Materials for Multimodal Medical Imaging Phantoms: A Comprehensive Review for Diagnostic and Training Applications

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ABSTRACT

In diagnostic imaging, recent advances have introduced a wide range of modalities for diverse clinical applications, creating a growing need for anthropomorphic phantoms capable of supporting both single- and multimodal evaluations. Such phantoms play a crucial role in improving diagnostic accuracy, quality assurance, and medical training. This study aimed to identify and critically evaluate materials suitable for the construction of multimodal phantoms that realistically mimic human tissues. We systematically analyze materials to simulate biological tissues in multimodal test objects and to compare their signal characteristics with those of human tissues across various imaging combinations, including Computed Tomography/Magnetic Resonance Imaging (CT/MRI), Ultrasound (US)/MRI, US/CT, and CT/MRI/US. The advantages and limitations of the investigated materials are discussed, and promising directions for future development are highlighted. In addition, the feasibility of combining multiple materials within a single phantom is demonstrated. Our findings indicate that materials intended for large-scale phantom production must be safe, exhibit reproducible properties, and maintain stable imaging characteristics over time. The materials and design considerations presented in this study provide a foundation for the standardization of multimodal phantom development.

Keywords

Multimodal Imaging; Phantoms, Imaging; Magnetic Resonance Imaging; Tomography, X-Ray Computed

Introduction

Phantoms are test objects composed of artificial tissues that simulate human organs and limbs and are designed to replicate quantitative and qualitative characteristics of the human body, including biological processes and properties that can be described by mechanical, optical, geometric, and biophysical parameters [1]. Healthcare systems have a high demand for these products [2]. Phantoms are essential for imaging system quality assurance, the evaluation of complex diseases, the development and validation of novel imaging techniques, and the training of medical professionals [3, 4].

The development of anthropomorphic phantoms depends on selecting appropriate materials that can reproduce properties of target biological tissues [5]. Ultrasound (US) test objects must replicate the speed of sound

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Received: 29 May 2025
Accepted: 14 February 2026

and the acoustic attenuation of the biologically mimicked tissue [6-8]. Magnetic Resonance Imaging (MRI) phantoms must have T1 and T2 signal intensities (longitudinal and transverse relaxation times) comparable to the simulated tissue, while allowing independent adjustment of each parameter [9]. Computed Tomography (CT) phantoms must maintain homogenous X-ray density measured in the Hounsfield Unit (HU) [10, 11]. Commercially available phantoms [12, 13], typically limited to single modalities, are expensive, and often cannot be customized for specific applications. Rapid advancement in medical imaging and the demand for precise diagnostic equipment necessitate the development of new phantoms that can simulate human tissues across multiple modalities. Multimodal phantoms add extra complexity since their materials and properties must imitate those of the original tissues across several imaging modalities. Therefore, a systematic review on materials suitable for use across multiple imaging modalities is essential. This review aims to identify and critically evaluate materials used in the construction of multimodal phantoms that realistically mimic a range of human tissues.

The review is based on a comprehensive search of primary research articles indexed in the PubMed database (National Institutes of Health, U.S. National Library of Medicine) that reported the use of multimodal medical imaging phantoms. The search was restricted to full-text, English-language primary research articles. Review articles, preprints, dissertations, book chapters, conference proceedings, and conference abstracts were excluded. The search strategy employed the keyword "multimodal phantom" and was limited to publications between January 1, 2014, and December 31, 2024, yielding 762 records.

Studies were included if they reported material composition data relevant to multimodal phantom fabrication, described fabrication conditions, and provided quantitative imaging signal characteristics. Articles focusing on mathematical or digital phantoms were excluded due to the absence of physical fabrication considerations, as were studies using animals as test objects. Titles and abstracts were independently screened by four authors, resulting in the identification of 30 articles eligible for full analysis. Additional relevant studies were identified through reference screening of the selected publications.

This review focuses exclusively on materials designed for multimodal imaging applications and excludes single-modality phantoms. Particular emphasis was placed on cost-effective polymer-based materials fabricated using 3D printing or molding techniques. The results are systematically organized and presented according to imaging modality combinations to enhance clarity and facilitate comparison.

CT/MRI multimodal phantoms

Test object for CT and MRI imaging must match the T1 and T2 relaxation times and X-ray density of the mimicked tissues. The following section presents an overview of compositions suitable for mimicking soft tissues and bones.

