Formulation and Characterization of Gypsum and Silicone-Based Materials Based On Hounsfield Unit Values As A Basis For Developing Anthropomorphic Phantoms On Ct-Scan

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Abstract.
Computed tomography (CT) imaging requires phantoms with tissue-equivalent Hounsfield Unit (HU) values, but commercial anthropomorphic phantoms are expensive and have limited flexibility. This study aims to formulate and characterize gypsum and silicone-based materials based on HU values as a basis for developing anthropomorphic CT phantoms. The study used a quantitative Research and Development (R&D) design with the ADDIE model. The population included potential materials for phantoms and anonymized CT images of patient heads. The sample consisted of six material formulas (two gypsum, four silicone) and 20 patient CT images. Instruments included a multislice CT scanner, a DICOM viewer with ROI tools, and precision measurement equipment. Data analysis used descriptive statistics on density, mean HU, percentage error, coefficient of variation (CV), HU difference between ROIs, and physical stability. The results showed that five of the six formulas met the accuracy criteria (error ≤15%), namely cortical gypsum (1.2%), trabecular gypsum (4.8%), muscle silicone (0.5%), gray matter silicone (9.9%), and white matter silicone (5.9%). Skin silicone exceeded the limit (26.2%). All materials showed excellent repeatability (CV 0.15–1.10%). The silicone material was homogeneous (HU difference ≤5 HU), while the gypsum was not homogeneous (12.7–13.0 HU). All phantoms were physically stable. Gypsum and silicone materials have the potential to be economical candidates for anthropomorphic CT phantoms, with the need for optimization of the skin silicone formula and gypsum homogeneity.
Keywords: Computed Tomography, Gypsum, Hounsfield Unit, Anthropomorphic Phantom, Silicone

I. INTRODUCTION

Computed Tomography (CT) imaging plays a crucial role in the diagnosis and management of various clinical conditions due to its high spatial resolution for detailed visualization of hard and soft tissues [1]. CT is used in diagnostics, oncology, orthopedics, and medical intervention planning. One important parameter is the Hounsfield Unit (HU), which is used to differentiate the density characteristics of various tissues. The HU value is influenced by image quality, reconstruction algorithm, exposure parameters, and object characteristics [2].

The HU value is also influenced by chemical composition, density, porosity, material homogeneity, and scanning parameters [3]. Therefore, material characteristics are an important aspect in the development of CT phantoms. Phantoms are used for image quality evaluation, HU calibration, density linearity testing, slice thickness, and artifacts. Phantom materials must have an X-ray attenuation response that resembles biological tissue, so formulation and characterization are required based on HU values, repeatability, homogeneity, and physical stability [4], [5].

The development of CT phantoms faces challenges such as limited design flexibility and composition of commercial phantoms, as well as high costs. These conditions make it difficult for educational institutions and healthcare facilities with limited financial resources to conduct CT testing independently, necessitating the development of more economical and adaptable local materials [6].

The cost of commercial phantoms is becoming increasingly significant in their use for HU evaluation and learning activities. The high price of phantoms can be a barrier for educational institutions, despite their benefits as training materials and image quality evaluation. Therefore, alternative local materials are needed that are economical, readily available, and have HU characteristics that closely mimic biological tissue [7].

The development of locally available phantoms using economical and easily modified materials remains limited. Gypsum has a suitable density to represent bone tissue, while silicone has physical characteristics that support its use as a soft tissue representation [8], [9]. Previous studies have demonstrated the potential of gypsum and silicone as phantom materials, but their characterization remains limited. Therefore, a more comprehensive evaluation based on HU values, repeatability, homogeneity, and physical stability is needed as a basis for the development of anthropomorphic phantoms.

This study aims to formulate and characterize gypsum and silicone-based materials based on Hounsfield Unit (HU) values as the basis for developing anthropomorphic phantoms for CT-Scan. This study is expected to produce radiological and physical characteristics data for local materials that are economical and easy to develop. The novelty of the study lies in the formulation of cylindrical gypsum and silicone materials with evaluation of HU values, suitability to biological tissue, repeatability, homogeneity, and physical stability as the basis for developing anthropomorphic phantoms for CT-Scan learning and research.

II. METHODS

This study uses a Research and Development (R&D) method with a quantitative approach and experimental design to formulate and characterize gypsum and silicone-based materials based on Hounsfield Unit (HU) values as the basis for developing anthropomorphic phantoms on CT-Scans. The development uses the ADDIE model which includes Analysis, Design, Development, Implementation, and Evaluation. The data obtained are in the form of material density, mean HU, standard deviation, percentage error, coefficient of variation (CV), HU difference between ROIs, and physical stability which are analyzed descriptively quantitatively.

The research instruments included a multislice CT-Scan, image analysis software or DICOM viewer, ROI measurement tool, digital scales, measuring cups, calipers or precision rulers, and a camera or mobile phone. HU measurements were performed using an 80 mm^2 ROI in the center area of the material with predetermined CT parameters. Analysis included material density using the formula $\rho = m/V$, mean HU and standard deviation, percentage error against biological tissue, repeatability based on CV from three scans, homogeneity based on the difference in HU between ROIs, and physical stability through observation of material conditions. Operational criteria included error ≤15%, CV ≤5%, homogeneity of gypsum ≤10 HU and silicone ≤5 HU, and the absence of major physical damage.

