

Technical Note

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Design and Construction of a Low-Cost Multipurpose Phantom for Quality Control of B-Mode Ultrasound Imaging

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Abstract

Periodic performance evaluation of ultrasound imaging systems is necessary to guarantee image quality and measurement accuracy in clinical practice. Nevertheless, commercial quality control phantoms are often costly and not readily accessible. This technical note describes the design and development of a low-cost, multipurpose tissue-mimicking phantom intended for routine quality control of ultrasound B-mode imaging systems. A compact, space-efficient phantom was constructed using a water-based tissue-mimicking material formulated from gelatin, agar, glycerin, and acoustic scatterers. Embedded targets were arranged to enable key standardized QC tests recommended by international quality control guidelines, including dead-zone assessment, axial and lateral resolution, distance-measurement accuracy, image uniformity, and depth penetration. A simplified, repeatable measurement protocol was implemented using clinical ultrasound systems under fixed imaging conditions.

The proposed phantom supports multiple quality control tests within a single structure, making it a suitable candidate for routine system verification and operator training. Its low cost and straightforward fabrication provide a practical alternative to commercial phantoms, especially in resource-limited areas.

Keywords Medical imaging, Ultrasound, Quality control, Multipurpose phantom.

1. Introduction

Nowadays, medical devices are widely used across various medical fields. Even the best medical measuring instruments and equipment are affected by wear and tear, environmental changes, and other factors, which can reduce their accuracy over time. The accuracy of instrument readings, one of the most important parameters for

medical devices, indicates how closely the equipment's test results match the true value. Given the importance of human health, periodic verification, safety, and performance testing of medical devices, adherence to national and international standards, quality control tests, and calibration are essential for reliable measurements. The importance of periodic quality assurance programs for



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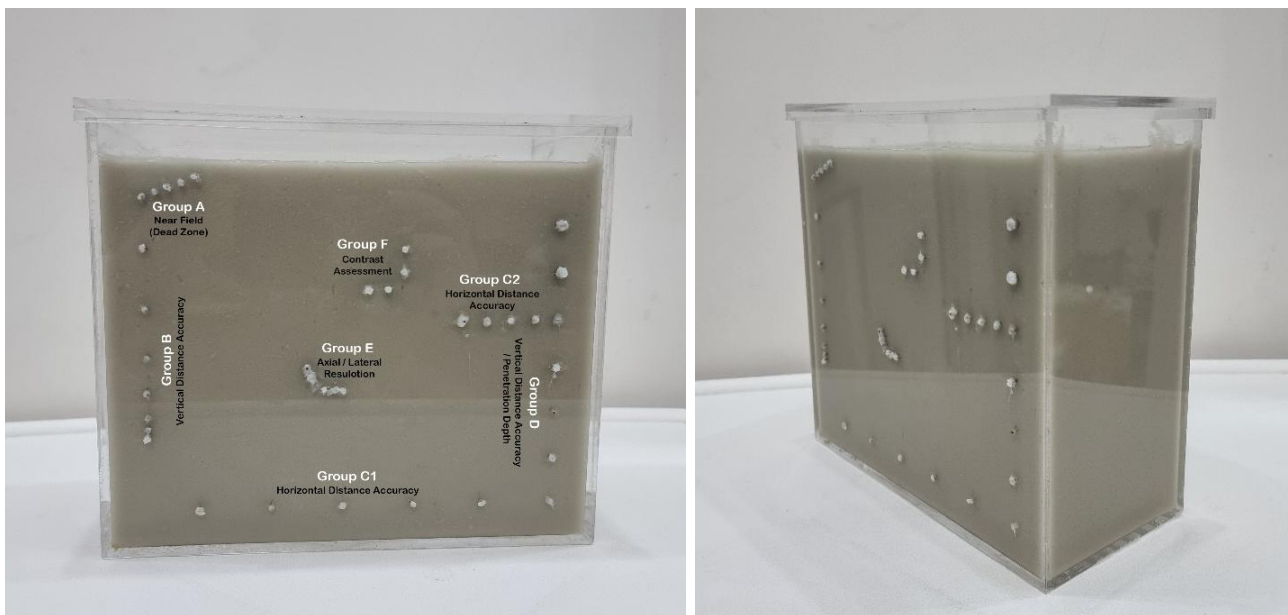


Fig 1. Front and side views of the constructed multipurpose ultrasound quality control phantom with labeled internal target groups.

medical devices has been increasingly recognized over the past decade. Such programs offers many advantages, such as maximizing effectiveness in delivering reliable treatment and minimizing risks to patients and operators, as well as unnecessary expenses. [1].