Niebuhr et al. [14] developed Anthropomorphic Dynamic breAthing Model)ADAM((Anthropomorphic Dynamic breAthing Model), a multimodal male pelvis phantom for CT/MRI-guided radiation therapy. The phantom matches real patient dimensions with an elliptical cross-section of 370 mm × 220 mm. The outer casing is made of Polymethyl Methacrylate (PMMA) with CT values of 129±5 HU at 120-kV tube voltage. Anthropomorphic features were achieved through three-dimensional (3D)-printed bones and silicone-molded internal organs. Imaging markers and dosimeter cavities were incorporated into the organ molds. The comparison of the properties of ADAM phantom materials with human tissues is presented in Table 1 [14-17].

In the ADAM phantom, a tube connects the bladder to the outer casing through the upper lid, allowing for precise bladder volume

Table 1: Radiological properties of the Anthropomorphic Dynamic Breathing Model (ADAM) phantom [14] compared to human tissues.

Tissue	Reference			Composition	Phantom		
	CT density, HU	T1, ms	T2, ms		CT density, HU	T1, ms	T2, ms
Muscles	40-44 [15]	856±61 [16]	27±8 [16] 47±13 [10]	3.5% agar, 1% NaF, 0.025 % MH	26±3	886±4	20±1
Cortical bone	1524 [15]	No signal	No signal	Strong gypsum	1845±75	No signal	No signal
Adipose tissue	(-95)-(-55) [15]	343±34 [16] 260±7 [17]	58±4 [16] 84±36 [17]	Peanut oil	102±23	283±25	110±3
Prostate gland	34 [15]	1317±85 [16]	88 [16]	1 % agar, 4% NaF, 0.013% MH	41±3	1407±42	94±2

CT: Computed Tomography, HU: Hounsfield Units, T1: spin-lattice relaxation time, T2: spin-spin relaxation time, NaF: Sodium Fluoride, MH: MultiHance

adjustment using a syringe. A 3D-printed model of the hollow pelvic bones is housed within a protective casing. To achieve a value of 1600 HU, the outer surface of the bone is enveloped in a gypsum layer and finished with a delicate coat of clear lacquer. The interior of the bone contains a carefully prepared mixture of vaseline and K_2HPO_4. Surrounding the bone is a muscle tissue simulation made from agarose gel, which has been doped with a gadolinium-based contrast agent (0.5 M MultiHance) to emulate T1 relaxation times, while sodium fluoride is incorporated to fine-tune the CT attenuation values. T2 relaxation time is also effectively simulated through this composition.

The remaining volume is filled with vegetable oil to simulate the fat tissue. A drainage bag was placed atop the phantom body to prevent excess pressure from organ expansion. This bag also stores oil during detector replacement. The bottom of the phantom features an opening providing access to the rectum interior. A syringe-connected silicone balloon filled with liquid or air can be inserted externally to increase the rectum diameter from 20 to 30 mm.

Three types of silicone were used for organ modelling. Translucent TFC® type 13 silicone (Trollfractory, Germany), featuring high elasticity and the hardness of 13 units on the Shore 00 Hardness Scale, has radiological properties closely resembling soft tissues (CT at 120 kV tube voltage: 169±5 HU, T1=807±15 ms, T2=246±23 ms). This material was selected for bladder and prostate gland construction. Orange Neukasil RTV22 (RTV Silicones Addition Systems, Germany) silicone with the hardness of 22 units on the Shore A hardness scale was used to create and reinforce the rectum model, securing the tubes and integrating the detector bags into the bladder. The RTV22 silicone has the following CT and MRI values: CT=218 HU, T1=782±11 ms, T2=123±6 ms. Yellow TFC Type 2-1 silicone with the hardness of 35 units on the Shore A Hardness scale was used as marker dots on the bladder and the prostate gland surfaces. This material demonstrated the highest contrast with the surrounding translucent silicone across all the imaging modalities: CT=355±8 HU, T1=581±19 ms, T2=35±2 ms. Jin et al. [18] developed an anthropomorphic multimodal pelvic CT-MRI phantom using polyurethane and silicone with varying silicone oil concentrations. They tested Dragon Skin 10 MEDIUM, VytaFlex 20, and PMC-780 DRY (Smooth-On, Inc., USA) combined with silicone oils of varying viscosities (100-300 centistokes) to create tissue-mimicking materials. Table 2 [18] presents acquisition findings from CT and 0.35 T MRI