The study population consisted of materials with the potential to be used as phantoms for HU testing on CT scans, as well as head CT images as comparative data for biological tissue. The samples consisted of six gypsum- and silicone-based material samples, as well as 20 anonymized patient head CT images. Gypsum was used as a candidate representation of cortical and trabecular bone, while silicone was used as a candidate representation of skin, muscle, gray matter, and white matter. The units of analysis included HU values, density, error percentage, CV, HU difference between ROIs, and material physical stability.

The research procedure follows the ADDIE model. The Analysis stage is carried out through literature studies and identification of phantom material requirements, the Design stage includes formula design and cylindrical samples using acrylic tubes, the Development stage is carried out through the creation and optimization of six trial gypsum and silicone formulas, the Implementation stage is carried out through CT-Scan scanning and HU measurements using ROI, while the Evaluation stage is carried out by analyzing density, HU suitability, accuracy, repeatability, homogeneity, and physical stability. The material is then assessed based on established operational criteria as the basis for the development of anthropomorphic phantoms.

This study used phantoms as the primary object and anonymized CT images of the patient's head as secondary data. The use of laboratory facilities, CT scans, and image data was carried out after obtaining permission from the relevant institutions. The study adhered to patient data confidentiality, the safety of materials and work procedures, radiation safety, and academic integrity by presenting all measurement results as they were obtained without manipulation.

Material manufacturing was conducted at the Postgraduate Laboratory of the Ministry of Health Polytechnic of Semarang and CT-Scan scanning was conducted at the Radiology Installation of Hospital in Central Java, Indonesia. The research included literature studies and needs identification from January to October 2025, design planning from December 2025 to January 2026, formula creation and optimization from January to March 2026, CT testing in March 2026, measurement and characterization from March to April 2026, analysis from April to May 2026, and product refinement in May 2026.

III. RESULTS AND DISCUSSION

Material Sample Making Results

The study yielded six cylindrical material samples, consisting of two gypsum formulations as candidates for bone tissue representation and four silicone formulations as candidates for soft tissue representation. Phantoms were fabricated using separate acrylic tubes, with the silicone measuring 5 cm in diameter and 4 cm in height and the gypsum measuring 6 cm in diameter and 5 cm in height. This design facilitated ROI placement and individual HU measurement. Physically, gypsum has a dense and rigid structure, while silicone is elastic and relatively homogeneous. All phantoms had stable shapes, relatively smooth surfaces, and showed no cracks, deformations, or large air cavities, making them ready for use in CT-Scan testing.

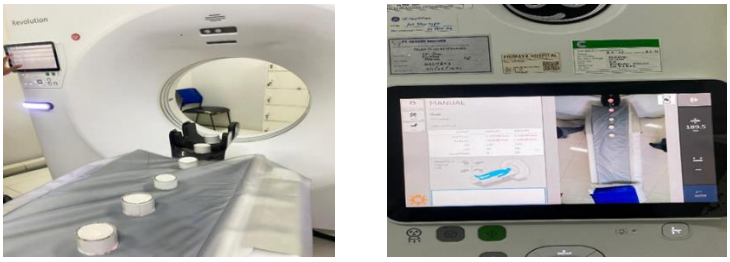
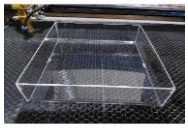


Fig. 1. Documentation of phantom during CT-Scan testing

Table 1 Research Tools

No	Tool Name	Tool Image	Amount	Function
1.	Acrylic mold		6 PCS	Forming a phantom ac-cordinglytwo-compartment design
2.	Digital scales		1 Set	Measuring the mass of materi-als(Gypsum and silicone)
3.	Measuring cup		1 Set	Measuring the vol-ume of water orliquid ingredi-ents
4.	Mixing con-tainer		4 pcs	Place for mixing ingredients
5.	Spatula		1 Set	Stir the mix-tureGypsum and silicone to make it homogeneous
6.	Gloves		1 Set	Protect hands dur-ing the mixing process

7.	Ruler		1 Set	Measuring phantom dimensions
8.	Digital measuring spoon		1 Set	Measuring the topic precisely
9.	Mini hand mixer		1 Set	Homogenize the mixture of ingredients
10.	CT-Scan Machine		1 Set	Performing a phantom scan
11.	Computer/ laptop		1 Set	Managing and analyzing CT data results
12.	Weasis	WEASIS	1 Set	Measuring HU value to measure ROI

Table 2 Research Materials

No.	Material Name	Material Image	Amount	Function
1.	Gypsum		Kg	Bone tissue replacement materialon phantom.
2.	Silicon Rubber		Kg	Replacement materialsoft tissue on the phantom.
3.	Harden Silicone		Gr	Helps the curing/hardening processan silicone