With the continuous advancement of medical imaging technologies for disease diagnosis and monitoring, ensuring the accuracy and proper functioning of these systems has become critically important. Quality control and regular periodic calibration procedures are among the most effective approaches to maintain the reliability and diagnostic accuracy of imaging equipment. One of the essential tools in this field are imaging phantoms, which can serve as a multipurpose tissue-mimicking model that enables evaluation of imaging parameters and calibration of the devices. [2, 3].

In this research, the focus was on a multipurpose quality control phantom designed and fabricated to assess the performance of ultrasound systems, featuring acoustic characteristics comparable to those of human soft tissue. The developed phantom was constructed to facilitate the simultaneous implementation of multiple quality control tests, which were set by relevant institutions. [4].

Material and Methods

Phantom Design Requirements

The design requirements for the proposed phantom were established to facilitate routine quality control of B-mode ultrasound imaging systems with a single, integrated structure. The phantom was intended to support multiple

standardized image quality and performance tests while maintaining a compact geometry suitable for routine clinical and educational use.

Among the most important design criteria were acoustic similarity to soft tissue, mechanical stability during repeated scanning, and compatibility with conventional clinical ultrasound probes. The structure of the internal targets was selected to enable evaluation of essential B-mode quality-control parameters, including image resolution, geometric accuracy, penetration depth, and image uniformity.

In addition, the phantom design emphasized low-cost fabrication, ease of preparation with readily accessible materials, and reproducible construction. Thus, the phantom incorporated various internal target groups to support evaluations of resolution, distance accuracy, image uniformity, contrast assessment, penetration depth, and beam characteristics and focal-zone assessment. These requirements were intended to provide a practical alternative to commercial quality-control phantoms, while maintaining the ability to perform standardized performance assessments under repeatable imaging conditions. [5].

Phantom Materials and Fabrication

The phantom was fabricated using a water-based tissue-mimicking material formulated to approximate the acoustic behavior of soft tissue while remaining low-cost and easy to prepare. The base material consisted of distilled water blended with gelatin and agar as gelling agents to provide mechanical strength and structural sta-

bility. Glycerin was added to adjust the acoustic properties, particularly sound velocity and attenuation, to appropriate values for diagnostic ultrasound imaging [6, 7, 8]. The mixture contained low-to-moderate concentrations of aluminum oxide and silicon carbide particles as acoustic scatterers to simulate realistic speckle patterns and increase backscatter uniformity in B-mode images. In addition, a small amount of benzalkonium chloride was included as a preservative to control the growth of bacteria and improve the long-term stability of the phantom [7]. The phantom housing was constructed from a clear plexiglass container, enabling visual inspection of internal structures during fabrication. The wire targets were mechanically fastened to the inner walls of the container before the tissue-mimicking mixture was cast. This fixation method prevented target displacement during pouring and solidification, ensuring accurate preservation of the intended target geometry and spatial configuration. [2, 9, 10]. All materials were selected for their availability and ease of handling; thus, the phantom could be fabricated without specialized laboratory equipment. The mixture was heated to a temperature sufficient to ensure complete dissolution of the solid components, thereby achieving a homogeneous distribution of the aluminum oxide and silicon carbide particles. After preparation, the tissue-mimicking mixture was carefully poured into the plexiglass container containing pre-positioned targets. Then, the phantom was allowed to cool and solidify at room temperature, resulting in a stable structure suitable for repeated ultrasound scanning under routine quality control conditions. The phantom was stored under refrigerated conditions to maintain material stability between imaging sessions. This construction method enabled reproducible fabrication while minimizing preparation complexity and cost.