Table 2: Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) compatibility test results [18]

Material	Silicone viscosity, centistokes	CT density, HU				MRI intensity, a.u.			
		Signal modifier weight, %							
		10	20	30	40	10	20	30	40
Dragon Skin 10 MEDIUM	3000	204.19	189.21	178.20	170.20	227.46	254.80	280.53	287.88
	1000	204.30	189.09	178.20	168.98	247.26	279.72	308.07	313.73
	500	204.00	188.36	177.00	167.75	238.22	265.64	301.92	315.73
	100	204.05	188.48	177.25	169.64	230.30	271.31	301.59	312.64
PMC™-780 DRY	3000	55.22	64.43	71.58	-	79.46	114.78	152.18	-
	1000	55.08	64.35	-	-	90.81	133.65	-	-
	500	55.08	63.87	-	-	89.18	130.48	-	-
	100	54.72	-	-	-	89.20	-	-	-
VytaFlex™ 20	3000	-0.11	14.74	19.86	27.25	208.47	223.84	248.49	250.95
	1000	-0.14	14.77	19.47	26.90	217.92	236.90	255.41	267.83
	500	0.08	14.99	20.47	26.94	197.60	221.43	244.85	249.31
	100	-0.48	14.28	17.88	25.14	197.71	224.63	233.93	240.84

CT: Computed Tomography, HU: Hounsfield Units; MRI: Magnetic Resonance Imaging, PMCTM: Premium Performance Urethane Rubber, VytaFlex™: Urethane Rubber

scans. Silicone oil addition influenced signal intensity across various ranges. The polymer lattice demonstrated limited silicone oil storage capacity before saturation.

The selected compositions were used to mimic prostate, soft tissues, bladder, and cancellous bone. Hardened olive oil was used to simulate adipose tissue. Table 3 [18] compares material compositions and acquisition findings between the phantom materials and biological tissues.

Saleh et al. [19] developed a multimodal anthropomorphic breast phantom with carcinoma for CT and MRI. The phantom simulated skin, pectoral muscle, adipose and fibroglandular tissues, and carcinoma. The design incorporated parameters for both ionizing radiation imaging (attenuation coefficient, electron density, and effective atomic number) and MRI (T1 and T2 relaxation times). Table 4 [19] presents each composition and its components. All compositions used deionized water and safflower oil to simulate water and fat content, respectively. The carcinoma composition excluded safflower oil to simulate a watery malignancy. For ionizing imaging methods, sodium chloride, aluminum oxide, and potassium chloride served as scattering particles.

Table 5 [19-24] compares CT values and 0.5 T relaxation times between breast phantom and reference tissue data.

Kobe et al. [25] developed an anthropomorphic spine phantom with artificial nerves and radiopaque bone for perineural intervention training. These procedures typically use CT guidance for bone landmark identification. However, CT's low contrast resolution limits soft tissue and nerve visibility. High-resolution T2-weighted fat-saturated sequences display nerves as high-contrast structures relative to the surrounding tissues.

The phantom was made using 1.5% agar as a jellifying agent, distilled water, 0.5% polysorbate 80 as an emulsifier, and castor oil. Serial dilutions of lipogels with castor oil

Table 3: Radiological properties of tissue-mimicking materials compared to human tissues as a reference [18]

Tissue type	Composition			CT density, HU		MRI intensity, a.u.	
	Material	Silicone oil					
		Viscosity, centistokes	Weight, %	Reference	Phantom	Reference	Phantom
Prostate gland	PMC™-780 DRY	1000	10	38.9±12.9	28.5±7.2	78.1±13.8	86.5±19.3
Soft tissue	PMC™-780 DRY	1000	10	48.9±14.1	56.8±7.3	85.1±39.8	94.3±7.7
Bladder	VytaFlex™ 20	1000	40	6.8±11.6	4.9±30.6	319.2±17.7	309.1±17.8
Cancellous bone	Dragon Skin 10 MEDIUM	1000	20	379.8±104.8	164.7±9.0	260.4±49.1	256.0±9.4
Cortical bone	Strong gypsum	-	-	740.4±318.0	603.4±186.4	38.3±9.1	12.4± 1.4
Adipose tissue	Olive oil, hardener	-	-	−93.2±8.0	−105.8±4.9	532.6±25.1	607.4±15.9

