

Photopolymer Ultrasound Phantoms: Measured Acoustic Properties and Evidence Requirements for Tissue Equivalence

Engineering review

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Abstract

Measured acoustic properties of printed photopolymers provide a basis for evaluating ultrasound phantom materials, but measurement alone does not establish tissue equivalence. This review considers three primary studies at explicitly limited access depth and distinguishes material characterisation from comparison with a named tissue. The studies concern different frequency ranges, processes and reference tissues; their results are not pooled into a common performance estimate. The engineering contribution is a proposed equivalence-assessment record connecting the material state, acoustic observable, measurement conditions, tissue reference and acceptance criterion. No numerical equivalence tolerance is established here. Elastography and tactile simulation are outside the evaluated claim. The result is a bounded account of what the inspected evidence supports and what a stronger tissue-equivalence claim would still require. An illustrative equivalence analysis distinguishes a measured difference from satisfaction of a justified margin and preserves frequency and specimen history.

Keywords: ultrasound phantom; photopolymer; sound speed; attenuation; tissue comparison; equivalence; measurement

1. Scope and access boundary

The engineering question is whether acoustic measurements on a photopolymer can support a specified tissue-equivalence claim. This requires distinguishing a measured property from the application-dependent judgement that it is sufficiently representative. The present review does not qualify a particular phantom or imaging system. X-ray attenuation and radiographic workflows remain outside its scope and belong to ER-191.

The evidence comprises two studies inspected at bibliographic-record and abstract depth and one inspected through selected publisher full-text sections. The assessment does not claim full-method verification of all three studies. Its proposed reporting structure is original engineering analysis, not a consensus standard or a validated acceptance procedure.

2. What the inspected studies establish

Jacquet and colleagues measured acoustic velocity, impedance and attenuation for six photopolymerised materials over 15–55 MHz and developed high-frequency imaging phantoms [1]. Their abstract identifies a surrounding medium with acoustic properties close to human skin. This supplies a named-tissue comparison at abstract depth, but the present assessment extracts no numerical equivalence tolerance from it.

Chen and colleagues examined gelatin and a modified photocured resin for biomimetic phantoms [2]. Selected methods and results distinguish resin comparisons with trabecular bone and intervertebral disc from gelatin-related observations. The abstract appears to reverse the hard/soft material ordering relative to the detailed account. This inconsistency is retained as an interpretation limitation. No ambiguous assignment is converted into a quantitative equivalence conclusion, and gelatin puncture observations are not assigned to the resin. A problematic printed molecular-weight unit is not adopted.

Bakaric and colleagues characterised eight photopolymer materials produced by PolyJet and stereolithography over 1–3.5 MHz [3]. The abstract reports sound speeds of 2020–2630 m/s and attenuation typically in the range 3–9 dB/(MHz cm). These are aggregate material-characterisation ranges, not values for a single specimen, named-tissue acceptance bands or a recommendation. The inspected abstract does not establish tissue equivalence.

3. Preserve the measurement context

The three studies should remain separate evidence records. The different frequency intervals alone prevent treating their reported values as measurements of one common condition. Differences in material, preparation, specimen and target tissue add further distinctions. This review performs no frequency extrapolation, material ranking or pooled estimate.

A proposed record would retain the material identifier, printing route, specimen geometry, conditioning, measurement method, frequency interval and reported uncertainty where available. An omitted descriptor would be marked unavailable. It would not be filled from another study of a similarly named material. This preserves the distinction between the conditions actually examined and the conditions a future application might require.

4. Specify the target before judging equivalence

An equivalence assessment could identify the named tissue, the particular acoustic observable and the use for which agreement is required. Sound speed, attenuation and impedance would remain separate observables. Agreement in one would not be treated as an automatic result for the others.

The tissue comparator would also need a defined source and conditions. A nominal label such as skin or bone is not, within the proposed assessment, a complete acceptance specification. A record could distinguish the reported comparator value from the allowable deviation selected for the intended use. The latter is a decision criterion requiring justification; it must not be created retrospectively merely to accommodate the material being assessed.

No universal tolerance is proposed here. The reviewed evidence at the inspected access depth does not provide a transferable numerical criterion spanning these studies and tissue targets.

5. Distinguish specimen agreement from phantom performance

A material coupon and an assembled phantom represent different assessment objects. The proposed framework would retain their results separately and identify any inference linking them. A phantom-level claim might concern a particular imaging task or geometry, while a coupon measurement concerns the material under its test conditions.

The framework asks for a task-specific test when the claim moves from material characterisation to system performance. It does not infer a need for any particular proprietary construction or prescribe how to manufacture the phantom. It also does not assume that geometrical resemblance supplies an acoustic acceptance result.

6. Handle uncertainty and source inconsistency explicitly

A proposed comparison record would distinguish variability among specimens, measurement uncertainty and uncertainty in the tissue reference wherever those components are reported. A range across several materials is a different quantity and should not be used as a specimen uncertainty estimate. Missing uncertainty prevents some comparisons; it does not justify assigning zero uncertainty.

