

Radiographic-Contrast Photopolymers for Phantoms, Sample Holders and X-Ray Workflows

Attenuation, Artefact and Dimensional Qualification

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Statement of Significance

A photopolymer that appears radiopaque, radiolucent or approximately tissue-like in one computed-tomography scan is not thereby qualified for a radiographic phantom or X-ray workflow. X-ray attenuation depends on photon energy and composition, while the measured CT number also depends on manufactured density, geometry, scan spectrum and reconstruction. When radiopaque particles are introduced into a photocurable resin, a second coupling appears: the same particles that modify X-ray response can change optical attenuation, scattering, cure depth, dispersion stability and dimensional fidelity during printing. A useful radiographic material therefore cannot be specified by a single Hounsfield-unit value or by filler percentage alone.

ER-191 treats the engineered object as a coupled material, manufacturing and imaging system. It separates intrinsic attenuation from density and path length; CT number from material identity; radiographic matching from shielding or dosimetry; and CAD geometry from the final reconstructed image. It also distinguishes two ways to engineer contrast: changing composition and changing effective density or internal architecture. Qualification is defined against a declared imaging task and energy range, with representative geometries and scan/reconstruction conditions, rather than against an isolated material coupon.

Abstract

Photopolymer additive manufacturing can create radiographic phantoms, calibration objects, sample holders and patient-derived structures with geometries that are difficult to manufacture conventionally. The central engineering difficulty is that radiographic fidelity is not a scalar material property. The linear attenuation coefficient varies with photon energy and composition; CT number additionally depends on the reference medium, scanner spectrum, object size, beam hardening, reconstruction and partial-volume effects. Commercial photocured resins span substantial but changing attenuation ranges, and published measurements show that their energy dependence can differ from the tissues or targets they are intended to represent [1-3]. Radiographic equivalence at one tube potential therefore does not prove equivalence over a different spectrum or acquisition protocol.

Contrast can be adjusted through composition, density and architecture. Mineral or other high-attenuation additives can modify the CT response of photoreactive resins [4,6], while stereolithography can also use controlled void architecture to tune effective radiodensity without changing the base chemistry [5]. These strategies carry different failure modes. Particle-filled formulations introduce dispersion, sedimentation and optical-cure coupling; composite stereolithography studies show that cure depth can either decrease or increase with filler loading depending on scattering and refractive-index relationships [7]. Density architecture introduces resolution, partial-volume, orientation and local-wall-thickness constraints. Both routes require validation on the actual manufactured geometry.

This review proposes a state-resolved qualification architecture for radiographic photopolymers. It requires formulation and lot identity, controlled printing and post-cure state, energy-resolved attenuation measurements, image-domain artefact assessment, dimensional verification and task-specific acceptance. It

explicitly excludes universal Hounsfield-unit targets, universal filler recipes, shielding claims and clinical-performance claims. The result is a framework for deciding whether a photopolymer object is fit for a stated radiographic function, not whether a material is generically “X-ray equivalent.”

Keywords: radiographic phantom; photopolymer; stereolithography; vat photopolymerisation; X-ray attenuation; computed tomography; Hounsfield unit; radiopacity; radiolucency; beam hardening; partial volume; radiopaque filler; dimensional metrology; imaging phantom; qualification

1. Scope, terminology and ownership

ER-191 addresses photopolymer materials and printed photopolymer structures whose intended function depends on their interaction with diagnostic or experimental X-rays. The owned applications are radiographic phantoms, attenuation-matched structures, radiopaque or radiolucent inserts, sample holders, positioning fixtures and other X-ray workflow components for which attenuation, contrast, artefact contribution or dimensional visibility matters.

The review owns formulation and measurement of X-ray attenuation and radiographic contrast, including energy dependence, additive state, filler dispersion, manufactured density, beam-hardening artefact, geometry fidelity and fitness for the declared phantom or fixture task. It does not own scintillation, radiation shielding or dosimetry, which remain with ER-019. It does not own organ-on-chip biological qualification, which remains with ER-012. ER-159 remains the broad survey of radiation-functional material families. ER-191 is narrower: it asks whether a specific manufactured photopolymer object produces the required X-ray interaction and image response under controlled conditions.