4.	Acrylic		Pcs	Container for forming phantoms

Table 3 Phantom Material Composition

Material type	Representativethe Network	Material	composition	Function
Gypsum	Cortical bone	Gypsum	159.05 g	Basic material forming solid bone structure
		Calcium carbonate	27.15 g	Increasedensity and mixing
		fine sand	13.86 g	Strengthen and compact the structure
		Water	44.53 g	Hydration mediaand mixing
Gypsum	Trabecular Bone	Gypsum	148.44 g	Basic material for the formation of porous bone structures
		Calcium Carbonate	27.15 g	Increasing density in a control
		fine sand	23.76 g	Helping to shape the structure thatmore per pore
		Water	47.47 g	Increaseporosity and helps hydration
Silicone	Skin	Silicon Rubber RTV	100 g	Basic forming materialssoft tissue structure
		Silicone Oil	15 g	Lowermaterial density
		Hollow	6 g	Reduce
		microball oons		density and increase porosity
		RTV Catalyst	5 g	Triggering the curing process
Silicone	Muscle	Silicone rubber RTV	100 g	Basic forming materials soft tissue structure
		Silicone Oil	15 g	Set the material density so that approaching the HU of the muscle
		RTV Catalyst	5 g	Triggering the curing process
Silicone	Gray Matter Brain	Silicone rubber RTV	100 g	Basic forming materials soft tissue structure
		Silicone oil	12 g	Moderately reduce density
		Hollow microball oons	2 g	Fine adjustment of HU value
		Pigment	0.05 g	Dye
		RTV Catalyst	5 g	Triggers for the curing process
Silicone	Brain white matter	Silicone rubber RTV	100 g	Basic materials forming soft tissue structures
		Silicone oil	16 g	Lowering the density further
		Hollow microball Oons	3 g	Lowering the HU value further
		Pigment	0.05 g	Dye

	RTV Catalyst	5 g	Triggering the curing process

Table 4 Physical Evaluation of Phantom

No.	Physical Parameters	Evaluation results
1.	Gypsum material structure	Has a solid and rigid structure
2.	Structure of silicone material	Elastic and relatively homogeneous
3.	Phantom surface condition	The surface is relatively smooth and flat
4.	Physical disability	No major defects found such as significant cracks or air cavities

Based on Table 4, the phantom is in good physical condition. Gypsum is dense and rigid, while silicone is elastic. The surface is relatively smooth without major defects, making the phantom stable for radiological testing.

Table 5 Evaluation of the Phantom Creation Process

No.	Evaluation Aspects	Evaluation Results
1.	TimeGypsum Hardening	About 24 hours
2.	Silicone curing time	About 24 hours
3.	Homogeneity of the mixture	Classified as good, indicated by the absence of separation materialsignificant and relatively even distribution of structures
4.	Manufacturing Process Constraints	Determination of the material formula so that the HU value of gypsum and silicone is close human bone and soft tissue tissue
5.	Process replication	The manufacturing method is capable of producing products repeatedly with relatively uniform results.

The phantom fabrication process was deemed consistent and produced material suitable for radiological testing and has the potential for replication.

Phantom Material Density Results

$$Densitas = \frac{massa}{volume}$$

Table 6 Density of Gypsum and Silicone Materials

Material	Total Mass (g)	olume (cm3)	ensity (g/cm3)
Cortical Gypsum	292.3	141.37	2.07
Trabecular Gypsum	292.4	141.37	2.07
Silicone Skin	134.6	78.54	1.71
Muscle Silicone	143.4	78.54	1.83
Gray Matter Silicone	140.4	78.54	1.79
Silicone White Matter	135.4	78.54	1.72

Based on Table 4.6, the phantom density is calculated from the mass of the material divided by its volume. The volume of gypsum is 141.37 cm³, while the volume of silicone is 78.54 cm³, based on the size of each compartment.

CT Parameters and ROI Measurement Techniques

Table 7 CT-Scan Parameters

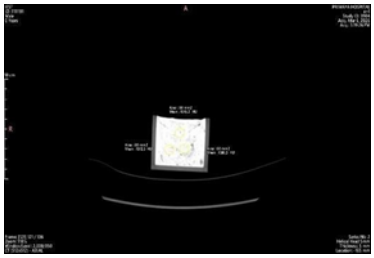
Parameter	Mark
KVp	120 kVp
Sir	AEC (actual mAs 52 mAs)
Slice thickness	5 mm
Kernel reconstruction	Helical Head 5 mm
FOV	250 mm
Matrix	512 X 512
Window Width / Window Level for bones	WW 2000 HU / WL 350 HU

Window Width / Window Level for software networking	WW 100–110 HU / WL 35–40 HU
ROI	80mm2

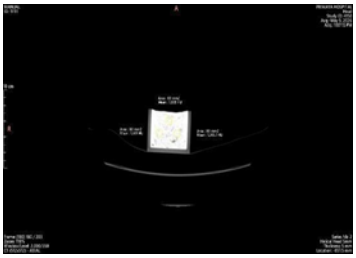
Scanning used 120 kVp, AEC with actual mAs 52 mAs, slice thickness 5 mm, FOV 250 mm, and matrix 512 × 512. These parameters were used to obtain stable images and support HU measurements. WW/WL settings were adjusted to the material, namely bone window for gypsum and soft tissue window for silicone. HU measurements were performed using an ROI of 80 mm² in the center of the material consistently to reduce the effects of partial volume and edge effects. The mean HU values, standard deviation, minimum, and maximum were then used to analyze the accuracy, repeatability, and homogeneity of the material.

