapy, along with an instrumented gynecological applicator was developed. The bulk of the phantom was made from PMMA (120 mm diameter) and incorporated 4 GaN-based dosimeters. An insert to the PMMA cylinder allowed for a connection of up to six treatment catheters. The phantom has a great potential as a routine QA system for brachytherapy, with testing showing deviations between the planned and measured dwell positions of 0.11 ±0.70 mm (1σ). The detected ratio for dwell position errors was 96% at 1 mm, and reached 100% at 1.5 mm and beyond. The detected ratio for dwell time errors was 90% at 0.2 s, and 100% at 0.3 s and beyond [25,26,113,114].

Of the publications included in this review, diodes in brachytherapy phantoms were not described until 2011. This was when Broisman and Shani [27] considered the application of spherical micro diodes for brachytherapy dosimetry of LDR ^{125}I and ^{103}Pd sources. Advantages of this solution came from small size diodes (1.8 mm diameter), causing little perturbation of the dose and from a 4π symmetry, with a potential for isotropic dosimetry. To characterize the spherical diodes, a range of PMMA phantoms were designed to hold a seed and diodes at fixed positions. Importantly, this paper demonstrates a 4π spherical symmetry in both the axial and azimuthal directions. Espinoza *et al*. focused on diode utilization for pre-treatment QA in HDR brachytherapy, with the design of a two-dimensional diode array phantom, so-called "magic phantom" [107]. It consisted of an 11 × 11 array of silicon p-type diodes with solid water above and below, enabling twenty catheters to be connected. The intended use was the reconstruction of a real-time source position within the phantom, according to the prescribed treatment plan. A further publication on the magic phantom was published two years later in 2015 [108], where additional software was created to compare dwell positions and dwell times measured with the planned treatment from the TPS. This paper also introduces the concept of a new metric called "position-time gamma index" to quantify the quality of delivered plan from the original treatment plan.

Table 7. Phantom details for needle insertions, training, tissue imaging and image registration

Clinical investigation purpose	Reference	Publication year	Materials			Body site				Imaging				Commercial phantom	Anthropomorphic?	EMT?
			PVC	Zerdine	Other	Prostate	Skull base	Breast	GYN	US	CT	MRI	Other			
Needle insertions	[116]	2012	X		Polymer clay/ glass beads	X				X	X	X			Y	
	[117]	2017	X			X				X						
	[118]	2014	X			X									Y	Y
	[119]	2007		X						X				C53[1]	Y	
	[120,121]	2012	X			X				X	X	X			Y	
	[122]	2019			Synthetic skull, plastecine, beef		X						CBCT[2]		Y	
Traning	[123]	2014				X				X				C53[1]	Y	
	[124,125]	2018			Ballistic gel, gelatin, propylene, glycol			X			X				Y	
	[126]	2014			Gel/rubber				X	X	X				Y	
Tissue imagaing	[127]	2014		X		X								C53[1]	Y	
Image registration	[128]	2002		X						X			Fluro[3]	C53[1]	Y	
	[129]	2002		X						X	X		MRS[4]		Y	

[1]CIRS prostate phantom, [2]Cone beam CT, [3]Fluroscopy, [4]Magnetic resonance spectroscopy

Commercially phantoms

Of the papers reviewed, only 15% utilized a commercial phantom. The most common was CIRS (Computerized Imaging Reference Systems, Inc., Norfolk, VA) prostate phantom, model 053 (Tables 2-5 and 7) [140]. From the literature, it appears that it could have started as an in-house phantom built with a CIRS specification for a study on combining MR spectroscopy with US/CT for prostate brachytherapy [129]. The Yezitronix prostate phantom is a direct competitor for the CIRS model; however, it was described in only one publication identified in this review [100], which may be due to its relatively recent release on the market. Other commercial phantoms mentioned in the reviewed articles included Kreiger phantom [7] for source measurements, Baltas phantom [34] for quality assurance in reconstruction techniques, Rando and Alderson phantoms modified for brachytherapy purposes [39,40,62,63], and CIRS 045 brachytherapy QA phantom for quality assurance in prostate US imaging [105,110].