The term **radiopacity** is used comparatively. It means stronger attenuation or greater radiographic visibility under stated conditions, not a universal category independent of spectrum or thickness. **Radiolucency** is similarly conditional. **Attenuation** refers to reduction of photon fluence through matter; **CT number** or **Hounsfield unit (HU)** is an image-domain quantity produced by a CT acquisition and reconstruction process. **Radiographic fidelity** means agreement with a declared target in the variables relevant to the intended task. That target may be a tissue-like attenuation response, a known contrast step, a low-artefact holder, a visible fiducial or a controlled heterogeneous structure.

The object of qualification is therefore not the liquid resin alone. It is the resin or composite in a defined manufactured and conditioned state, with geometry, density, post-cure history and imaging protocol attached to its identity.

2. Why radiographic contrast is not a material constant

X-ray attenuation is energy dependent. NIST XCOM tabulates photon interaction coefficients as functions of photon energy and composition [11]. In a polychromatic diagnostic beam, the object is therefore exposed to a spectrum rather than to one energy, and the transmitted spectrum changes as photons pass through the object. A material that produces the desired attenuation at one effective beam quality can diverge when tube potential, filtration or object thickness changes.

The 2021 study by Ma, Buschmann, Unger and Homolka measured printing materials, including photocured resins, from 70 to 140 kVp and showed that their CT response is energy dependent [1]. The 2026 update by Hofmann, Buschmann and Homolka repeated the principle with a newer set of commercial materials and again found a wide range of attenuation among photopolymer resins [2]. These datasets are valuable for screening, but their more important engineering message is that “the HU of the resin” is incomplete language unless the acquisition state is specified.

Linear attenuation also depends on manufactured density. Voids, incomplete packing, trapped bubbles, internal lattice architecture and unintended porosity change the amount of material in the beam path.

Kalidindi and co-workers measured multiple 3D-printing materials for phantom construction and treated attenuation as something to be characterized in the printed state rather than inferred from polymer family alone [3]. Ma et al. likewise optimized print conditions before comparing attenuation, explicitly separating low density caused by manufacturing from the underlying material response [1].

Geometry adds another layer. For projection radiography, transmitted intensity depends on the line integral of attenuation along the beam path. For CT, the reconstruction estimates local attenuation from many projections, but the result is affected by finite voxel size, reconstruction assumptions, noise and spectrum. A thick object made from a moderately attenuating polymer can produce a stronger projection signal than a thin object of a more attenuating formulation. A single radiopacity adjective therefore cannot specify a component.

3. Composition, density and path length must remain separate variables

A useful qualification record separates three variables that are often collapsed: composition, density and path length. Composition controls elemental interaction probabilities. Density converts mass attenuation behaviour into linear attenuation. Geometry determines the path through that linear attenuation field.

This separation prevents several common errors. First, changing filler loading can modify both composition and density, so a measured HU shift does not reveal which contribution dominates. Second, a print parameter that changes trapped void fraction can change image response without changing liquid-resin chemistry. Third, a thin-wall phantom feature can appear less attenuating because of partial volume even when the local solid material is unchanged.

For formulation work, the minimum identity therefore includes base resin, reactive diluent/oligomer architecture where controlled, photoinitiator system, radiographic additive identity, additive concentration on a declared basis, particle-size/distribution information where relevant, dispersant or stabilizer state, mixing history and lot genealogy. For the printed object it adds machine, optical configuration, layer strategy, orientation, post-cure history, conditioning, measured dimensions and an appropriate density or mass-volume descriptor.

The objective is not to create a universal metadata burden. The objective is to retain enough state information to distinguish a composition change from a manufacturing-density change and from an imaging-protocol change when the measured contrast shifts.

4. Energy dependence is part of the specification

A phantom intended for one fixed CT protocol can be qualified more narrowly than a phantom intended to behave realistically across several tube potentials. These are different engineering claims.

