

Beyond the working curve: industrial perspectives on cross-platform process equivalence in vat photopolymerization

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Highlights

- Working-curve standardisation is necessary but not sufficient for cross-platform process equivalence in vat photopolymerization.
- Part-level outcomes depend on spectral, atmospheric and material-state factors not captured by working-curve parameters alone.
- Cross-platform material qualification cannot be inferred from working-curve matching alone.
- Calibration accommodates platform-specific variability within a defined operational scope rather than eliminating it.
- Working-curve standardisation is a foundation, not the endpoint, of cross-platform qualification.

Abstract

Context. The working curve introduced by Jacobs remains a widely used reference for characterising cure depth as a function of radiant exposure in vat photopolymerization. Recent interlaboratory studies have shown that conventionally measured working-curve parameters can vary markedly between laboratories and that improved spectral control and procedural standardisation substantially improve reproducibility.

Position. Working-curve agreement is necessary for meaningful comparison, but it is not sufficient to establish cross-platform process equivalence. Part-level outcomes can also depend on the spectral distribution and spatial delivery of light, oxygen-related interfacial effects and thermal conditions, and the state and handling history of the resin.

Approach. This Perspective surveys peer-reviewed literature and public standards relevant to working-curve measurement, optical delivery, oxygen inhibition, process-parameter sensitivity and additive-manufacturing qualification. Three observation domains are used to organise the discussion: spectral, atmospheric and material-history. They are presented as categories for observation rather than as a causal model or ranked hierarchy.

Implications. Cross-platform qualification should therefore retain the working curve as a metrological anchor while confirming performance at part level under the operational conditions of intended use.

Scope. No new experimental data, universal equivalence criterion or quantitative causal hierarchy is proposed.

Keywords: vat photopolymerization; working curve; cross-platform variability; process equivalence; material qualification; oxygen inhibition; photopolymer cure; additive manufacturing standardisation

1. Introduction

The working curve developed by Jacobs in the early 1990s remains a foundational method for relating cure depth to radiant exposure in vat photopolymerization [1]. The method has been adopted across stereolithography, digital light processing (DLP) and masked stereolithography (MSLA), and it continues to be discussed in modern treatments of vat-photopolymerization materials and process design [2,6,10]. Recent work has highlighted, however, that the apparent simplicity of a two-parameter working-curve fit can obscure substantial measurement sensitivity to light-source spectrum, radiometry, protocol and fitting range [3-5].

This issue matters increasingly as photopolymer materials are transferred among printers that differ in optical architecture, exposure spectrum, build geometry, atmosphere and process-control strategy. A parameter set measured on one platform or in one laboratory is therefore not automatically a complete predictor of part-level behaviour on another platform.

A NIST-led interlaboratory study involving 24 laboratories demonstrated this limitation directly at the measurement level: reported penetration depth, D_p , varied by as much as seven-fold and critical radiant exposure, E_c , by as much as seventy-fold under participants' established procedures [3]. A subsequent interlaboratory study showed that a standardised protocol using calibrated, spectrally restricted light sources could reduce this dispersion substantially [4]. In parallel, Caplins and co-workers demonstrated that spectral bandwidth can produce systematic departures from the monochromatic Jacobs model and developed a polychromatic treatment of the working curve [5].

This Perspective considers what follows after those metrological improvements. Its central position is that working-curve standardisation is necessary for cross-platform comparison but is not sufficient, by itself, to establish process equivalence at part level. The discussion is organised around three observation domains: spectral non-equivalence of optical hardware, atmospheric non-equivalence at the curing interface, and material-history non-equivalence of resin state. The domains are organisational rather than exhaustive, and no universal ranking among them is proposed.

2. The working-curve standardisation effort

In its familiar form, the Jacobs working curve is written as

$$C_d = D_p \ln(E/E_c),$$

where C_d is cure depth, E is incident radiant exposure, E_c is the fitted critical radiant exposure associated with the onset of measurable cure under the test conditions, and D_p is the fitted characteristic penetration depth that determines the slope of cure depth versus the logarithm of exposure [1,3]. These quantities are useful descriptors, but measured values are not purely intrinsic resin constants. They depend on the resin together with the wavelength distribution, radiometric characterisation, exposure geometry, cure-depth range and measurement procedure [3-6].