Target Configuration and Phantom Geometry

The internal target configuration of the phantom was de-

signed to enable multiple B-mode quality-control tests within a single integrated structure. Targets were arranged at predetermined depths and lateral positions in accordance with standardized quality-assurance requirements, enabling systematic evaluation of key image-quality parameters. The target layout and spatial configuration were designed in accordance with established quality control guidelines and were consistent with the internal structures of commercially available, standard-compliant ultrasound phantoms. [10, 11].

The internal geometry of the phantom was designed within a plexiglass container with internal dimensions of 210 mm × 100 mm × 180 mm (length × width × height). Approximately 20 mm of the upper section remained unfilled during fabrication; therefore, the effective tissue-mimicking region and target arrangement occupied a depth of approximately 160 mm.

The phantom incorporated seven distinct target groups (A, B, C1, D, C2, E, and F), each designed to support specific ultrasound quality-control assessments. Most target groups were constructed using wire targets with a uniform diameter of 1 mm, except for Group D, which included wire targets with progressively decreasing diameters (2.7, 2.2, 1.7, 1.2, 1.0, 0.8, and 0.6 mm) to evaluate depth penetration and visualization performance at different target sizes.

Group A consisted of five wire targets positioned in a stepwise arrangement near the phantom surface at depths ranging from 5 to 13 mm, with a spacing of 2 mm between adjacent wire targets to support dead-zone evaluation. Group B included seven vertically aligned wire targets beginning at a depth of 32 mm for vertical distance accuracy measurements. Unlike the other target groups, which employed uniform spacing between adjacent wire targets, Group B was designed with progressively decreasing intervals. The separation between consecutive wire targets was 25, 20, 15, 10, 5, and 3 mm, respective-

Table 1. Phantom specifications

Housing Material:	Clear plexiglass (wall thickness = 4 mm)
Overall Dimensions:	210 mm × 100 mm × 180 mm
Scanning Surface:	210 mm × 100 mm × 160 mm
Phantom weight:	5.2 kg
Tissue-mimicking Material:	Water-based tissue-mimicking material
Speed of sound:	1540 m/s at 23°C
Targets Material	Metal wire

ly. This configuration was intended to support vertical distance accuracy evaluation, focal-zone assessment and beam profile evaluation.

Group C1 consisted of five horizontally aligned wire targets located near the lower region (140 mm) of the phantom with 30 mm lateral spacing to assess horizontal distance accuracy.

Group D contained seven vertically distributed wire targets separated by 20 mm intervals along the depth direction to evaluate penetration depth, beam response characteristics, lateral response width, and vertical distance accuracy. As previously mentioned, the progressively decreasing wire diameters enabled assessment of visualization performance across different target sizes.

Group C2 consisted of four wire targets positioned adjacent to the third target of Group D at a depth of 60 mm for horizontal distance accuracy near the surface.

Group E contained eight closely spaced wire targets positioned within an approximately 12 mm region near the center of the phantom, and the lateral spacing between adjacent wire targets from left to right was 3, 3, 3, 4, 3, 1 and 2 mm, respectively to support axial and lateral resolution evaluation. In addition, Group F consisted of four wire targets incorporating small attached beads to simu-

late high-contrast targets and tissue inclusions for qualitative contrast assessment. The spacing between adjacent wire targets in this group was approximately 10 mm.

The different target groups were designed to support several standardized B-mode quality-control evaluations. Closely spaced wire targets were incorporated to assess axial and lateral resolution by determining the minimum resolvable distance between adjacent reflectors. Linear target arrangements with known separations were incorporated to evaluate the accuracy of distance measurements and geometric fidelity. In addition, homogeneous regions without discrete targets were included to assess image uniformity and background speckle characteristics. The test setup consisted of targets positioned at increasing depths to evaluate penetration depth characteristics. Hence, the spatial positions of the target groups were selected to minimize overlap between test regions while enabling multiple measurements to be acquired efficiently in a single imaging session. [2, 10].