Ma et al. showed that the energy dependence of photocured resins can differ from that of soft tissues [1]. Hofmann et al. extended the material survey with current photopolymers and again reported attenuation as a function of tube potential rather than as a single value [2]. The consequence is direct: a one-point HU match at 120 kV, for example, cannot be promoted to a general statement of tissue equivalence over 70 to 140 kV unless the energy dependence has actually been measured and accepted.

The same principle applies outside tissue-mimicking phantoms. A low-contrast sample holder that is unobtrusive under one X-ray spectrum may become more visible at another energy. A fiducial that is just detectable under one geometry may saturate or generate artefact under another. A contrast calibration object designed for a particular acquisition should therefore state its intended spectrum or protocol range.

Where the intended use spans multiple spectra, qualification should use multiple beam qualities or another justified energy-resolved method. Where use is intentionally narrow, the specification can be narrow, but that

limitation must travel with the object. “Qualified at protocol X” is a valid statement. “X-ray equivalent” without an energy domain is not.

5. Commercial photopolymers are screening candidates, not fixed radiographic standards

Commercial SLA, DLP and material-jetting photopolymers can provide useful baseline attenuation without deliberate radiopaque modification. The literature demonstrates a broad range of measured CT responses across available resins [1-3]. The 2026 update is particularly important for change control because it shows that the available resin landscape continues to evolve [2].

This variability creates opportunities and risks. A commercially available resin may already be close enough to a desired attenuation range for a specific phantom or holder, avoiding the rheological, optical and settling complications of a filled formulation. Conversely, a resin selected only for mechanical properties or transparency may generate an unacceptable CT background or may drift away from a target when the supplier changes formulation.

A catalogue name is not a radiographic specification. Manufacturers can alter resin composition to improve printability, colour, mechanical performance or regulatory status. Even without a declared formulation change, batch variation, pigment state, cure conversion and post-cure can alter density or composition enough to matter for a tight imaging requirement. The correct approach is to qualify the actual material state used in production and define what changes trigger remeasurement.

Published attenuation tables are therefore valuable for down-selection, not for final release. They reduce the search space. They do not transfer the authors' scanner, spectrum, specimen geometry, post-cure state or lot identity to another laboratory.

6. Radiopaque fillers create two coupled optical systems

When an additive is introduced to raise X-ray attenuation, the formulation must satisfy two optical problems simultaneously. It must interact with ionizing photons in the intended way, and it must still accept the actinic light used for photopolymerisation with adequate spatial control.

Badiuk, Sasaki and Rickey modified stereolithography photoreactive materials with mineral powders to shift CT response in an anthropomorphic phantom [4]. Gokdeniz, Buyuksungur and Kolsuz likewise demonstrated a heterogeneous radiopacity phantom using a filled stereolithographic approach [6]. These studies show that radiographic response can be formulated rather than merely selected from an existing resin catalogue.

The addition is not radiographically free and it is not photochemically free. Fei and co-workers showed in composite stereolithography that filler loading can change cure depth through scattering and refractive-index interactions, and that the direction of the change is system dependent [7]. It is therefore unsafe to use a rule such as “more filler always means less cure depth” or its opposite. The full resin-filler optical system must be measured.

For ER-191, the engineering implication is a coupling gate. Any meaningful change in radiopaque particle identity, surface treatment, particle-size distribution, loading, dispersant, base resin, wavelength or optical geometry can affect both the X-ray response and the photopolymerisation response. Radiographic tuning must therefore be followed by print/cure requalification, while cure tuning must be followed by confirmation that the intended attenuation field has not been lost through composition or density change.

7. Dispersion, sedimentation and spatial homogeneity

A nominal filler concentration does not prove a spatially uniform printed composition. Particle-filled photopolymers can develop concentration gradients through incomplete mixing, agglomeration, settling, selective retention, filtration, recirculation history or residence time in the vat. The radiographic consequence

is a spatial attenuation gradient; the photopolymerisation consequence can be a spatial optical and cure gradient.

The qualification question is therefore not only “what filler percentage was weighed?” but also “what composition was present where the object was cured?” Representative controls can include top/middle/bottom sampling, time-resolved sampling after mixing, density or ash/mineral-content measurements, microscopy, elemental mapping or direct radiographic uniformity checks, depending on the formulation and risk. The measurement method must itself have sufficient spatial resolution to detect the gradient that would matter for the application.