CT Image Results and ROI Placement

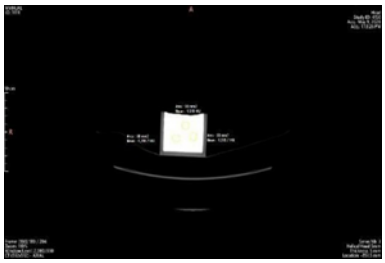
The CT scan results showed that all phantom materials could be clearly visualized in axial images. Gypsum material as a representation of bone appeared more hyperdense than silicone as a representation of soft tissue, indicating differences in X-ray attenuation capabilities. The images selected for measurement were slices with intact, homogeneous material and had clear boundaries. ROIs measuring 80 mm² were placed at three points in the center of each material, namely cortical gypsum, trabecular gypsum, and silicone representing skin, muscle, gray matter, and white matter. ROI placement was done to avoid material edges, inter-compartmental boundaries, artifacts, and partial volume effects. A bone window was used for gypsum material and a soft tissue window for silicone material, while the window settings only affected visualization and did not change the HU value. The values obtained included the average HU, standard deviation, minimum, and maximum, which were then used for accuracy, repeatability, and homogeneity analysis. Thus, the CT images were deemed suitable for quantitative analysis of Hounsfield Unit values.



(a) Scan 1

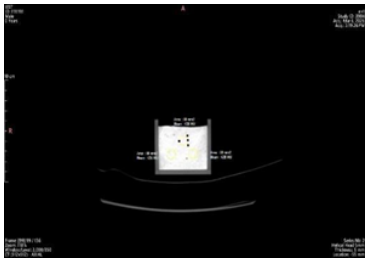


(b) 2nd Scan

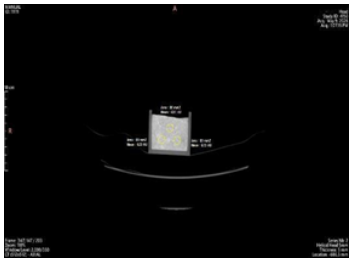


(c) 3rd Scan

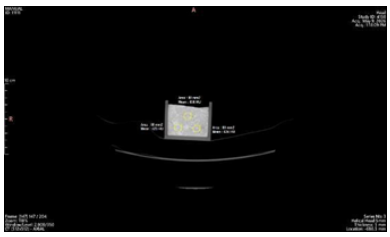
Fig. 2 CT Image Results and ROI Placement on Cortical Bone Gypsum Material



