

Stereolithography 3D-printed stents with silica and zirconia nanoparticle reinforcement for intracranial aneurysm treatment

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SUMMARY

Intracranial aneurysms restrict blood flow in the brain, causing hemorrhages and severe neurological damage. Flow diverter stents (FDSs) are used to redirect blood flow, but current clinical metallic FDSs are associated with risks such as thrombosis, arterial narrowing, and interference with imaging. This study explored whether the mechanical strength and radiopacity (the ability of a material to block X-rays and appear visible under fluoroscopic or radiographic imaging) of stereolithography (SLA) 3D-printed stent materials could be improved through nanoparticle reinforcement. We hypothesized that adding silica nanoparticles would enhance tensile strength and that zirconia nanoparticles would increase radiopacity. Inspired by the principles of bioresorbability, we printed specimens using a biocompatible resin formulation, selected for its compatibility with potential degradable additives and its suitability for future translation to bioresorbable systems. We incorporated silica (0.5 wt.% and 2 wt.%) to enhance mechanical strength, and zirconia (5 wt.% and 10 wt.%) to increase radiopacity. Tensile testing demonstrated that the incorporation of silica nanoparticles increased the ultimate tensile strength of the 3D-printed materials compared with the control, with greater improvements observed at higher silica concentrations. Computed tomography imaging showed enhanced radiopacity, increasing from 63 HU (control) to 132 HU and 176 HU in 5 wt.% and 10 wt.% zirconium-infused stents. Scanning electron microscopy confirmed successful nanoparticle incorporation but also revealed increased agglomeration at higher concentrations. These findings demonstrate that nanoparticle reinforcement can significantly improve the mechanical and imaging properties of SLA-printed stent materials, offering a promising alternative to conventional metallic stents for intracranial aneurysm treatment.

INTRODUCTION

Intracranial aneurysms are balloon-like bulges in weakened brain artery walls, caused by blood flow pressur pushing the wall outward (1). Enlarged aneurysms restrict blood flow, compress nerves or brain tissue, and may rupture if untreated, leading to hemorrhages, strokes, seizures, or brain damage (1). Even post-rupture, complications like vasospasm, a sustained narrowing of cerebral arteries— can further restrict blood flow, worsening neurological conditions (2, 3). The three primary treatments for intracranial aneurysms—clipping, coiling, and flow diversion—each have distinct limitations that compromise their overall effectiveness (3). Clipping is a surgical procedure in which a small metal clip

is placed at the neck of the aneurysm to block blood flow into it, but it carries associated surgical risks (3). Coiling is a minimally invasive procedure in which platinum coils are delivered into the aneurysm to promote clot formation and occlusion; however, aneurysms may reopen over time, sometimes requiring retreatment (3). Flow diverter stents (FDSs) offer a less invasive and more durable solution, especially for large aneurysms that cannot be easily treated with clipping or coiling (1). These mesh stents are placed within the affected artery to redirect blood flow away from the aneurysm, promoting shrinkage and healing of the vessel wall (3). Clinical data have shown that FDSs result in high rates of aneurysm occlusion with lower retreatment rates compared to traditional techniques (4). A large comparative study specifically analyzing paraclinoid aneurysms found that flow diversion was not only safe and effective but also led to better visual outcomes than either coiling or clipping, particularly in patients presenting with visual symptoms (5, 6). However, clinically used metallic FDSs have notable drawbacks: they can cause thromboembolism, often requiring long-term dual antiplatelet therapy; they contribute to neointimal hyperplasia, which may lead to in-stent stenosis; and they produce imaging artifacts in computed tomography (CT), magnetic resonance imaging (MRI), and X-ray scans that interfere with follow-up assessments (7-9).

Bioresorbable flow diverter stents (BFDSs) offer an alternative with reduced thrombogenicity, minimized long-term complications, and improved imaging compatibility (7). Their temporary nature also helps reduce neointimal hyperplasia and is especially beneficial in pediatric cases, where permanent stents may interfere in vascular development (7). Moreover, additive manufacturing techniques such as stereolithography (SLA) 3D printing enable precise, rapid, and cost-effective customization of BFDSs tailored to patient-specific needs (10).

This study explored the design and development of flow diverter stents using SLA 3D printing and a biocompatible photopolymer resin modified with poly(ϵ -caprolactone-co-glycolide) (PCGL) to improve bioresorbability. While a fully bioresorbable resin was not accessible due to material constraints, the selected resin has undergone International Organization for Standardization (ISO)-certified biocompatibility testing and represents a promising candidate for future translation; however, photopolymer resins like these are not currently used clinically for intracranial flow diverter stents. The resin was separately enhanced with silica nanoparticles to improve mechanical strength and zirconia nanoparticles to increase radiopacity; each additive was evaluated independently to address distinct limitations of current metallic stents, including risk of in-stent stenosis and poor imaging compatibility.

Silica nanoparticles have been shown to enhance the tensile strength and stiffness of polymer composites by acting as rigid fillers that improve load transfer within the polymer matrix (5). Zirconia, in contrast, is widely used in medical imaging and dental applications due to its high atomic number and radiodensity. Its high radiodensity increases the contrast of polymer materials under computed tomography (CT) imaging (2). Reported studies on polymer–nanoparticle composites have typically used silica concentrations below 5 percentage by weight (wt. %) to achieve significant reinforcement without inducing brittleness or agglomeration, and zirconia concentrations in the 5–10 wt.% range to maximize radiopacity while maintaining processability (2, 5). Guided by these precedents and initial printability assessments, this study incorporated silica at 0.5 wt.% and 2 wt.% and zirconia at 5 wt.% and 10 wt.% to evaluate the balance between mechanical and imaging performance. Thus, we hypothesized that incorporating silica would improve mechanical durability, while zirconia would increase radiopacity. To evaluate this hypothesis, we conducted two main phases of analysis: mechanical testing to assess tensile strength improvements from silica nanoparticles, and CT imaging to determine the effect of zirconia nanoparticles on radiopacity. Our results demonstrate that silica and zirconia nanoparticle integration yields substantial increases in both mechanical strength and CT visibility, respectively, compared to control specimens. These findings suggest that SLA-printed BFDSs with tailored material compositions may represent a viable and customizable approach to intracranial aneurysm treatment.