Agglomerates require separate consideration. A formulation can have the correct mean composition while containing local high-attenuation clusters. In a CT phantom these can appear as spots, streaks or local beam-hardening sources. In the printer they can scatter or absorb actinic light and create local cure defects. A bulk average cannot release such a state when local image uniformity matters.

The acceptance criterion should be expressed in the same spatial scale as the use case. A large homogeneous background phantom may tolerate a different local variation than a small radiopaque insert or a thin holder wall adjacent to a low-contrast region. No universal coefficient of variation or sedimentation time is justified across these systems.

8. Geometry can tune radiodensity without changing chemistry

Composition is only one radiographic design lever. Effective density and internal architecture can also control the reconstructed signal. D'hondt and co-workers used stereolithography-based printing to create part-solid pulmonary nodule phantoms with realistic morphology and heterogeneous radiodensities, using controlled internal architecture and validating the result by CT [5]. This route is conceptually different from loading the resin with a high-attenuation powder.

Architectural tuning has advantages. It can preserve a known printable resin chemistry and avoid some filler-dispersion problems. It also allows spatially varying effective density from one base material. However, it introduces its own constraints. The internal feature size must be manufacturable; walls and gaps must remain within process capability; trapped resin or incomplete drainage can shift effective density; orientation can alter feature fidelity; and the CT voxel can average solid and void into an apparent intermediate value.

This means a CAD lattice fraction is not itself a radiographic state variable. The relevant quantity is the manufactured architecture after printing, cleaning and post-cure, followed by the reconstructed response under the intended scan. A nominal 50% solid design, for example, is not automatically equivalent to half the attenuation of a fully dense object because path topology, voxel averaging, trapped material and beam geometry can matter.

Composition and architecture can also be combined, but then the qualification space expands. A filled resin printed as a porous architecture needs both composition-state and geometry-state control. The design should use the minimum number of coupled degrees of freedom needed for the task.

9. CT number is a measurement result, not a formulation label

Hounsfield units are convenient because they map reconstructed attenuation relative to water and air, but they are produced by a measurement system. Scanner spectrum, calibration, object size, field of view, reconstruction kernel, iterative reconstruction, slice thickness, voxel size, region-of-interest placement and artefact correction can all influence the reported value.

For that reason, a formulation specification written only as “500 HU resin” is incomplete. The statement needs a protocol, specimen geometry and measurement definition. If the intended application is cross-scanner or cross-protocol, the qualification study must measure that transfer rather than assume it.

Kalidindi et al. provide a material depository that is useful precisely because the materials were printed and scanned under declared conditions [3]. Ma et al. measured across multiple tube potentials to expose energy dependence [1]. Hofmann et al. repeated the approach with a later material population [2]. These studies support a measurement architecture, not a universal table of permanent resin constants.

A robust internal specification can use a reference phantom, a defined water or air calibration, fixed acquisition parameters and a declared region-of-interest rule. Where absolute attenuation coefficients are needed, the conversion method and energy basis should be documented. Where the target is only relative contrast, the reference object and contrast metric should be defined. The metric must match the decision.

10. Beam hardening, photon starvation and reconstruction artefacts

High-attenuation material can create an apparent image defect that is not a defect in the physical object. Ma et al. explicitly excluded very highly attenuating filled materials from quantitative CT characterization where severe beam-hardening and quantum-starvation artefacts would compromise measurement [1]. This illustrates an important qualification boundary: increasing radiopacity can eventually reduce measurement fidelity.

Beam hardening occurs because lower-energy photons are preferentially removed, changing the spectrum through the object. The result can include cupping, streaks and biased reconstructed values. Photon starvation can occur along highly attenuating paths when too few photons reach the detector. Reconstruction algorithms may then amplify streaks or structured noise. Metal-like or high-Z inclusions can also create local artefacts whose magnitude depends on geometry and spectrum.

These effects mean that a nominal target attenuation cannot be optimized independently of artefact. A phantom intended to create a particular bright feature may fail if the feature generates a larger surrounding artefact than the target being studied. A sample holder can fail even if its own mean CT number is known, because edges or thick intersections generate streaks through the specimen.