Where a source contains conflicting descriptions, the record should preserve the conflict and state which conclusions are withheld. A later clarification or direct examination of underlying data could change that assessment. Until then, selecting the convenient description would make the conclusion less traceable. This principle is particularly relevant to the inconsistent material assignment noted for [2].

7. Define equivalence as a comparison with a named reference

The proposed equivalence assessment begins with the target tissue, frequency range, temperature and measurement configuration. Let c_P and c_T denote measured sound speeds for a phantom and a named tissue reference under comparable conditions. Their difference is one observable. A separate comparison is needed for attenuation as a function of frequency. Agreement in sound speed does not determine agreement in attenuation, scattering or mechanical response.

Before analysing a candidate, the investigator would define a justified margin for the specific use. A confidence interval lying inside that margin could support a bounded equivalence claim under the adopted statistical model. Failure to find a significant difference would not establish equivalence. If the margin is absent, the defensible report is a difference with uncertainty, not a pass/fail statement.

For illustration, suppose a hypothetical phantom differs from its reference by 2% in speed, with an interval extending from -1% to +5%. A margin of $\pm 3\%$ would not be satisfied by that interval even though its central value lies inside the margin. The numbers are illustrative and are not proposed tissue-equivalence tolerances. They show why a central estimate alone cannot close the claim.

8. Retain frequency and specimen history in the evidence table

An expanded comparison would list each material at the tested frequencies and distinguish measured attenuation from a fitted frequency dependence. A coefficient normalised by frequency should not be treated as a universal constant when the underlying dependence has not been established over the receiving band. Extrapolation beyond measured frequencies would be labelled as a model prediction and would carry the model assumptions.

The same table would retain specimen thickness, orientation, conditioning and measurement method when available. Repeated readings of one specimen describe a different source of variation from independent prints, and independent prints from one material batch do not establish between-batch reproducibility. The analysis should preserve those levels rather than assigning every reading the same independence.

For a proposed phantom programme, the next experiment would follow the largest decision-relevant uncertainty: material variation, frequency response, geometry, conditioning or reference uncertainty. Elastographic and tactile claims would remain separate because they require different observables. This framework permits the three retained acoustic sources to be compared critically without pooling their unlike tissues, routes and frequency bands into a fictitious average phantom.

9. Critical evidence comparison across manufacturing routes

Jacquet et al. [1] investigated a photopolymer-jetting phantom for high-frequency ultrasound imaging. Chen et al. [2] investigated biomimetic phantoms using modified gelatin and photocured printed resin in a context directed toward ultrasound-guided minimally invasive procedures. Bakaric et al. [3] measured ultrasonic attenuation and dispersion in printed photopolymer materials over 1 to 3.5 MHz. The three studies provide complementary but non-equivalent evidence: an imaging phantom demonstration, a composite biomimetic preparation and a frequency-resolved materials measurement. The existence of a viable phantom geometry is not evidence that a formulation matches multiple tissue acoustical properties; conversely, agreement in attenuation over a specified frequency range does not establish imaging fidelity for an anatomical device.

Frequency is central to the interpretation. Bakaric et al. [3] provide attenuation and dispersion measurements over a stated band; their results should not be assumed valid at the higher frequencies examined in some imaging-phantom settings without separate measurement. The printing process also changes the evidence target: jetting, layerwise photocuring of bulk resins and hybrid hydrogel-resin assemblies may differ in voids, interfaces, acoustic impedance and viscoelastic response. Any synthesis must preserve specimen provenance, orientation, formulation, exposure and post-processing before comparing reported performance.

10. Acoustic-property budget and coupled image response

A minimum acoustic dataset should distinguish longitudinal sound speed, frequency-dependent attenuation, acoustic impedance, backscatter or scattering structure where relevant, and the variability of these quantities across a fabricated part. Impedance depends on both density and sound speed; matching one does not necessarily match the other. Imaging performance also depends on the transducer and pulse sequence, coupling medium, boundary geometry and beam path. Thus image contrast or perceived echogenicity cannot serve as a substitute for direct acoustic characterization.

Useful uncertainty reporting includes measurement bandwidth, calibration reference, temperature, hydration or immersion history, repeated positions within a specimen and between-build variability. Nonuniform attenuation across printed strata can produce path-dependent image artefacts even where a bulk-averaged measurement appears reasonable. Material characterization and application-level

performance should be treated as related, separately evidenced outcomes rather than collapsed into a single assertion of tissue equivalence.

11. Geometry, stability and service conditions

Anatomical fidelity and acoustic fidelity require distinct acceptance tests. Printed channel diameter, wall thickness, void incidence and surface roughness should be recorded against a defined reference geometry. Ultrasound-guided intervention phantoms additionally require needle visibility, insertion force, puncture damage and repeated-use stability where relevant. Soft tissue-like deformation cannot be inferred from static shape alone. A realistic-looking phantom may fail as a training tool if insertion dynamics or imaging response are inconsistent with the specified tissue target.