The overall phantom geometry was designed to be compact and space-efficient, ensuring compatibility with conventional clinical ultrasound transducers. The integrated target geometry enables thorough B-mode quality-control assessments with a single phantom.

Table 2. Geometric characteristics and internal target configuration of the proposed multipurpose ultrasound phantom.

Target Group	Number of targets	Approximate Depth	Inter-target Spacing	Wire Diameter	Primary QC Application
Group A	5	5-13 mm	2 mm	1 mm	Dead-zone evaluation
Group B	7	32-110 mm	25, 20, 15, 10, 5, 3 mm	1 mm	Vertical distance accuracy, Focal-zone assessment and beam-profile evaluation
Group C1	5	140 mm	30 mm	1 mm	Horizontal distance accuracy
Group D	7	20-140 mm	20 mm	2.7, 2.2, 1.7, 1.2, 1.0, 0.8, 0.6 mm	Penetration depth and beam-response evaluation
Group C2	4	60 mm	10 mm	1 mm	Horizontal distance accuracy
Group E	8	80-92 mm	3, 3, 3, 4, 3, 1, 2 mm	1 mm	Axial and lateral resolution
Group F	4	30-47 mm	10 mm	1 mm	High-contrast target assessment

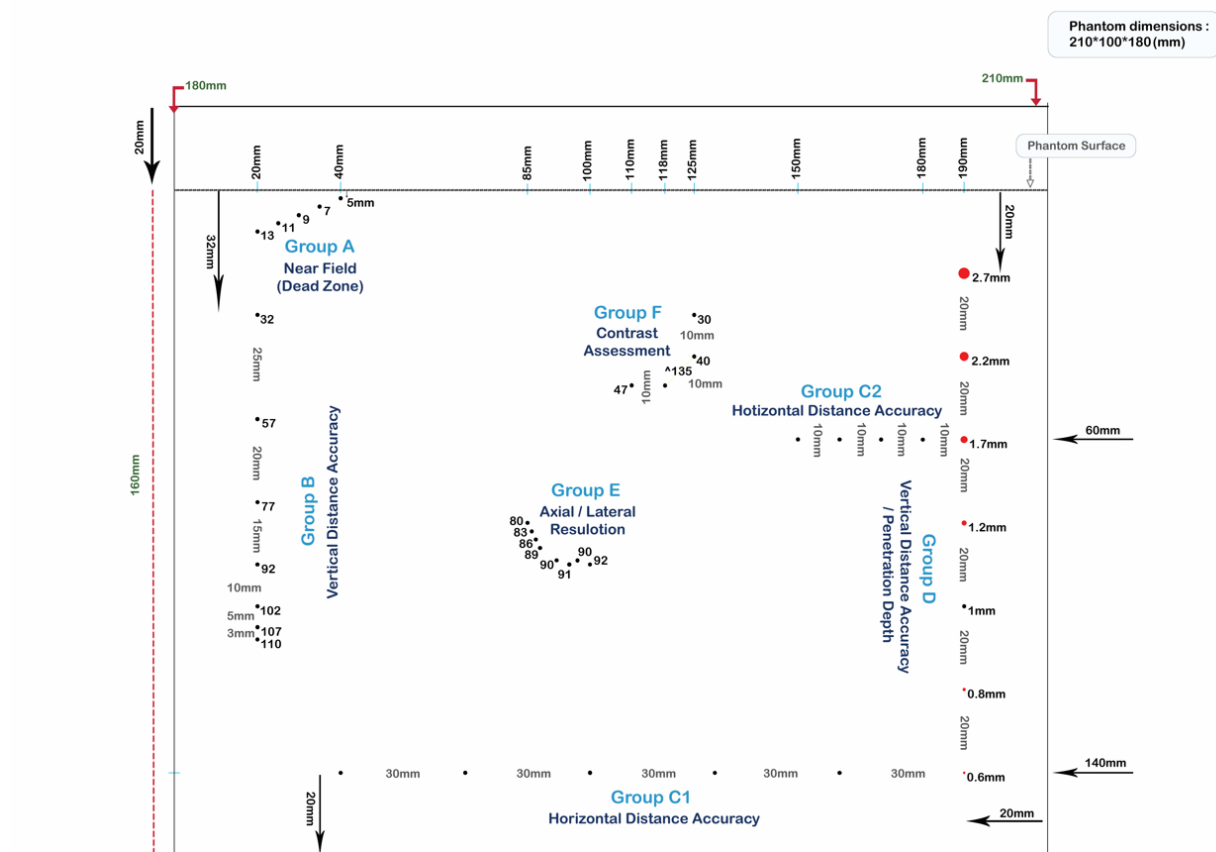


Fig 2. Schematic representation of the internal target configuration of the proposed multipurpose ultrasound phantom, including groups of A, B, C1, D, C2, E and F, designed for dead-zone evaluation, vertical and horizontal distance accuracy measurements, penetration-depth assessment and high-contrast target assessment.

Experimental Setup and Imaging Protocol

Ultrasound imaging experiments were performed using clinical diagnostic ultrasound systems operating in B-mode. Two transducers were employed: a linear probe and a phased-array probe. The appropriate transducer was selected according to the depth range of the corresponding target group for each quality control test. The linear probe was used for shallow measurements, and the phased-array probe was used for deep targets. The effective imaging depth of the phantom was approximately 16 cm, corresponding to the thickness of the tissue-mimicking material. Accordingly, for each test, the transducer was selected based on the target depth. [12].

The transducer was placed directly over the designated target group for each test, and image-quality factors such as gain, dynamic range, focal-zone position, transmit frequency, and time-gain compensation (TGC) were adjusted at the beginning of the measurement. After achieving the desired image quality, all subsequent measurements for the selected test were conducted with fixed imaging settings, without further adjustments. The quantitative quality control tests, including uniformity, dead zone,