Qualification should therefore inspect not only a region-of-interest mean but also spatial residuals, streaks, edge behaviour and background perturbation. A material can pass the attenuation target and fail the artefact target. Those are separate release criteria.

11. Partial volume and dimensional fidelity are coupled

A physical feature and its image representation are linked through spatial resolution. If a wall, pore, channel or contrast boundary approaches the effective imaging resolution, a voxel can contain more than one material state. The reconstructed value becomes an average or nonlinear mixture rather than the true local attenuation of either phase.

This makes dimensional metrology part of radiographic qualification. A printed wall that is thicker than intended changes both geometry and attenuation path. A feature that is dimensionally correct but below the imaging resolution can still appear blurred or biased. D'hondt et al. validated both morphology and radiodensity in SLA-generated pulmonary-nodule phantoms rather than treating one as a substitute for the other [5]. Jahnke et al. likewise framed realistic CT phantoms around both anatomical detail and attenuation behaviour [10].

The correct acceptance strategy depends on the task. If the phantom is used to test detectability of a small feature, edge-spread and apparent size may matter more than a bulk HU average. If the component is a sample holder, the critical dimension may be the distance between specimen and detector or the holder thickness along the beam. If the object is a calibration insert, volume-averaged attenuation may be sufficient provided the region of interest excludes edges.

CAD dimensions should therefore be connected to manufactured dimensions and then to image-domain dimensions. A pass at only one of those stages leaves an unresolved transfer.

12. Heterogeneous phantoms require spatial, not only scalar, qualification

Many useful phantoms are intentionally heterogeneous. Bone-like structures, pulmonary nodules, vessels, lesions and multi-material calibration objects require spatial distributions of attenuation rather than one mean value. Gokdeniz et al. addressed heterogeneous bone radiopacity [6], while D'hondt et al. engineered spatially variable nodule density [5]. Wang, Falkson and Guo provide a complementary non-photopolymer example in which image-domain grayscale targets were mapped to radiopaque printed structures and then checked by CT; that study is useful for the target-to-manufactured-image validation concept but not for resin formulation claims [8].

A heterogeneous target creates additional verification needs. The composition or architecture map must be manufacturable. The transition between regions must have the intended sharpness or gradient. The printed object must not introduce unintended mixing or voids. The imaging protocol must resolve the intended differences. The reconstruction must preserve the spatial pattern sufficiently for the planned experiment.

The comparison can therefore include image registration between design/target and scanned phantom, spatial error maps, histogram or region analysis, line profiles and task-specific feature metrics. A global mean can be misleading because positive and negative local errors can cancel.

This is also where manufacturing genealogy matters. If one region uses a filled resin and another uses an unfilled resin, interface bonding, differential cure, cleaning and post-cure can create gaps or local composition mixing. If heterogeneity is generated from one resin by varying architecture, the controlling variable becomes the actual manufactured solid fraction and feature resolution. The validation method should follow the chosen architecture rather than impose a generic phantom test.

13. Phantoms, fixtures and sample holders have different acceptance questions

A tissue-mimicking phantom usually seeks a defined attenuation field that resembles a target under stated imaging conditions. A calibration object may seek stable, known contrast steps rather than biological realism. A sample holder or fixture may instead seek low, known or spatially confined attenuation so that it does not corrupt the specimen measurement. These are different tasks even if they use the same resin.

For a phantom, the primary acceptance can include attenuation match, energy dependence, heterogeneity, dimensional accuracy and image texture where relevant. For a holder, the main questions can be whether the material intersects the beam, whether thick ribs or fasteners create streaks, whether the holder's signal overlaps the specimen's, and whether geometry is stable enough to maintain positioning. For a visible fiducial, strong local contrast may be desirable, but the surrounding artefact must remain acceptable.

The same physical resin can therefore be acceptable in one workflow and unacceptable in another. A moderately attenuating polymer may be useful as a phantom background and intrusive as a holder around a low-contrast sample. Qualification should begin with the imaging task, not with a generic claim that the material is radiopaque or CT-compatible.