CT: Computed Tomography, HU: Hounsfield Units; MRI: Magnetic Resonance Imaging, PMCTM: Premium Performance Urethane Rubber, VytaFlex™: Urethane Rubber

concentrations ranging from 0 to 100% produced a composition that mimics the relaxation times of muscle, adipose tissue, and bone marrow. Serial dilutions of Calcium Carbonate ($CaCO_3$) and Barium Sulfate ($BaSO_4$) in synthetic polyurethane resin enabled precise radiodensity adjustment of the L1-L5 vertebral bodies and sacrum in CT. Nerve tissue was modeled using polyethylene fibers impregnated with 2% agar. Table 6 [25] presents MRI values for the test samples. They align closely with the known MRI values of 394±16 ms as T1 and 161±10 ms as T2 for muscle tissue, 1160±45 ms as T1 and 40±14 ms as T2 for adipose tissue, and 822±21 ms as T1 and 67±6 ms as T2 for bone marrow [25].

The 30% castor oil composition produced muscle-equivalent attenuation measured in HU, 50% matched adipose tissue, and 40% effectively simulated bone marrow relaxation times. Table 7 [25] shows CT results for bone-mimicking compositions with varying salt concentrations. Reference values were 1118±80 HU for cortical bone and 220±15 HU for spongy tissue.

Cortical bone was simulated using 68.5 g polyurethane resin, 30 g $CaCO_3$, and 1.5 g $BaSO_4$, while cancellous bone was simulated with 10 g $CaCO_3$ and 90 g polyurethane resin.

US/MRI multimodal phantoms

The design of phantoms for US and MRI necessitates the precise replication of acoustic properties for ultrasonic imaging and the relaxation properties pertinent to MRI. While agar or gelatin are commonly employed to simulate soft tissue characteristics in US phantoms [26-28], these substances exhibit a limited operational lifespan and shelf stability. In contrast, certain silicone materials not only provide enhanced longevity but also effectively replicate the mechanical properties of soft tissues. Consequently, silicones have become a preferred choice in the production of MRI phantoms [29-31]. However, the phantoms that are equally suitable for both US and MRI

Table 4: Composites for a multimodal breast phantom [19]

Mimicked tissue	Component	Mass, g
Skin	Deionized water	360
	Surfactant X-100	20
	Polyvinyl acetate (PVA)	40
	Benzalkonium chloride	2
	Sugar	240
	Safflower oil	80
Adipose tissue	NaCl	0.5
	Fibroglandular tissue	27.5
	Surfactant X-100	25
	Safflower oil	66
	Olive oil	12.5
	Beeswax	100
	Agar	1.75
	KCl	1
Fibroglandular tissue	SiC	1
	Fibroglandular tissue	165.95
	Surfactant X-100	10
	Safflower oil	42.5
	Glycerin	32.5
	Agar	6.75
	Aluminum oxide	3.75
	KCl	1
	Benzalkonium chloride	1.25
Carcinoma	NaCl	1.75
	Agar	8.75
	Sugar	55
	Deionized water	175
	Benzalkonium chloride	0.875
	KCl	0.475
Pectoral muscle	Agar	12
	Sugar	180
	Deionized water	436.5
	Benzalkonium chloride	2.5
	Surfactant X-100	10
	Safflower oil	40

have limited coverage in the literature, with the most prominent applications in simulating a prostate gland [32, 33].

Bowen et al. [34] developed a bimodal lung phantom and reported the results of the comparison of its materials with human tissues in Table 8 [34, 35]. The structural framework of the phantom consisted of a polyvinyl chloride (PVC) rib cage coated with transparent Gorilla™ epoxy adhesive (Gorilla Glue Company, USA). Muscle, adipose, and skin tissues were simulated using silicone-based materials mixed with Asbury Carbons® graphite powder as a scattering agent. Lung tissue was modeled using Soma Foama™ 25 silicone foam (Smooth-On, Inc., USA) [34, 35]. The structural support consisted of Polyvinyl Chloride (PVC) rib cage coated with Gorilla™ transparent epoxy glue (Gorilla Glue Company, USA). Various silicones mixed with Asbury Carbons® graphite powder (scattering agent) simulated muscle, adipose, and skin tissues. Soma Foama™ 25 (Smooth-On, Inc., USA) silicone foam simulated the lung tissue.