(a) Scan 1

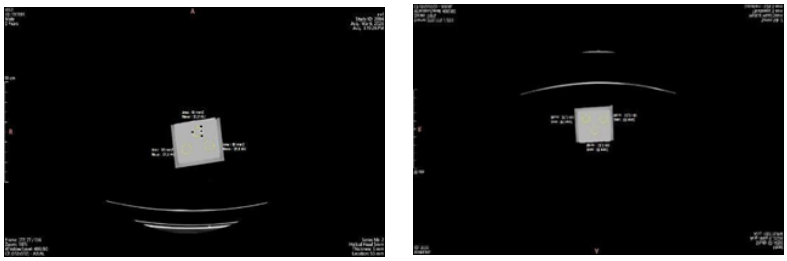


(b) 2nd Scan

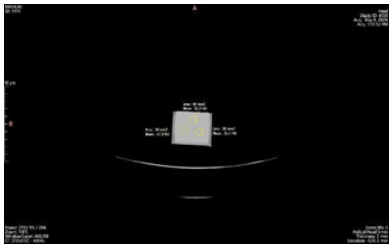


(c) 3rd Scan

Fig. 3. CT Image Results and ROI Placement on Trabecular Gypsum Material

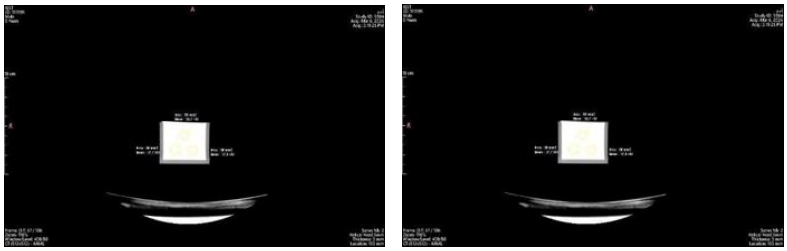


(a) Scan 1 (b) 2nd Scan

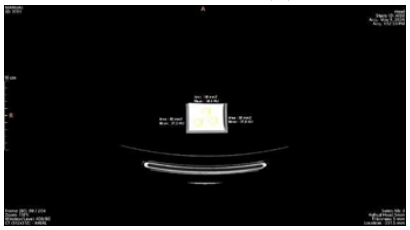


(c) 3rd Scan

Fig. 4. CT image results and ROI placement on silicone skin material

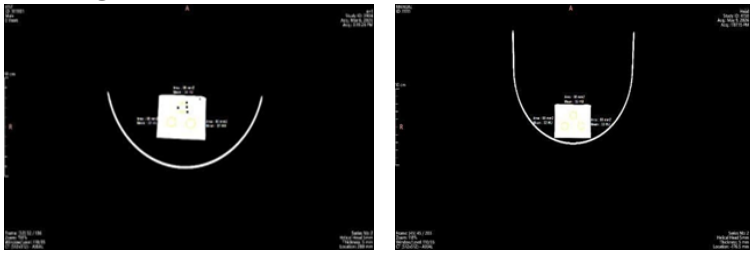


(a) Scan 1 (b) 2nd Scan

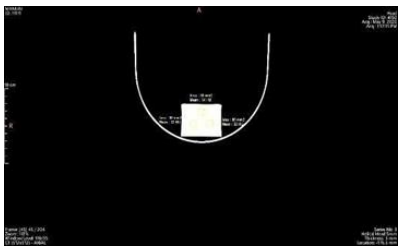


(c) 3rd Scan

Fig. 5 CT Image Results and ROI Placement on Muscle Silicone Material

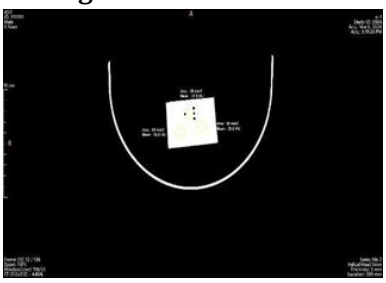


(a) Scan 1 (b) 2nd Scan

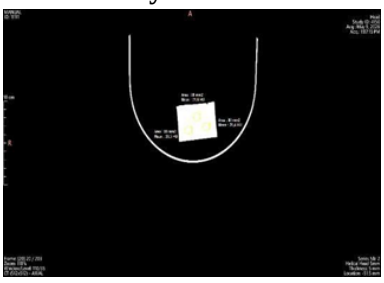


(c) 3rd Scan

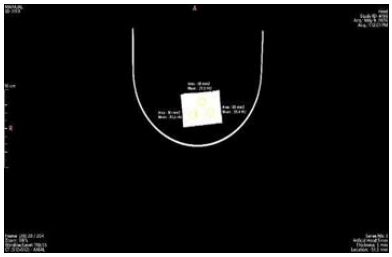
Fig. 6 CT Image Results and ROI Placement on Gray Matter Silicone Material



(a) Scan 1



(b) 2nd Scan



(d) 3rd Scan

Fig. 7 CT Image Results and ROI Placement on White Matter Silicone Material

Based on the CT image results and ROI placement, it can be concluded that all phantom materials can be analyzed quantitatively. Consistent ROI placement on each material supports the validity of the HU value measurements, so the obtained data can be used for accuracy analysis of human biological tissue, repeatability, and homogeneity of the phantom material.

Hounsfield Unit (HU) Phantom Measurement Results

Table 8 Hounsfield Unit (HU) Phantom Measurement Results

Material	Network	Scan Ke-	ROI 1 (HU)	ROI 2 (HU)	ROI 3 (HU)	Mean	Standard Deviation (SD)
Gypsum	T.Cortical	1	1315.2	1300.3	1313.3	1309.6	8.1
Gypsum	T.Cortical	2	1308.0	1305.1	1301.0	1304.7	3.5
Gypsum	T.Cortical	3	1310.0	1293.7	1299.7	1301.1	8.2
Gypsum	Trabecular	1	636.0	628.0	624.0	629.3	6.1
Gypsum	Trabecular	2	637.0	623.0	623.0	627.7	8.1
Gypsum	Trabecular	3	636.0	624.0	623.0	627.7	7.2
Silicone	Skin	1	33.5	35.8	37.8	35.7	2.2
Silicone	Skin	2	33.5	35.8	37.2	35.5	1.9
Silicone	Skin	3	33.5	35.7	37.2	35.5	1.9
Silicone	Muscle	1	38.7	37.8	37.7	38.1	0.6
Silicone	Muscle	2	38.5	37.9	37.3	37.9	0.6

Silicone	Muscle	3	38.5	37.8	37.3	37.9	0.6
Silicone	Gray Matter	1	34.0	32.0	32.0	32.7	1.2
Silicone	Gray Matter	2	35.0	33.0	32.0	33.3	1.5
Silicone	Gray Matter	3	34.0	32.0	32.0	32.7	1.2
Silicone	White Matter	1	21.9	20.8	20.8	21.2	0.6
Silicone	White Matter	2	21.6	20.4	20.5	20.8	0.7
Silicone	White Matter	3	21.5	20.4	20.4	20.8	0.6

Based on Table 8, there are differences in Hounsfield Unit (HU) values for each phantom material. The mean value is the average of the three ROIs, while the SD indicates the variation in HU values between ROIs. The smaller the SD, the more uniform the distribution of HU values.