The minimum object specification should state intended modality, acquisition range, location relative to the beam and detector, target contrast or maximum permitted interference, geometry and acceptance method. This makes later change control possible.

14. Molecular-imaging evidence defines a useful boundary, not an equivalence

The original scientific gate for this topic identified Gear et al., who incorporated a radioisotope into a photopolymer resin and printed molecular-imaging phantoms with controlled activity distributions [9]. That work is relevant to ER-191 for one narrow reason: it demonstrates that an imaging-relevant functional distribution can be integrated with photopolymer manufacturing and then verified spatially.

It does not show that radioactive activity and X-ray attenuation are interchangeable material functions. Activity is an emission-source property. X-ray attenuation is a transmission interaction with an external beam. Their metrology, safety, calibration and application boundaries are different. ER-191 therefore uses the study as architecture evidence only and retains nuclear-medicine and dosimetric ownership outside this review.

The same discipline applies to any multifunctional phantom. A component may need radiographic contrast plus fluorescence, conductivity, mechanical compliance or another function. Each function requires its own measurement and acceptance criterion. Passing one does not validate the others. Multifunctionality increases the need for a state-resolved qualification record rather than reducing it.

15. Failure modes and discriminating measurements

A radiographic photopolymer can fail through several distinct mechanisms that may produce similar image symptoms. Low measured attenuation can result from incorrect formulation, under-loaded filler, low manufactured density, internal voids, architecture error, energy mismatch or reconstruction bias. A streak can result from a local high-Z agglomerate, excessive path length, beam hardening, photon starvation or an unrelated scanner artefact. A blurred boundary can result from print geometry, motion, partial volume or reconstruction kernel.

Troubleshooting should therefore proceed by competing hypotheses. If attenuation is low but mass and dimensions are correct, composition or imaging energy may be suspect. If attenuation varies with height in the print, sedimentation or cure-dependent density may be considered. If an apparently high-attenuation region is confined to edges or thick paths, beam-hardening or partial-volume effects should be tested before changing formulation. If the CAD geometry is correct but the CT geometry is not, physical metrology can separate manufacturing error from imaging resolution.

Useful discriminators include gravimetric density, ash or elemental analysis, microscopy, top-to-bottom composition sampling, optical/cure-depth testing of the liquid composite, dimensional metrology, scans at multiple beam qualities, repeat scans with altered orientation, reconstruction-kernel comparisons, and scans of simple reference coupons made from the same lot. The minimum test set is chosen by the failure hypothesis and intended task.

A corrective action is accepted only when it fixes the relevant failure without creating another. Increasing filler to recover HU can degrade printability. Raising exposure to recover cure can broaden features. Thinning a holder to reduce attenuation can reduce stiffness or positioning accuracy. Qualification therefore remains multi-objective.

16. Qualification architecture and change control

A practical ER-191 qualification can be organized as a linked chain from target to accepted object.

First, define the imaging task. State the modality, beam-quality range, relevant geometry, target contrast or attenuation behaviour, dimensional requirement and permitted artefact. Second, define the material state, including resin/filler identity, lot, mixing and storage history. Third, establish printable and cureable processing without assuming that a radiopaque modification preserves the unfilled-resin process window. Fourth, manufacture representative coupons and geometries. Fifth, measure physical dimensions and density before attributing an image difference to chemistry. Sixth, acquire radiographic/CT data under the intended protocol or protocol family. Seventh, evaluate attenuation, energy dependence, spatial uniformity, artefact and task-specific image metrics. Eighth, define the accepted state and change triggers.

Change control should include base-resin supplier or formulation, radiographic additive identity or lot, loading basis, particle size or surface treatment, dispersant, mixing equipment or time, storage duration, printer/light engine, layer strategy, post-cure, orientation, part geometry, scan spectrum and reconstruction.

Not every change requires a full requalification, but every change should be screened against the state variables it can affect.

For a commercial unfilled resin used directly, formulation visibility may be limited. In that case, supplier lot and measured radiographic response become more important. A new lot can be bridged by a defined attenuation and print-state test. For a custom filled resin, the internal composition and mixing controls can support a more mechanistic equivalence decision.