The first NIST-led interlaboratory study made the practical consequences visible. Twenty-four laboratories measured aliquots from the same resin batch using their established procedures. The reported spread reached approximately seven-fold in D_p and seventy-fold in E_c [3]. The authors identified procedural differences, variation among light engines, uncertainty associated with applying the Jacobs equation outside its assumptions, and limitations in thickness measurement as important contributors.

The second interlaboratory study moved from diagnosis toward a standardised method. Participants used calibrated light-source assemblies with narrow spectral bands, and the resulting aggregate values were markedly more consistent. The study reported $D_p = 39.2 \pm 3.7 \mu\text{m}$ and $E_c = 12.3 \pm 3.0 \text{ mJ cm}^{-2}$ at 385 nm, and $D_p = 69.3 \pm 3.8 \mu\text{m}$ and $E_c = 17.9 \pm 2.3 \text{ mJ cm}^{-2}$ at 405 nm [4]. These results provide a strong basis for interoperable working-curve measurement.

The spectral problem is not merely experimental noise. Caplins et al. showed that the Jacobs model assumes monochromatic illumination and that broadband sources can produce departures from the model when the source spectrum overlaps a region in which resin absorption varies strongly with wavelength [5]. Their polychromatic treatment links the working curve explicitly to the source spectrum and wavelength-dependent absorption. Consequently, two printers described by the same nominal wavelength and irradiance can still differ in the effective optical excitation delivered to a given resin.

These developments strengthen the working curve as a measurement. They do not, however, transform it into a complete predictor of production-state behaviour. Part-level output remains a function of the complete process state, which can include optical delivery beyond a single scalar irradiance value, oxygen-related surface kinetics, temperature, layer-renewal mechanics, resin condition and post-cure history.

3. Hardware factors not represented by a two-parameter working curve

Different vat-photopolymerization architectures deliver patterned light in materially different ways. MSLA systems use a liquid-crystal mask between an LED light engine and the resin. DLP systems use a digital micromirror device and projection optics. Laser-based stereolithography scans a focused beam. These architectures can differ in spectral distribution, spatial uniformity, pixel or beam profile, optical path and exposure modulation [2,5,10].

The interlaboratory study itself found substantial spectral variability among nominally similar commercial printers, with enough variation to change measured D_p markedly even before other sources of uncertainty were considered [3]. This result is important because a nominal label such as “405 nm^B” does not uniquely specify the spectral distribution reaching the resin. The follow-up spectral study reinforces the point by showing that bandwidth and the local slope of the resin absorption spectrum can alter the measured working-curve behaviour [5].

DLP adds a second level of optical control through spatially resolved exposure. Pixel-level grayscale manipulation has been used to improve geometric accuracy by locally adjusting delivered exposure [11], while theoretical and experimental DLP working-curve models show that projector geometry and exposure conditions must be treated explicitly [12]. These studies support a broader interpretation of “optical equivalence”: matching nominal wavelength and average irradiance does not necessarily reproduce the spatial and spectral energy distribution experienced by the resin.

The resin-window interface can also be part of the operative process state. Higgins, Brown and Killgore combined DLP with atomic-force microscopy to observe the printing process in situ at nanoscale resolution [9]. Continuous liquid interface production provides an even more conspicuous example in which oxygen transport through a permeable window deliberately changes interfacial polymerisation and enables continuous separation from the window [19]. These cases illustrate that local interface conditions can matter to cure and separation while remaining outside the two fitted parameters of a conventional working curve.

The implication is not that a working curve is inadequate as a material-characterisation tool. Rather, its predictive scope is limited. A working curve can establish a controlled relation between exposure and cure depth, while platform-level optical transfer and interface conditions still require independent verification when the objective is cross-platform part equivalence.

4. Three observation domains: spectral, atmospheric and material-history

4.1 Spectral domain

The spectral domain concerns non-equivalence between nominally matched light sources. Relevant variables include peak wavelength, full width at half maximum (FWHM), and the wavelength-dependent absorption coefficient of the resin, $\alpha(\lambda)$. The NIST interlaboratory work documents instrument-to-instrument spectral variability [3], and the polychromatic analysis of Caplins et al. demonstrates why spectral bandwidth can change the working curve when resin absorption is wavelength dependent [5].