Discussion

Iridium-192 is clinically the most used HDR brachytherapy source, and prostate and gynecological brachytherapy are two of the most common techniques (Tables 1-7). It was therefore not surprising that the results of this literature review showed most phantoms developed for these purposes. More surprising was the continued use of TLDs throughout the twenty-year period (Tables 1-3), despite a variety of dosimeters available on the market. TLDs are considered a reliable and validated method for dosimetry in brachytherapy due to their flat energy response and high sensitivity. However, they are labor-intensive in preparation and are disturbed by artifacts, such as volume averaging, self-attenuation, and positioning errors [18]. The uptake of Gafchromic film was unexpectedly slow, considering its less-labor intensive property than TLDs. It had been shown to be ideal for the measurement of dose distributions in regions of changing energy spectra and high-dose gradients as early as in 1991 [141]. Here, the dosimeter chosen for each phantom has a direct effect on the measurement result and therefore must be chosen with full consideration of its purpose. An example is a glass dosimeter being used because it was shown to be more reproducible than TLD's; however, there was no discussion of its high atomic number ($Z = 12$), density ($\rho = 2.61$ g/cm^3), and angular dependence of 8% compared to 3% for TLDs, which could have affected the brachytherapy results [63].

Deformable 3D dosimeters are of interest in brachytherapy phantoms. However, further research is needed to develop gel dosimeters, which have suitable mechanical properties and can measure accurate dose when interstitial techniques are used, particularly considering the evidence that infiltration of oxygen may inhibit the polymerization process [23]. If these issues could be resolved and a practical workflow established for reading out the dose in a clinical department, then is a great potential for 3D gel dosimeters used in brachytherapy phantoms. At present, publications on gel dosimetry focused on characterizing the dosimeters and establishing read-out techniques rather than phantom designs. This was summarized in a study by Farhood *et al*. [142], a systematic review paper on clinical applications for polymer gel dosimeters in radiotherapy.

Almost half of the US phantom studies used the CIRS prostate phantom. This was probably due to easy commercial availability of this phantom, which increased the number of studies performed with US, since this was the primary imaging modality, for which the phantom was designed. Excluding these studies, the next highest frequency of phantoms designed for imaging were those for MRI. This may reflect the change in imaging practice for gynecological brachytherapy from orthogonal imaging to 3D imaging with CT, CT and MRI-fused, and ultimately, MRI only. A similar transition is true for LDR prostate brachytherapy, from single US imaging, to MRI and US-fused, and potentially, MRI only.

Currently, ultrasound QC for prostate brachytherapy tends to be performed with the CIRS brachytherapy phantom; however, this is not suitable for inserting needles and therefore cannot be used for the complete QC as recommended by the AAPM Task Group 128 or the later GEC-ESTRO/ACROP recommendations published in 2020 [143]. The phantom design of Leong *et al*. has a potential to simplify this QC process, and is relatively simple for clinical users to manufacture. Progress in designing phantoms to digitize QA and QC can be seen in the magic and multi-slit phantoms. Although there is a clear benefit in terms of reduced use of consumables and potential time saving, the equipment must also be practical. There is a concern regarding the multi-slit phantom design and lack of availability of digital radiography within the afterloader room. Phantoms designed for use with electromagnetic tracking should also be included as potential QA tools as demonstrated by Kellermeier *et al*. [115] and Damato [85]. The potential benefit for this technology in brachytherapy is considerable, as discussed by Tanderup *et al*. in their paper outlining prospects of technology innovation [2].