vertical and horizontal distance measurement accuracy, axial and lateral resolution, and penetration depth, were performed independently three times to assess measurement consistency and ensure compliance with acceptable tolerance limits; the mean values were then used for analysis. In addition, several qualitative tests were performed, including evaluations of the focal-zone, beam profile, as well as gray-scale contrast based on visual image assessment [2, 13, 14]. All measurements were made on the ultrasound system display using the built-in measurement tools.

The experimental protocol was designed in accordance with routine clinical quality control practices, enabling repeatable, practical assessment of ultrasound imaging performance using the proposed multipurpose phantom.

Results

The proposed multipurpose phantom successfully supported both quantitative and qualitative quality control tests under routine B-mode imaging conditions. The obtained images enabled clear visualization of the embedded target groups at the phantom's effective imaging depth.

Table 3. Summary of quantitative quality-control test results for the proposed multipurpose ultrasound phantom

QC Test	Nominal Value (mm)	Measured Mean Value (mm)	Relative Error (%)	Acceptance Limit	Result
Dead zone	5	5.0	0	≤ 5 mm	Pass
Vertical distance accuracy	20	20.2	1%	± 2 mm	Pass
Horizontal distance accuracy	20	20.3	1.5%	± 2 mm	Pass
Penetration depth ¹ (Linear probe, 7-10 MHz)	100	98	2%	Acceptance criterion: Visualization depth close to the expected 100 mm range for the linear probe	Pass
Penetration depth (Phased-array probe, 2-4 MHz)	160	≥ 160 (limited by phantom depth)	N/A ²	Full phantom depth coverage (≤ 160 mm)	Pass
Axial resolution	1	1.0	0	≤ 1 mm	Pass
Lateral resolution	1.2	1.3	8.3%	≤ 1.5 mm	Pass

Quantitative measurements from repeated independent trials indicated that the phantom's performance remained consistent and stable across all evaluated parameters. Mean values from three independent measurements for each quantitative test closely matched the known geometric dimensions of the embedded targets. Across all quantitative tests, the measured deviations were within acceptable tolerance limits defined by international quality control guidelines, as summarized in Table 3. All quantitative tests met the acceptance criteria defined by the corresponding standards.