US/CT multimodal phantoms

Little et al. [36] developed a method for creating abdominal aortic aneurysm phantoms, using 3D-printing with water-soluble materials creating wall-less vascular structures within surrounding tissue. A Polyvinyl Alcohol (PVA) aorta model was placed inside an acrylic box with both ends of the vessel exposed. A polylactic acid-printed spine segment was included to enhance anatomical accuracy. The surrounding tissue was simulated using Gel-wax (Mindsets, UK). Gel-wax is used to create insoluble vessels, and the outer mold is made of a water-soluble polymer. After this, the mold is filled with water, the outer part dissolves, and the internal structure of the vessels is preserved. Glass microspheres were added to the wax at a concentration of 0.5% for acoustic scattering, and then the mixture was poured into an acrylic box around the aorta and spine model. After wax solidification, the box

Table 5: Comparison of human [20-24] and phantom tissues [19]

Tissue	CT density, HU		T1, ms		T2, ms	
	Phantom	Reference	Reference (0.5 T)	Phantom (0.5 T)	Reference (0.5 T)	Phantom (0.5 T)
Carcinoma	87.467	91.920 [20]	-	569	-	58
		72.500 [21]				
		65,94 [22]				
Adipose tissue	-55	-108.750 [22]	102 [23]	131	80 [23]	82
		-68.700 [21]				
Fibroglandular tissue	60.033	65.200 [21]	-	819	-	51
		46.880 [22]				
Pectoral muscle	62.367	52.250 [22]	560 [23]	586	34 [23]	53
		from -29 to 150 [24]				
Skin	132.493	100.750 [22]	-	172	-	73

CT: Computed Tomography, HU: Hounsfield Units, T1: spin-lattice relaxation time, T2: spin-spin relaxation time

Table 6: Relaxation times of test samples with varying castor oil concentrations [25]

No.	Castor oil, %	T1, ms	T2, ms
1	0	1899±70	162±5
2	0	1887±93	162±7
3	5	1740±77	135±8
4	10	1638±47	113±4
5	20	1369±27	79±1
6	30	1040±68	67±2
7	40	755±38	47±1
8	50	575±69	38±2
9	70	287±115	28±1
10	100	156±22	18±1

T1: spin-lattice relaxation time, T2: spin-spin relaxation time

was immersed in de-ionized water for 24 h. The open ends of the mimicked vessel served as entry points for water. The PVA aorta was dissolved, creating wall-less vessels within the tissue-mimicking material.

Ultrasonography visualized the main aortas, renal, and superior mesenteric arteries as hypoechoic areas. The surrounding gel-wax appeared as a homogeneous hyperechoic medium surrounding the vascular network. To

Table 7: Relaxation times of test samples with varying castor oil concentrations [25]

No.	$CaCO_3$, %	$BaSO_4$, %	CT density, HU
1	0	0	-20±9
2	5	0	58±10
3	10	0	190±9
4	20	0	406±12
5	30	0	636±22
6	40	0	906±33
7	30	0.50	791±394
8	30	0.75	551±67
9	30	1.00	641±62
10	30	1.25	761±97
11	30	1.50	1205±179
12	30	1.75	1466±144
13	30	2.00	2203±134
14	40	1.50	3000±137
15	40	2.00	3015±77

CT: Computed Tomography, HU: Hounsfield Units

Table 8: Comparison of relaxation times between phantom materials [34] and corresponding biological tissues [35] as a reference

Tissue	Reference		Composition	Phantom	
	T1, ms	T2, ms		T1, ms	T2, ms
Skin	-	-	Ecoflex™ 00-20	995±1.3	63.79±0.51
Muscles/adipose	1121±148	34	Ecoflex™ 00-10, with 0.12% by weight of Asbury Carbons®)	1100±2.9	40.72±0.63
Lung	-	-	Soma Foama™ 25 silicone foam	1121±21	35.11±0.61

T1: spin-lattice relaxation time, T2: spin-spin relaxation time

improve the vessel visibility on CT, the phantom was immersed in a Visipaque water-iodixanol mixture (GE Healthcare, USA). The test object provided a realistic tissue representation. The contrast agent inside the vessels was clearly distinguishable from the surrounding tissue.