For cross-platform qualification, nominal wavelength should therefore be treated as an incomplete descriptor. Where feasible, the source spectrum and its overlap with the resin absorption spectrum provide a more informative basis for comparison.

4.2 Atmospheric domain

The atmospheric domain concerns conditions that influence radical polymerisation at interfaces exposed to oxygen. Oxygen inhibition in free-radical photopolymerisation is well established [7,8]. In vat photopolymerization specifically, Saygin et al. demonstrated that oxygen-inhibition zones can have measurable mechanical consequences and that oxygen exposure during fabrication can modify local material response [22]. Continuous liquid interface production similarly uses controlled oxygen permeation as a process mechanism [19].

The most defensible atmospheric variables are therefore oxygen availability at the curing interface and temperature, because both can affect polymerisation kinetics. Resin replenishment or flow between layers can also alter the local interface state, but its quantitative

importance is architecture- and process-specific and should not be assumed without measurement. This Perspective therefore treats oxygen partial pressure, build temperature and a resin-renewal descriptor as observation variables rather than as a universal causal model.

4.3 Material-history domain

The material-history domain concerns the condition of the resin at the time of use. Photopolymer performance depends on composition, optical absorption, reactive species, viscosity and the distribution of any fillers or pigments [10,13,20]. Storage time, storage temperature, light exposure and handling can plausibly alter one or more of these variables, particularly in multicomponent or filled systems. The available literature is much stronger on formulation chemistry and processing sensitivity than on controlled, long-duration cross-platform studies of resin ageing.

For that reason, resin age, storage temperature and an effective photoactive-species descriptor are retained here as qualification variables to record and control, not as proof that a particular degradation mechanism necessarily dominates a given production failure. This distinction is important: the material-history domain identifies a source of potentially different initial states between laboratories or production sites, while the magnitude and mechanism of any resulting performance change must be established experimentally for the material in question.

Across all three domains, relative influence is application-specific. The framework is deliberately non-hierarchical.

5. The printed part as the observable test point

A printed part integrates the complete exposure, material and process history. Part-level testing therefore provides the practical point at which cross-platform equivalence must ultimately be evaluated.

Hardware-side effects are documented in several forms. In-situ AFM-DLP measurements resolve local cure behaviour at the printing interface [9]. Grayscale DLP work shows that deliberately redistributing pixel-level exposure changes geometric accuracy [11]. DLP working-curve modelling likewise demonstrates that exposure geometry affects cured thickness [12]. These observations show that part geometry and local conversion can respond to optical variables not reducible to a single nominal wavelength or irradiance value.

Process parameters also translate into mechanical outcomes. Hazzazi and Mohsenzadeh reported statistically significant contributions of exposure time and light intensity to fatigue-life variation in DLP-printed photopolymer specimens [18]. In a separate dental study, Lee, Son and Lee found that printing temperature and post-curing duration affected double-bond conversion, tensile behaviour and dimensional reproducibility in resin workflows using SLA and MSLA equipment [21]. These studies do not constitute a universal cross-printer equivalence test, but they demonstrate that process conditions beyond a working-curve pair can materially affect part-level results.

The atmospheric contribution is supported most directly by oxygen-inhibition studies. Oxygen can quench propagating radicals and alter conversion near exposed interfaces [7,8]. In vat photopolymerization, Saygin et al. connected oxygen inhibition to mechanical consequences in printed material [22]. The magnitude of this effect depends on chemistry and process geometry, which is precisely why matching D_p and E_c cannot by itself guarantee identical interfacial conversion or mechanical response.

Cross-technology geometric comparisons further reinforce the need for part-level validation. Ozer et al. compared resin models produced by different vat-photopolymerization technologies and found technology-dependent differences in trueness and precision [23]. Such application-specific studies should not be generalised to all resins or printers, but they show the type of evidence required when equivalence is claimed at the part rather than measurement level.

Material-history effects are less systematically quantified in the cross-platform literature than spectral and process-parameter effects. Accordingly, this Perspective does not claim universal ageing rates, photoinitiator-depletion kinetics or sedimentation behaviour. Instead, resin state is treated as a controlled input that should be documented when comparing production results among sites or platforms.