A detailed explanation behind the reason for the phantom's design can be overlooked in the publications, and it seems that this is particularly the case when it comes to the choice of materials. For example, the use of MAGIC-A, where 0.5% agarose has been added to the mixture without any explanation of its purpose. Most commonly, agarose is used to thicken a liquid or for modifying relaxation properties for MRI [53]. An important discrepancy was identified by Zhu *et al*. in the accuracy of robotic seed placement between a phantom and cadaver experiment [122]. The phantom experiment demonstrated placement of seeds closer to the intended position than seen in the cadaver experiment. This was likely due to different needle-tissue interactions between the two test objects. The cadaver better represents the complex model of needle-tissue interactions. That said, the mechanical tissue properties of a cadaver are still not representative of the in-vivo situation where the tissue is lubricated. This is a feature that, to the authors knowledge, is not modelled in phantom designs for radiotherapy and is identified as an issue by a partner urologists of the phantom design in a study by Hungr *et al*. [116]. Whilst a simple phantom fails to model the complexity of soft tissue, the

results may still be of benefit if they demonstrate a relative improvement of the technique.

The choice of phantom material is important for accurate dosimetry; however, the recommendations in the literature are not always followed. An example is the use of PMMA instead of the recommended plastic water for LDR in the design of an eye plaque brachytherapy phantom [11,16], using ^{103}Pd source. However, the authors acknowledged the correction of PMMA to liquid water by including it in the uncertainty analysis. Similarly, the dimensions of the PMMA phantom designed by Gholami *et al*. were used to test the agreement of TG43 TPS calculations to Gafchromic film measurements and were smaller (18 × 16 × 18 cm) than that considered necessary for water equivalence with an ^{192}Ir source (radius > 10 cm) [50]. These are considerations that the reader should be aware of when interpreting the results.

There is a need to improve the tissue mimicking materials available for brachytherapy in order to achieve substitutes, which meet the three requirements of radiative, imaging, and mechanical properties. A report that was commonly cited in the papers reviewed was ICRU report 44 [144] published in 1989, which would benefit from a later edition. Progress in manufacturing deformable phantoms can be drawn from external beam phantom development. An example is the ADAM phantom designed for CT and MRI of the whole male pelvis, focusing on mimicking the imaging and radiative properties of tissue, with organ motion from bladder and rectal filling [145]. The authors identified a peak in the CT number spectrum, which is not present in patients, likely caused by high kV absorption materials (PMMA or silicon); therefore, further research into alternative materials would be beneficial. Consideration is needed when using any high atomic number material at lower energies, where the photoelectric effect dominates due to the cross-section of the photoelectric being approximately proportional to Z^3. Research is also ongoing in the field of material science, and its findings will contribute to brachytherapy phantoms development. A recent example from advanced material technologies is the publication on 3D printing organ models with physical properties of tissue [146]. It is likely that future phantom advancement will continually use 3D printing, also referred to as "rapid prototyping". We found just a few examples of this in the review [33,54,86,126], which may be a limitation of the search criteria in excluding patient specific phantoms, where 3D printing was gradually used in brachytherapy [147].

This present review considered more complex phantoms, excluding those requiring little to no manufacturing, such as slabs of solid water or simple water bath phantoms. This may cause some limitation of the study from a wider perspective of all possible phantoms; however, it focuses on more relevant designs, which have been reported in the literature.

Conclusions

In this paper, information on brachytherapy phantoms developed over the last 20 years were collected and can be used in aiding future phantom designs for departments or commercial companies. A substantial body of work has been published on phantom designs from the brachytherapy community, but a standardized method of reporting technical aspects of the phantoms is lacking. In-house phantom development demonstrates an increasing interest in MRI tissue mimicking materials, which is not yet reflected in the commercial phantoms available for brachytherapy.

Studying phantom design provides insight into the way, in which brachytherapy practice has changed over time and demonstrates customized and broad nature of the treatments offered. Phantoms provide possibility of overall quality assurance and specific quality control of the brachytherapy process; however, further development and improvement are required to keep pace with rapidly evolving clinical and scientific techniques.

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