CT/MRI/US multimodal phantoms

Complex clinical problems and risk assessment require test objects compatible with three imaging modalities. Chmarra et al. [37] described the manufacturing process for a multimodal liver phantom suitable for US, CT, and MRI. The phantom hosts three tissue types: liver parenchyma, tumor lesions, and portal veins. Candle gel served as the primary component of liver parenchyma. Homogeneous echogenicity for the parenchyma was achieved using uniformly distributed Sephagex® G2580 beaded gel filtration medium (Sigma-Aldrich, USA). The tumor tissue was simulated using a mixture of agar represented by Agarose A0169 (Sigma-Aldrich, USA), G2580 99% glycerol, and distilled water. Silicone string with star-shaped cross-section simulated portal veins. Comparative analysis of patient and phantom imaging across CT, MRI, and US confirmed the phantom's suitability.

Rethy et al. [38] developed a multimodal liver phantom for laparoscopic surgery, compatible with CT, MRI, and US. The test object included liver parenchyma, blood vessels, tumor inclusions, and gallbladder. A pump system circulated fluid through the portal vein to hepatic veins, draining into the suprarenal inferior vena cava via flexible rubber tubes.

The liver parenchyma was imitated using a mixture of polyurethane Elasturan 6005/264 (BASF Polyurethanes GmbH, Germany) and ISO 136/131 with 0.6% Sephagex® G2580 (Sigma-Aldrich, USA). Portal vein and vena cava segments were created as hollow tubular structures using the parenchymal mixture. The test object hosted three tumor types, namely, metastatic lesions, hepatocellular carcinoma, and benign cysts. The tumors shared the same baseline component as the parenchyma with added 5% calcium carbonate. Metastases were designed as spheres of 1.1 and 1.6 cm in diameter. The same spherical molds with diameters of 1.1 and 1.6 cm were used to create the cysts. The spheres were coated with the mixture from which the parenchyma was made; after the cysts were formed, they were filled with water and sealed. The gallbladder was also made from a mixture of Elasturan 6005/264 and ISO 136/131 polyurethane with 0.6% Sephagex® G2580.

He et al. [39] developed a multimodal breast phantom for quality assurance imaging. The phantom incorporated microcalcifications, affected fibers, and tumors of various sizes. The phantom structure was fabricated using a PVC powder mixed with dioctyl terephthalate plasticizer. 3% of graphite powder was added to enhance US echogenicity. To control the quality of the simulated microcalcifications,

fiber damage, and tumors, four types of inserts were 3D-printed to enable detailed assessment of the imaging characteristics and resolution. Another objective was to provide quality assurance of the detection sensitivity based on the tumor size, depth resolution, and threshold performance capacities across different imaging systems.

The ratio of PVC to plasticizer markedly influenced the imaging properties of the materials. The authors tailored the ratio to closely approximate the characteristics of both breast and tumor tissues. Specifically, the glandular tissues, which exhibit an imaging value of 40 HU [40], were replicated using a ratio of 49.2 g of PVC to 400 mL of plasticizer ($12.3 \times 10{-}2$ g/mL), resulting in a measured imaging value of 36.2 HU. In contrast, for tumor simulation, which registers at 60 HU [41], a concentration of $15.2 \times 10{-}2$ g/mL was employed, yielding an imaging value of 59.4 HU. Notably, the phantom exhibited T1 and T2 relaxation times of 206.81±17.50 ms and 20.22±5.74 ms, respectively, which were shorter than the corresponding values for natural breast tissue. Additionally, the echo velocity measured at 1397.9 m/s facilitated hyperechoic imaging.

The mammograms, MRI scans, and ultrasound images acquired from the multimodal phantom showed detection rates over 90% for microcalcifications, lesions, and tumors, thus demonstrating enhanced lesion detection sensitivity through multimodal fusion.

Comprehensive information on tissue-mimicking materials for multimodal phantom development is summarized in Table 9.

Table 9 shows that for soft tissue modeling, polymers of natural and synthetic origin are typically used in combination with various modifying additives; water-based compositions are used to imitate body fluids, oils for adipose tissue, and gypsum to create bone structures.

Discussion

Multimodal imaging plays an increasingly important role in patient diagnosis, treatment, and monitoring. A critical criterion for clinical implementation is equipment quality assurance, which requires appropriate test objects. Therefore, materials capable of accurately simulating human tissue properties require particular attention. Phantoms must be fabricated from safe, non-toxic materials that maintain structural integrity and characteristics over time. Material selection should focus on properties that align with specific scientific, educational, clinical, or technical research objectives. Numerous materials are already widely employed in phantom fabrication. These include PLA, ABS, thermoplastic elastomers, hydrogels, and aqueous salt solutions. Simultaneously, continuous exploration of new compound classes and their combinations aimed to enhance phantom realism.