6. Implications for material development and qualification

The practical distinction is between **parameter comparability** and **process equivalence**. A standardised working curve improves parameter comparability: laboratories can measure D_p and E_c using a common procedure and spectrally characterised exposure [3-5]. Process equivalence is a stronger claim. It requires evidence that the resulting part meets defined requirements under the relevant printer, resin, environmental and post-processing conditions.

This distinction is consistent with the wider additive-manufacturing qualification landscape. ISO/ASTM 52900:2021 provides foundational terminology [15], while ISO/ASTM 52920:2023 addresses qualification principles and requirements for industrial additive-manufacturing processes and production sites [16]. For laser powder-bed fusion, ISO/ASTM 52930:2021 specifies installation, operational and performance qualification of PBF-LB equipment [17]. These documents illustrate the broader principle that qualification extends beyond a single material parameter to the controlled manufacturing system.

The vat-photopolymerization literature is also moving toward stronger metrology, reporting practice and process understanding. The recent early-career Perspective by Dhand et al. surveys current challenges and opportunities across resin design, optical control and next-generation vat-photopolymerization processes [14]. Reviews of modern photopolymer materials similarly emphasise the coupling between chemistry and processing [2,10,20].

For material developers and users, a defensible cross-platform workflow therefore has two levels. First, establish a reproducible working-curve measurement under defined spectral and procedural conditions. Second, verify the intended part-level metrics on the target platform under the actual production conditions of use. Depending on application, those metrics may include dimensions, conversion, tensile or flexural properties, fatigue response, surface quality, optical response or other functional requirements.

Calibration remains essential within this workflow. Platform-specific adjustment of exposure, layer thickness, temperature, grayscale compensation or post-cure conditions can accommodate differences among systems. Such calibration should be described as establishing a validated operating window for a defined resin-platform-process combination, not as evidence that the underlying platforms are physically identical.

Under this interpretation, working-curve standardisation is the metrological foundation for cross-platform comparison, while part-level validation is the evidence required for practical equivalence.

7. Scope and limits

This Perspective contains no primary experimental data. It synthesises peer-reviewed literature and public documentary standards. The three observation domains are organisational and not exhaustive; other variables such as build orientation, support strategy, wash protocol, post-cure spectrum and post-cure thermal history can also affect final properties [10,21].

No causal ranking is assigned to spectral, atmospheric and material-history domains. The relative importance of each must be determined for the specific material, printer architecture and application. Likewise, this Perspective does not define a universal numerical threshold for “cross-platform equivalence”. Any such threshold should be derived from application requirements and a documented qualification plan.

The material-history discussion is intentionally conservative because controlled evidence connecting long-term resin history to cross-platform part outcomes is less mature than the evidence for working-curve variability, spectral effects and oxygen inhibition. Variables such as resin age and storage temperature are therefore presented as parameters to record and control rather than as universal failure mechanisms.