Cortical bone gypsum had the highest mean value, namely 1301.1–1309.6 HU, with SD 3.5–8.2, indicating high attenuation characteristics and a fairly uniform HU distribution. Trabecular bone gypsum had a mean of 627.7–629.3 HU with SD 6.1–8.1. The values were lower than cortical gypsum, but still higher than all silicone materials, in accordance with the differences in density and X-ray attenuation capabilities.

In silicone materials, the HU values are lower, namely skin silicone of 35.5–35.7 HU, muscle 37.9–38.1 HU, gray matter 32.7–33.3 HU, and white matter 20.8–21.2 HU. The SD values are also relatively small, namely 1.9–2.2 in skin, 0.6 in muscle, 1.2–1.5 in gray matter, and 0.6–0.7 in white matter, which indicates good measurement homogeneity.

Overall, gypsum exhibited higher HU and attenuation values, making it suitable for representing bone tissue, while silicone had lower HU values and was more suitable for representing soft tissue. These results can then be compared with the HU values of reference human tissue to assess the suitability of the phantom material.

Hounsfield Unit Measurement Results in Human Biological Tissue as Comparative Data

Table 9 Distribution of ROI Measurements in Human Biological Networks

No.	Network	ROI area	Number of Patients	ROI Per Patient	Total ROI
1.	Cortical Bone	10 mm²	20	3	60
2.	Trabecular Bone	20 mm²	20	3	60
3.	Muscle	70 mm²	20	3	60
4.	Skin	15 mm²	20	3	60
5.	Gray Matter	15 mm²	20	3	60
6.	White Matter	70 mm²	20	3	60
Total					360

Based on Table 9, HU measurements were performed on six tissue types from 20 patients. Each tissue was measured with three ROIs per patient, resulting in 60 ROIs per tissue and a total of 360 ROIs. These data were used as a comparison for the HU values of human biological tissues.

Table 10 Results of Hounsfield Unit Measurements in Human Biological Tissue

No.	Network	ROI area	Number of Patients	Total ROI	Overall Mean HU	Standard Deviation (SD) Overall	Min HU	Max HU
1.	Cortical Bone	10 mm²	20	60	1321.5	111.2	1145.8	1529.8
2.	Trabecular Bone	20 mm²	20	60	659.7	74.5	534.5	769.3
3.	Muscle	70 mm²	20	60	37.8	2.9	33.4	43.1
4.	Skin	15 mm²	20	60	28.2	4.9	21.4	35.2
5.	Gray Matter	15 mm²	20	60	36.5	3.1	32.5	43.2
6.	White Matter	70 mm²	20	60	22.2	1.4	20.3	26.5

Based on Table 10, cortical bone has the highest Mean HU of 1321.5 HU, followed by trabecular bone at 659.7 HU. In soft tissue, the Mean HU is muscle 37.8 HU, gray matter 36.5 HU, skin 28.2 HU, and white matter 22.2 HU, respectively. This pattern is in accordance with CT characteristics, namely bone has higher attenuation than soft tissue.

HU variation between patients is greater in bone tissue than in soft tissue, which may be influenced by differences in anatomy and tissue density. These human tissue HU data were then used as a comparison to assess the suitability of gypsum materials to bone and silicone materials to soft tissue.

Analysis of the Accuracy of HU Material Values Against Comparative Data

Table 11 Analysis of Accuracy of HU Values of Phantom Materials against Human Biological Tissue

No.	Phantom Material	Reference Network	Mean HU-Material	Mean HURef-erence	HU Difference	Error %	Accuracy Interpretation
1.	Cortical Bone Gypsum	Cortical bone	1305.1	1321.5	16.4	1.2	Meets accuracy criteria
2.	Trabecular Bone Gypsum	Trabecular bone	628.2	659.7	31.5	4.8	Meets accuracy criteria
3.	Muscle Silicone	Muscle	38	37.8	0.2	0.5	Meets accuracy criteria
4.	Silicone Skin	Skin	35.6	28.2	7.4	26.2	Does not meet accuracy criteria
5.	Silion Gray Matter	Gray Matter	32.9	36.5	3.6	9.9	Meets accuracy criteria
6.	Silicone White Matter	White Matter	20.9	22.2	1.3	5.9	Meets accuracy criteria

Based on Table 11, five of the six phantom materials met the error tolerance limit of ≤15%. Cortical bone gypsum had an error of 1.2% and trabecular bone gypsum 4.8%. For silicone, the errors were 0.5% for muscle, 9.9% for gray matter, and 5.9% for white matter, respectively. These results indicate that these materials have HU values that are quite consistent with the biological tissues they represent.

Meanwhile, the skin silicone had an error of 26.2%, falling short of the accuracy criteria. This indicates that the skin silicone formulation still needs to be optimized to more closely match its attenuation characteristics and HU values to human skin tissue.

Overall, 5 of the 6 phantom materials met the accuracy criteria, while the silicone skin requires further development.