Photopolymer networks can change when immersed, aged or thermally cycled. Repeat acoustic-property measurements after conditioning should therefore be linked to mass uptake, dimensional change and mechanical response. This is a proposed qualification approach, not evidence that the cited studies demonstrated every failure mode. If a phantom combines dissimilar materials, interface adhesion, trapped bubbles and degradation of coupling interfaces must be assessed because such defects change ultrasound propagation independently of each constituent material.

12. Design of a discriminating validation study

A defensible comparison would use a named tissue or established reference phantom under matching temperature and frequency conditions, with a pre-specified target window for each clinically relevant observable. The experimental plan would independently measure speed of sound and attenuation, then test imaging of calibrated structures and intervention-related features using the actual ultrasound configuration. Replicate builds, multiple spatial locations and storage-time points are necessary to separate formulation differences from manufacturing variability. Numerical acceptance bands must be application-specific and justified by the diagnostic or training task; the accessible sources do not support universal limits.

13. Engineering synthesis

The strongest conclusion from these sources is that photopolymer processing can produce experimentally useful ultrasound phantoms, but equivalence is multidimensional and contingent on the instrument, frequency band and task. Future reviews should tabulate each study by process, material state, frequency, directly measured acoustic observables, conditioning and imaging endpoint. Claims should be graded separately as material-property match, functional image match or validated task performance. A broad label such as tissue-equivalent is scientifically inadequate without that explicit target and measurement context.

14. Frequency-aware interpretation of tissue-equivalence claims

Ultrasound-phantom equivalence is a frequency- and task-dependent property, not an intrinsic label for a resin. A phantom can match one target value of acoustic velocity while differing in attenuation, scattering or impedance. Those differences can produce clinically important changes in image texture or apparent boundary position even when a bulk measurement is close to the chosen reference. A scientifically useful review must therefore record the measurement frequency, temperature, sample thickness, fabrication orientation and target tissue comparator.

The distinction between material-property agreement and imaging-task performance is central. A hydrophone or transmission measurement may establish a specimen characteristic, but the relevant phantom may also need to reproduce known inclusions, speckle behaviour or a specific lesion-detection task. Comparative studies should be grouped by what was measured and should report the uncertainty associated with each measurement chain rather than treating all imaging outcomes as equivalent.

Time dependence should also be considered. Water uptake, temperature changes and ageing may alter polymer dimensions or acoustic response during service. An engineering qualification programme should specify a service interval and test changes against the actual application requirement. Evidence obtained on an initial laboratory coupon does not alone establish longitudinal performance of a complex printed phantom.

Critical synthesis: multidimensional acoustic equivalence

Tissue equivalence is not a single attenuation number. It depends jointly on speed of sound, density, acoustic impedance, frequency-dependent attenuation, scattering, nonlinear response where relevant and stability under storage and repeated scanning. A printed material that resembles tissue at one ultrasound frequency may cease to be representative at another frequency or when used in a different transducer geometry.

Experimental reports should identify specimen temperature, frequency band, sample thickness, immersion medium, calibration reference and uncertainty propagation. Mechanical print accuracy should be evaluated separately from acoustic property accuracy; the former does not establish clinically meaningful image contrast. Studies of composite inclusions and bulk matrices should be classified by internal architecture, because scattering mechanisms differ.

Comparative validation should include both material-level measurements and an imaging task using a defined scanner and reference target. Proposed acceptance criteria should be linked to that task, for example detectability or measurement bias, rather than an unqualified claim of tissue equivalence. In the absence of reproducible multimodal benchmarks, evidence remains application-specific.

15. Limits and research priorities

The present acoustic evidence does not establish elastographic or tactile equivalence. No shear-modulus acceptance interval or photopolymer-specific tactile validation is extracted. Mechanical observations in a source are not silently promoted into either claim. These excluded modalities would require their own evidence and assessment criteria.

The immediate research priority is to recover the complete measurement and comparator records for a defined acoustic application, then evaluate whether they support a predeclared equivalence criterion. Repeated measurements, state tracking and a phantom-level test could

form parts of that programme where the intended claim requires them. The programme proposed here remains unvalidated and supplies no numerical pass threshold.

16. Conclusions

The inspected literature establishes that acoustic properties of printed photopolymers have been measured and that some studies make comparisons with named tissues. It does not establish a common tissue-equivalence tolerance across the different systems assessed here. A defensible equivalence claim would retain the material state, acoustic endpoint, frequency conditions, tissue comparator and justified criterion as separate, traceable elements. The present contribution is that assessment structure, not a declaration of qualified phantom performance.

Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. The company develops and supplies photoresins and related process materials. No proprietary formulation, manufacturing sequence, process window or comparative product recommendation is disclosed.

Data availability

No new experimental dataset was generated. Published measurements remain attributed to their individual studies; no pooled dataset was constructed.

References

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