Figure 1

Observation domains in cross-platform vat photopolymerization

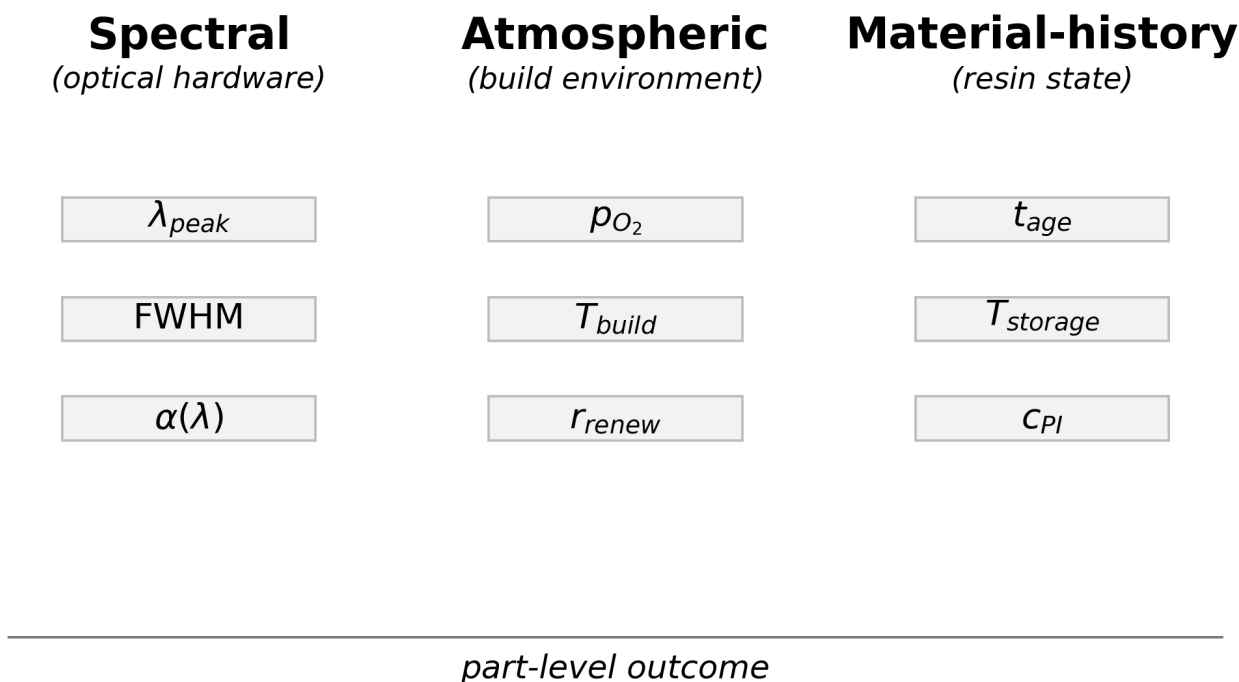


Figure 1. Observation domains discussed in this Perspective. The spectral domain comprises source peak wavelength (λ_{peak}), spectral width (FWHM) and wavelength-dependent resin absorption $\alpha(\lambda)$. The atmospheric domain comprises oxygen partial pressure (p_{O_2}), build temperature (T_{build}) and a resin-renewal descriptor (r_{renew}). The material-history domain comprises resin age (t_{age}), storage temperature ($T_{storage}$) and an effective photoactive-species concentration descriptor (C_{PI}). The columns are parallel observation categories rather than components of a causal model. Part-level outcome is the shared test point at which differences among operating states may become measurable.

Disclosure statement

The author is the founder and Scientific Director of 3Dresyns® (Resynr Technologies S.L., Donostia / San Sebastián, Spain), a manufacturer of photopolymer systems for vat photopolymerization and related additive manufacturing platforms. No 3Dresyns® products, proprietary formulations or unpublished internal data are discussed in this Perspective. The scientific claims are based on the cited peer-reviewed literature and public standards.

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Data availability

This Perspective does not include primary experimental data, human or animal subjects, or new datasets. The material discussed is available in the cited literature and standards.

Ethics statement

Not applicable. This Perspective reports no research involving human participants, animals or primary biological specimens.