Repeatability Analysis of Phantom Material HU Values

Table 12 Repeatability Analysis of HU Values of Phantom Material

No.	Phantom Material	Mean HUScan 1	Mean HUScan 2	Mean HUScan 3	Overall Mean HU	Standard Deviation (SD)	CV (%)	Repeatability Interpretation
1.	Cortical Bone Gypsum	1309.6	1304.7	1301.1	1305.1	4.3	0.33	RepeatabilityVery good
2.	Trabecular Bone Gypsum	629.3	627.7	627.7	628.2	0.9	0.15	RepeatabilityVery good
3.	Silicone Skin	35.7	35.5	35.5	35.6	0.1	0.32	RepeatabilityVery good
4.	Muscle Silicone	38.1	37.9	37.9	38.0	0.1	0.30	RepeatabilityVery good
5.	Silkon Gray Matter	32.7	33.3	32.7	32.9	0.3	1.05	RepeatabilityVery good

6.	Silicone White Matter	21.2	20.8	20.8	20.9	0.2	1.10	RepeatabilityVery good

Based on Table 12, all phantom materials have CV values below 5%, thus they are included in the very good repeatability category. Cortical bone gypsum has a CV of 0.33% and trabecular gypsum 0.15%, while skin silicone has 0.32%, muscle 0.30%, gray matter 1.05%, and white matter 1.10%. Low CV values indicate relatively small inter-scan HU variations and good measurement consistency. Thus, all phantom materials have very good HU value stability on repeated scans with the same CT-Scan parameters.

Material Homogeneity Analysis

Table 13 Analysis of Phantom Material Homogeneity

No.	Phantom Material	HU Difference Scan 1	HU Difference Scan 2	HU Difference Scan 3	Average Difference HU	Tolerance Limit	Interpretation of Homogeneity
1.	Cortical Bone Gypsum	14.9	7.0	16.3	12.7	≤10 HU	Less homogeneous
2.	Trabecular Bone Gypsum	12.0	14.0	13.0	13.0	≤10 HU	Less homogeneous
3.	Silicone Skin	4.3	3.7	3.7	3.9	≤5 HU	Homogeneous
4.	Muscle Silicone	1.0	1.2	1.2	1.1	≤5 HU	Homogeneous
5.	Gray Matter Silicone	2.0	3.0	2.0	2.3	≤5 HU	Homogeneous
6.	Silicone White Matter	1.1	1.2	1.1	1.1	≤5 HU	Homogeneous

Based on Table 13, cortical and trabecular bone gypsum have HU differences of 12.7 HU and 13.0 HU, respectively, so they do not meet the homogeneity limit of ≤10 HU. Meanwhile, all silicone materials have HU differences of ≤5 HU and are declared homogeneous. Thus, silicone materials are more homogeneous than gypsum, while variations in gypsum are likely caused by uneven material distribution or the presence of porosity and air bubbles.

Final Evaluation and Initial Validation of Material Characteristics

Table 14 Phantom Validation and Feasibility

Parameter	Results	Criteria	Status
HU Accuracy	Five of the six materials met the accuracy criteria. Cortical bone gypsum, trabecular bone gypsum, muscle silicone, gray matter silicone, and white matter silicone had an error of ≤15%, while skin silicone had an error of 26.2%.	Error ≤15%	Partially fulfilled
Repeatability	All phantom materials had CV values ≤5%, with a CV range of 0.15%–1.10%.	CV ≤5%	Fulfil
Material homogeneity	The silicone material was declared homogeneous because the average HU difference was ≤5 HU. The cortical bone gypsum and trabecular bone gypsum materials did not meet the homogeneity criteria because the average HU difference was 12.7 HU and 13.0 HU, respectively.	Gypsum ≤10 HU; silicone ≤5 HU	Partially fulfilled
Material stability	The phantom maintains a stable physical structure during the CT-Scan process so that all material compartments can be visualized and ROI measurements can be made consistently without significant defor-mation interference.	No major cracks, no deformation, and no large cavities that interfere with the measurement.	Fulfil

Based on Table 14, five of the six formulas had an error value of ≤15%, while the skin silicone had an error of 26.2%, thus still requiring optimization. All formulas had good repeatability with CV ≤5%. In terms of homogeneity, all silicone materials met the limit of ≤5 HU, while gypsum did not meet the limit of ≤10 HU. Overall, gypsum and silicone materials have the potential to be used as components of anthropomorphic CT-Scan phantoms, with further optimization of the skin silicone and gypsum materials.

Discussion

Discussion of Formulation Results and Phantom Material Manufacturing

This study successfully developed a cylindrical CT-Scan phantom using gypsum as a bone representation and silicone as a soft tissue representation. Physically, the phantom has a stable structure, a fairly smooth

surface, and no damage that interferes with HU measurements. The separation of the compartments allows each material to be evaluated based on HU values, accuracy, repeatability, homogeneity, and stability. These results indicate that the phantom is suitable as a preliminary product, although improvements in several parameters are still needed to improve its suitability as a CT-Scan quality test phantom.