The release unit should be explicit. It may be a material lot, a printed batch, an individual phantom or a calibrated insert set. The tighter the application claim, the closer the measurement should be to the released unit.

17. Minimum reporting and limitations

A report intended to support reuse or comparison should identify the photopolymer and additive state, printer and post-cure state, specimen geometry, density or mass information where relevant, X-ray/CT system, tube potential and filtration if available, reconstruction settings, voxel or slice dimensions, region-of-interest rule, number of specimens and repeats, measured attenuation/CT response, dimensional result and observed artefacts. When a target material or tissue is invoked, the target data and energy/protocol domain should also be stated.

This review does not define a universal HU range for soft tissue, bone, water equivalence or radiolucency. It does not define a universal radiopaque-filler loading or particle-size window. It does not prescribe one printer, wavelength, exposure, post-cure, scan voltage or reconstruction kernel. It does not establish shielding performance, dose equivalence, scintillation efficiency or clinical diagnostic performance.

Several evidence limitations remain. Commercial formulations are incompletely disclosed and can change. Published attenuation datasets are scanner- and protocol-dependent even when carefully measured. Composite photopolymer studies often optimize printability or attenuation separately rather than measuring the full coupling between radiographic composition, optical cure and long-term dispersion stability. Phantom validation frequently targets one clinical or experimental scenario rather than transfer across scanners and spectra.

Future work should therefore emphasize energy-resolved characterization of custom photopolymer composites, direct mapping between filler distribution and reconstructed attenuation, stability after storage and repeated imaging, interlaboratory transfer, and uncertainty budgets that propagate material, manufacturing and imaging contributions separately.

18. Conclusions

Radiographic photopolymers should be qualified as manufactured imaging components, not described by a single material adjective. X-ray attenuation depends on photon energy and composition, while the measured image depends additionally on density, geometry, acquisition and reconstruction. Published measurements of photocured resins demonstrate both a wide material range and significant energy dependence [1-3]. A one-protocol CT-number match is therefore a bounded result, not a universal equivalence claim.

Radiographic response can be engineered through composition and through architecture. Mineral additives can shift the CT response of photoreactive resins [4,6], but filler introduction creates dispersion and photopolymerisation coupling that must be requalified [7]. SLA architecture can tune effective radiodensity without changing base chemistry [5], but then feature fidelity, trapped material and partial volume become controlling variables. Neither approach removes the need to validate the actual printed geometry.

The practical qualification rule is to keep the states separate and then reconnect them with evidence: control formulation and lot; verify dispersion where relevant; establish print and cure capability; measure

manufactured density and dimensions; characterize attenuation over the intended energy range; inspect beam-hardening, partial-volume and reconstruction artefacts; and accept the object against a declared imaging task. Phantoms, calibration objects, fiducials and sample holders may use the same photopolymer yet require different acceptance criteria.

ER-191 therefore rejects universal claims such as “CT-equivalent resin,” “bone-like filler percentage,” or “radiolucent holder” without a declared protocol and geometry. The defensible claim is narrower and more useful: a defined photopolymer object, manufactured in a controlled state, has demonstrated the required attenuation, artefact and dimensional behaviour for a stated X-ray workflow.

Related Engineering Review boundaries

ER-019 retains scintillation, shielding and dosimetry. ER-012 retains organ-on-chip material qualification. ER-159 retains the broad survey of radiation-functional material families. ER-044 and ER-076 retain generic filled-resin optical and cure-depth physics in vat photopolymerisation. ER-191 owns attenuation-matched or contrast-engineered photopolymer components for radiographic phantoms, holders and X-ray workflows.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. The paper is an engineering synthesis and does not make a comparative commercial-product recommendation. No 3Dresyns product is claimed to be universally tissue-equivalent, shielding-qualified, dosimetrically equivalent or clinically validated by this review.

Data availability and AI-assistance statement

No new experimental dataset was generated. The review synthesises the cited scientific literature and controlled Engineering Review corpus. Generative AI assisted drafting and corpus organisation but is not an author. Juan Segurola retains responsibility for the final article.