In addition to the quantitative assessments, qualitative evaluations confirmed the phantom's suitability for routine quality control applications. Image uniformity, contrast visibility, beam characteristics, and focal-zone performance were clearly observable using the appropriate transducers. Furthermore, during a 60-day observation period under refrigerated storage conditions, no structural deformation, target displacement, mold formation, cracking, liquid separation, odor generation, or deterioration in image quality was observed during repeated scanning sessions.

Table 4. Summary of qualitative quality-control assessments

QC Test	Evaluation Method	Acceptance Criterion	Result
High-contrast target assessment	Visual	Clear visualization and complete target discrimination	Pass
Image uniformity	Visual	Uniform image without brightness reduction	Pass
Beam profile	Visual	Normal beam focusing and symmetry	Pass
Focal-zone assessment	Visual	Maximum clarity at focal depth	Pass
Lateral response width	Visual	Minimum width at focal region	Pass
Gray-scale contrast	Visual	Complete differentiation of gray-scale levels	Pass

Overall, the results indicated that the proposed phantom provided reliable, repeatable, and standard-compliant performance across a variety of B-mode quality control evaluations.

Discussion

This study demonstrates that a low-cost, water-based multipurpose phantom can effectively support routine B-mode ultrasound quality-control evaluations in accordance with established international standards. This phantom contains multiple test targets within a compact structure, enabling comprehensive evaluation of the system without requiring multiple specialized phantoms. The quantitative results confirmed that the measurement discrepancies across all tests were well within the acceptable limits set by international quality control guidelines, including recommendations from organizations such as AIUM, AAPM, and IEC. The use of repeated independent measurements not only enhanced reliability but also enabled assessment of measurement consistency under standard imaging conditions. These findings suggest that the constructed phantom can provide stable, repeatable performance comparable to that of commercially available quality control phantoms.

The qualitative assessments also confirmed that the phantom was suitable for routine quality control applications. The clear representation of image uniformity, contrast behavior, beam characteristics, and focal-zone performance showed that the acoustic properties of the tissue-mimicking material and the spatial arrangement of targets were appropriate for diagnostic ultrasound imaging. The proposed design offers several advantages over com-

mercial multipurpose phantoms, including reduced fabrication costs, ease of preparation with readily available materials, and flexibility in phantom geometry and target configuration. [4, 15]. These features make the phantom suitable for routine quality assurance, educational purposes, and research applications even in resource-limited settings.

Since the proposed phantom was fabricated using water-based tissue-mimicking materials, long-term stability was considered during the evaluation process. The phantom was stored under refrigerated conditions between imaging sessions and was allowed to reach room temperature before ultrasound examinations.

During a 60-day observation period, including repeated quality-control measurements and imaging sessions, no visible mold formation, cracking, liquid separation, odor generation, structural deformation, or target displacement was observed. In addition, no deterioration in image quality was detected during the repeated assessments. These findings indicate that the proposed phantom maintained acceptable structural and imaging stability under the applied storage conditions throughout the evaluation period. Although no deterioration in imaging performance was observed during the evaluation period, further long-term studies including repeated measurements of acoustic properties such as sound velocity and attenuation would be useful to fully characterize phantom stability.

Although the present study focused on B-mode imaging performance, the phantom design can be adapted to support additional ultrasound modalities following long-term stability evaluation and further structural modifications.

Conclusion

This paper describes the design, fabrication, and evaluation of a low-cost multipurpose phantom for routine quality control of B-mode ultrasound imaging systems. The proposed phantom integrates multiple standardized test targets within a compact structure and was constructed using readily available, water-based tissue-mimicking materials.

The experimental results showed that the phantom provided stable, repeatable, and compliant performance with respect to international standards across a wide range of quantitative and qualitative quality-control tests. All quantitative evaluations were conducted in accordance with the acceptance criteria set out in the respective international guidelines, confirming that the multipurpose design can be reliably used for routine system verification. Because this phantom has a low fabrication cost, an easy preparation method, and a flexible target configuration, it represents a practical alternative to commercial phantoms. Overall, the proposed phantom provided a practical solution for expanding routine ultrasound quality assurance in clinical, educational, and resource-limited settings.

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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