Discussion of Material Density and Its Relationship with Hounsfield Unit Values

Material density influences the HU value, where materials with higher densities tend to produce higher HU. Gypsum has a higher HU value, namely 1305.1 HU in cortical bone and 628.2 HU in trabecular bone, making it suitable for representing bone tissue. Meanwhile, silicone produces a lower HU, namely 20.9–38.0 HU, making it more suitable as a representation of soft tissue. These differences indicate that gypsum and silicone are capable of producing different attenuation characteristics according to the target tissue. However, the HU value is not only influenced by density, but also by chemical composition, homogeneity, water content, air voids, and CT scanning parameters.

Discussion of the Proximity of Material HU Values to Comparative Data of Biological Tissues

The results showed that most phantom materials had HU values close to the target biological tissue. Cortical gypsum (1305.1 HU) and trabecular gypsum (628.2 HU) were in accordance with their reference values, making them good for representing bone tissue. In the silicone group, muscle silicone (38.0 HU), gray matter (32.9 HU), and white matter (20.9 HU) also showed good agreement with the reference tissue. However, skin silicone (35.6 HU) was still higher than the reference (28.2 HU), requiring reformulation. Overall, gypsum and silicone have the potential to be used as candidate CT-Scan phantom materials, with further optimization especially in the skin silicon formula.

Discussion of the Accuracy of HU Values of Phantom Materials

The results of the accuracy analysis showed that five of the six phantom materials met the error criteria of ≤15%, namely cortical bone gypsum (1.2%), trabecular bone gypsum (4.8%), muscle silicone (0.5%), gray matter silicone (9.9%), and white matter silicone (5.9%). Muscle silicone had the best accuracy due to the lowest error. Meanwhile, skin silicone had an error of 26.2%, so it did not meet the criteria and required composition optimization to reduce the HU value to be closer to skin tissue. Overall, gypsum and silicone showed potential as anthropomorphic phantom materials, although the formula of skin silicone still needs to be refined.

Discussion of Repeatability of HU Values in Repeated Scans

The results showed that all phantom materials had excellent repeatability, indicated by CV values below 5%, namely 0.15–1.10%. This indicates that gypsum and silicone are capable of producing stable and consistent HU values in repeated CT scans with the same parameters. Although the silicone skin did not meet HU accuracy, the material still had good repeatability, so the problem was more related to the suitability of the composition to the skin tissue, rather than measurement stability. Thus, repeatability is one of the main strengths of the developed phantom.

Discussion of the Homogeneity of HU Values of Phantom Material

The results showed that all silicone materials had good homogeneity, with a difference in HU of 1.1–3.9 HU, thus meeting the limit of ≤5 HU. In contrast, gypsum did not meet the homogeneity criteria, with a difference of 12.7 HU in cortical bone and 13.0 HU in trabecular bone, exceeding the limit of ≤10 HU. The inhomogeneity of gypsum is likely caused by particle sedimentation, distribution of calcium carbonate and fine sand, variations in water content, and the formation of micro-voids. Therefore, optimization of the mixing, pouring, and hardening processes is required to ensure a more uniform distribution of density and HU values of gypsum.

Final Interpretation of Material Characteristics and Development Potential of Anthropomorphic Phantoms

Overall, the study shows that gypsum and silicone materials have the potential to be developed as anthropomorphic CT-Scan phantom materials. Five of the six formulas have a HU error of ≤15%, all materials have good repeatability with CV ≤5%, and show stability of HU values for more than two months. The silicone material also has good homogeneity, while gypsum still requires homogeneity improvement. Thus, this local material has the potential to be used for learning, basic research, and simple HU evaluation, but still requires

formula optimization, development of anatomical shapes, and validation on various parameters and CT devices before it can be used as a standard phantom or a replacement for commercial phantoms.

IV. CONCLUSION

This study shows that gypsum and silicone-based materials have potential as candidates for anthropomorphic CT-Scan phantom materials. Five of the six formulas met the criteria for accuracy of HU values with an error of ≤15%, all formulas showed good repeatability with CV ≤5%, and the materials remained physically stable throughout the observation period. All silicone materials met the homogeneity criteria of ≤5 HU, while cortical and trabecular bone gypsum did not meet the limit of ≤10 HU. Skin silicone is a formula that still requires optimization because it has an error of 26.2%. Practically, the developed materials have the potential to be used as learning media, basic research, and simple evaluation of HU values with materials that are relatively easy to obtain and economical.

Limitations of this study include the limited number of formulas and samples, the use of a single scanning protocol and a single CT scanner, and the relatively simple phantom shape that does not fully mimic complex human anatomy. The evaluation also did not cover all CT scan quality testing parameters and cross-device validation. Further research is recommended to optimize the composition of the skin silicone, improve the homogeneity of the gypsum through standardization of the mixing and hardening process, and develop a more representative anthropomorphic design. Testing on various CT parameters and different devices, including long-term stability evaluation, is also needed to strengthen validation. The results of this study can be the basis for the development of a more economical local phantom before being directed as a standard phantom.

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