References

- [1] Jacobs PF. *Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography*. Dearborn, MI: Society of Manufacturing Engineers; 1992.
- [2] Schwartz JJ. Additive manufacturing: Frameworks for chemical understanding and advancement in vat photopolymerization. *MRS Bulletin*. 2022;47:628-641. doi:10.1557/s43577-022-00343-0.
- [3] Kolibaba TJ, Killgore JP, Caplins BW, Higgins CI, Arp U, Miller CC, Zong Y, Poster DL. Results of an interlaboratory study on the working curve in vat photopolymerization. *Additive Manufacturing*. 2024;84:104082. doi:10.1016/j.addma.2024.104082.
- [4] Kolibaba TJ, Killgore JP, Caplins BW, Wendland RJ, Arp U, Miller CC, Zong Y, Higgins CI, et al. Results of an interlaboratory study on the working curve in vat photopolymerization II: Towards a standardized method. *Additive Manufacturing*. 2025;110:104919. doi:10.1016/j.addma.2025.104919.
- [5] Caplins BW, Kolibaba TJ, Arp U, Miller CC, Zong Y, Poster DL, Higgins CI, Killgore JP. Influence of spectral bandwidth on the working curve in vat photopolymerization. *Additive Manufacturing*. 2024;85:104172. doi:10.1016/j.addma.2024.104172.
- [6] Bennett J. Measuring UV curing parameters of commercial photopolymers used in additive manufacturing. *Additive Manufacturing*. 2017;18:203-212. doi:10.1016/j.addma.2017.10.009.
- [7] Decker C. Photoinitiated crosslinking polymerisation. *Progress in Polymer Science*. 1996;21(4):593-650. doi:10.1016/0079-6700(95)00027-5.
- [8] Ligon SC, Husár B, Wutzel H, Holman R, Liska R. Strategies to reduce oxygen inhibition in photoinduced polymerization. *Chemical Reviews*. 2014;114(1):557-589. doi:10.1021/cr3005197.
- [9] Higgins CI, Brown TE, Killgore JP. Digital light processing in a hybrid atomic force microscope: In situ, nanoscale characterization of the printing process. *Additive Manufacturing*. 2021;38:101744. doi:10.1016/j.addma.2020.101744.
- [10] Ligon SC, Liska R, Stampfl J, Gurr M, Mülhaupt R. Polymers for 3D printing and customized additive manufacturing. *Chemical Reviews*. 2017;117(15):10212-10290. doi:10.1021/acs.chemrev.7b00074.
- [11] Montgomery SM, Demoly F, Zhou K, Qi HJ. Pixel-level grayscale manipulation to improve accuracy in digital light processing 3D printing. *Advanced Functional Materials*. 2023;33:2213252. doi:10.1002/adfm.202213252.
- [12] Li Y, Mao Q, Yin J, Wang Y, Fu J, Huang Y. Theoretical prediction and experimental validation of the digital light processing (DLP) working curve for photocurable materials. *Additive Manufacturing*. 2021;37:101716. doi:10.1016/j.addma.2020.101716.
- [13] Crivello JV, Reichmanis E. Photopolymer materials and processes for advanced technologies. *Chemistry of Materials*. 2014;26(1):533-548. doi:10.1021/cm402262g.
- [14] Dhand AP, Bean RH, Chiaradia V, Commisso AJ, Dranseike D, Fowler HE, Fraser JM, Howard H, et al. Advances in vat photopolymerization: early-career researchers shine light on a path forward. *RSC Applied Polymers*. 2025;3(3):574-591. doi:10.1039/D5LP00010F.
- [15] ISO/ASTM 52900:2021. *Additive manufacturing - General principles - Fundamentals and vocabulary*. Geneva / West Conshohocken: International Organization for Standardization / ASTM International; 2021.
- [16] ISO/ASTM 52920:2023. *Additive manufacturing - Qualification principles - Requirements for industrial additive manufacturing processes and production sites*. Geneva / West Conshohocken: International Organization for Standardization / ASTM International; 2023.
- [17] ISO/ASTM 52930:2021. *Additive manufacturing - Qualification principles - Installation, operation and performance (IQ/OQ/PQ) of PBF-LB equipment*. West Conshohocken: ASTM International; 2021.
- [18] Hazzazi F, Mohsenzadeh R. Optimizing DLP 3D printing parameters to enhance fatigue performance of photopolymer resins for orthopedic applications. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*. 2025;239(22):9362-9373. doi:10.1177/09544062251367481.
- [19] Tumbleston JR, Shirvanyants D, Ermoshkin N, Janusziewicz R, Johnson AR, Kelly D, Chen K, Pinschmidt R, et al. Continuous liquid interface production of 3D objects. *Science*. 2015;347(6228):1349-1352. doi:10.1126/science.aaa2397.
- [20] Maturi M, Locatelli E, Sanz de Leon A, Comes Franchini M, Molina SI. Sustainable approaches in vat photopolymerization: advancements, limitations, and future opportunities. *Green Chemistry*. 2025;27:8710-8754. doi:10.1039/D5GC02299A.
- [21] Lee JM, Son K, Lee KB. Optimizing printing temperature and post-curing time for enhanced mechanical property and fabrication reproducibility of 3D-printed dental photopolymer resins. *Applied Sciences*. 2025;15(21):11552. doi:10.3390/app152111552.
- [22] Saygin V, Snapp K, Gongora AE, Kolaghassi R, Brown KA. Mechanical consequences of oxygen inhibition in vat polymerization. *Advanced Materials Technologies*. 2023;8:2202022. doi:10.1002/admt.202202022.
- [23] Ozer G, Bursa MC, Kokat AM. Trueness and precision of resin models produced by different vat-photopolymerization 3D printing technologies for full-arch implant-supported restorations. *Journal of Dentistry*. 2026;173:106811. doi:10.1016/j.jdent.2026.106811.

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