Organic gelling agents are safe, inexpensive, and easy to use, and can imitate most tissues by varying concentration and selecting appropriate additives; however, they have a short service life without preservatives. Therefore, periodic replacement of the composition is necessary as performance characteristics decrease or deterioration occurs due to microbial contamination.

Gels can also be used to fill cavities or be cast into molds, for example, to create tissues surrounding lesions or tumors. The use of gels inside complex test object housings can lead to air bubble formation during pouring and create difficulties during subsequent cleaning and composition replacement. Synthetic gel-forming polymers, such as acrylamide, can be used as an alternative to natural polymers.

Gel compositions provide realistic simulation and are often used to model soft tissues, which is especially important for improving imaging system accuracy.

Water-based compositions can reproduce the body's fluid environments, assisting in equipment calibration.

Silicones and polyurethanes are universal materials. The variety of grades with different

Table 9: Tissue-mimicking material compositions for multimodal phantoms

No.	Composition	Simulated tissue	Modality			Advantages/Disadvantages
			Ultra-sound	CT scan	MRI	
1	Agarose gel, gadolinium-based contrast agent, sodium fluoride	Muscle		✓	✓	Inexpensive and easy to manufacture; relaxation time adjustable by varying component concentrations; limited service life requiring periodic replacement
2	Agar, sugar, water, benzalkonium chloride, Triton X-100, safrole oil	Pectoral muscle		✓	✓	Easy to manufacture; requires periodic replacement
3	Silicones	Soft tissues (bladder, prostate, rectum)		✓	✓	Fast curing, heat resistant, wide range of grades with varying properties, long-term stability
4	Polyurethane, silicone oil	Prostate, soft tissue, bladder		✓	✓	Durable, good soft tissue conformity, long-term stability
5	Silicone, graphite powder	Muscle, adipose tissue, skin	✓		✓	Requires careful attention to ensure uniform graphite powder distribution
6	Gel wax, glass microspheres	Soft tissue	✓	✓		Requires careful attention to ensure uniform microsphere distribution
7	Candle gel, gel filtration resin	Liver parenchyma	✓	✓	✓	Provides target signal in all modalities
8	Polyurethane, silicone oil, gel filtration resin	Liver parenchyma	✓	✓	✓	Provides necessary signal in all modalities; requires longer curing time
9	SiC, water, X-100, safrole oil, glycerin, agar, aluminum oxide, KCl, benzalkonium chloride	Fibroglandular tissue		✓	✓	Complex multicomponent composition
10	PVC, dioctyl terephthalate, graphite powder	Mammary glandular tissue	✓	✓	✓	Provides necessary signal in all modalities; requires careful monitoring of uniform graphite powder distribution

No.	Composition	Simulated tissue	Modality			Advantages/Disadvantages
			Ultra-sound	CT scan	MRI	
12	Peanut oil	Adipose tissue		✓	✓	May become rancid over time; requires replacement
13	Olive oil with hardener	Adipose tissue		✓	✓	May become rancid over time; requires replacement
14	Water, NaCl, X-100, polyvinyl acetate, benzalkonium chloride, sugar, safrole oil, olive oil, bees-wax, agar, KCl	Adipose tissue		✓	✓	Complex multicomponent composition
15	Water, X-100, polyvinyl acetate, benzalkonium chloride, sugar, safrole oil	Skin		✓	✓	Complex multicomponent composition
16	Polyethylene fibers impregnated with agarose	Nervous tissue		✓	✓	Simple manufacturing,
17	Silicone foam	Lung tissue	✓		✓	Fast curing time, realistic tissue simulation
18	$CaCO_3$, $BaSO_4$, polyurethane resin	Bone		✓	✓	Requires careful attention to ensure uniform inorganic component distribution
19	PVC, epoxy adhesive	Bone	✓		✓	High strength, fast curing time
20	Gypsum	Cortical bone		✓	✓	Simple manufacturing
21	Silicone, silicone oil	Cancellous bone		✓	✓	Simple manufacturing
22	Agarose, water, gel filtration resin, glycerin	Liver tumors	✓	✓	✓	Provides necessary signal in all modalities; requires periodic replace-ment
23	Polyurethane, silicone oil, gel filtration resin, $CaCO_3$	Liver tumors	✓	✓	✓	longer curing time is required

CT: Computed Tomography; MRI: Magnetic Resonance Imaging, PVC: Polyvinyl Chloride

elasticity and rigidity allows for the creation of strong, durable, and realistic test objects, making them ideal for testing and calibration. Concurrently, it is crucial to select modifying additives that improve acoustic and relaxation properties to match those of biological tissues. Silicones and polyurethanes can be used to fabricate anthropomorphic phantoms, including those with complex configurations, providing high accuracy for developing and testing new diagnostic methods.

Healthy tissues and pathologically altered structures have different magnetic, acoustic, optical, and thermal properties. Some materials simulate healthy human tissue, while others are designed to recreate pathological conditions. Given inter-individual differences in tissue composition, no ideal material exists for tissue simulation. However, modifying composition and selecting appropriate ratios of known components helps create the most realistic characteristics. This approach is particularly useful for comprehensive quality control of new radiation therapy methods and surgical planning. Another promising area is the development of multimodal test objects with integrated software for medical equipment quality control.

Multimodal phantoms open the way for conducting experiments without putting patients' health at risk, optimizing early-stage research methods, calibrating equipment, and qualitative comparisons across different devices and image processing algorithms. Such test objects are powerful tools for training medical professionals in US guidance and practical skills before they work with real patients [37]. They are capable of ensuring a realistic representation of the patient's anatomy, assisting in learning specific equipment, and helping evaluate possible surgical intervention scenarios.

According to the results of our study, the market offers a limited number of multimodal phantoms, and the manufacturing technologies are both expensive and labor-intensive.

As the field progresses, new materials and innovative combinations of existing compositions are needed to better simulate human tissue. Additionally, lowering production costs is crucial to speed up the development of anthropomorphic test objects tailored for specific tasks [42]. 3D printing offers a promising solution. This technology can work with diverse materials and accurately replicate complex human organ structures.

Limitations of the review

Only anthropomorphic multimodal phantoms were considered; geometric phantoms were excluded from this analysis. Materials used exclusively for individual modalities (ultrasound, CT, or MRI) were also excluded.

It is important to note that numerical values of human biological tissue parameters, against which test object characteristics are compared, can be affected by study temperature and time parameters, equipment specifications, and settings (e.g., ultrasound wave frequency of 1, 3, or 5 MHz; MRI magnetic field strength of 1.5 or 3 T).

Conclusion

This paper reviews materials suitable for multimodal phantoms simulating various human tissues. The reviewed materials are easily accessible and relatively inexpensive. They can replicate human anatomy and simulate medical imaging characteristics of human tissues across several modalities. Further improvements to multimodal test objects could expand their use for simulating patient-derived tissues and training medical procedures.

When developing a multimodal phantom, several key aspects must be considered. First, the scope of use should be defined, including the applicable imaging modalities, necessary functionalities, and the specific anatomical regions, organs, or tissues to be simulated. Next, the purpose of the phantom must be determined, whether for scientific research, medical education, device quality control, or other applications. Additionally, the required simulated properties, such as the presence or

absence of pathological conditions, must be specified. Finally, the design of individual modules and the overall phantom architecture must be carefully planned. Subsequently, appropriate material compositions must be selected, the phantom fabricated, and testing performed to evaluate imaging characteristics across selected modalities.

The selection and identification of appropriate modeling compositions can be time-consuming and resource-intensive. Comprehensive information on various compound classes and their signal characteristics can significantly streamline this process. Therefore, the attention and efforts of the research teams are concentrated on creating new compositions with characteristics more suitable for modelling human tissues.

Authors' Contribution

The study was conceptualized by VY. Alexandrovich. The investigation was carried out by Ch. Marina Valeryevna and Zh. Zhou. The methodology was developed by O. Olga Vasilievna. Formal analysis was performed by VY. Alexandrovich. The original draft of the manuscript was written by Ch. Marina Valeryevna. The manuscript was reviewed and edited by L. Denis Vladimirovich and JFS. Costa-Júnior. All authors read, revised, and approved the final version of the manuscript.

Funding

This article was prepared by a team of authors as part of the research project "Materials and phantoms for calibration of diagnostic equipment and simulation training".

Conflict of Interest

None

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