RESULTS

To evaluate the effect of silica nanoparticles on tensile performance, we tested dumbbell-shaped resin specimens with 0 wt.%, 0.5 wt.%, and 2 wt.% silica following American Society for Testing and Materials (ASTM) D638 standards (11). The standardized dumbbell geometries were not representative of the stent structure itself but were used to obtain consistent, comparable measurements of material's properties independent of the stent design. We measured significantly different tensile strengths across our groups (**Figure 1**; one-way ANOVA, $p < 0.00001$). The control specimen had an ultimate tensile strength of 20.99 MPa, while the 0.5 wt.% and 2 wt.% silica-reinforced specimens exhibited significantly higher strengths of 22.15 MPa and 25.56 MPa, respectively (Tukey's post-hoc, $p < 0.05$ between all groups). These findings confirmed that silica nanoparticle reinforcement improved mechanical durability in SLA-printed resin composites. Notably, the 0.5 wt.% silica specimens exhibited lower displacement at failure compared to the control, suggesting increased brittleness at low silica concentrations. In contrast, the 2 wt.% silica specimens showed both higher tensile strength and greater displacement at failure, indicating improved strength without a loss of ductility.

Radiopacity of the samples was assessed by measuring Hounsfield units (HU) using CT imaging software. Baseline samples containing 0 wt.% zirconia nanoparticles were compared to those with 5 wt.% and 10 wt.% zirconia. Higher HU values indicate increased radiopacity. The control sample measured an average of 63 HU (range: 60–65), while the 5 wt.% and 10 wt.% zirconia-reinforced samples measured averages of 132 (range: 129–133) HU and 176 HU (range: 175–179), respectively (**Figure 2**, $n=3$ per group). A one-way

ANOVA revealed a statistically significant difference in radiopacity among the three groups ($p < 0.001$). Post-hoc Tukey analysis confirmed that each incremental increase in zirconia content resulted in a significant increase in radiopacity ($p < 0.001$ for all comparisons), validating the effectiveness of zirconia nanoparticles in enhancing CT visibility.

Scanning electron microscope (SEM) imaging confirmed that silica and zirconia nanoparticles were successfully incorporated into the resin matrix. At higher reinforcement concentrations, a greater area fraction of nanoparticles was visible, consistent with the increased mechanical and radiopacity performance observed. However, the images also revealed notable nanoparticle agglomeration in both the 2 wt.% silica and 10 wt.% zirconia samples (**Figure 3**).

DISCUSSION

This study demonstrates that reinforcing SLA-printed bioresorbable resin with silica and zirconia nanoparticles improves mechanical properties and radiopacity, respectively, advancing the design of FDSs for intracranial aneurysm treatment. The observed increases in tensile strength with higher silica content suggest that silica reinforcement enhances the load-bearing capacity of the resin, which is critical for withstanding arterial pressure during implantation and degradation. Similarly, the rise in HU values with added zirconia in-

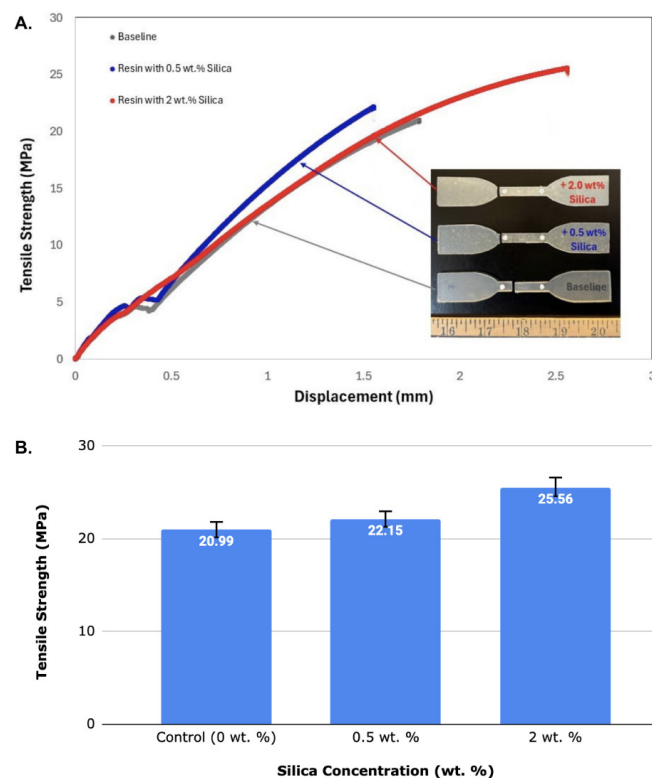


Figure 1: Silica nanoparticle reinforcement improves tensile strength of SLA-printed resin. (A) Load–displacement curves of resin specimens with 0 wt.%, 0.5 wt.%, and 2 wt.% silica under ASTM D638 conditions (11). (B) Corresponding bar graph of mean ultimate tensile strength (UTS) values with error bars representing range ($n = 3$ samples per group). Differences between all groups were statistically significant (one-way ANOVA, $p < 0.00001$; Tukey post-hoc $p < 0.05$). Representative fractured specimens are shown in the inset.

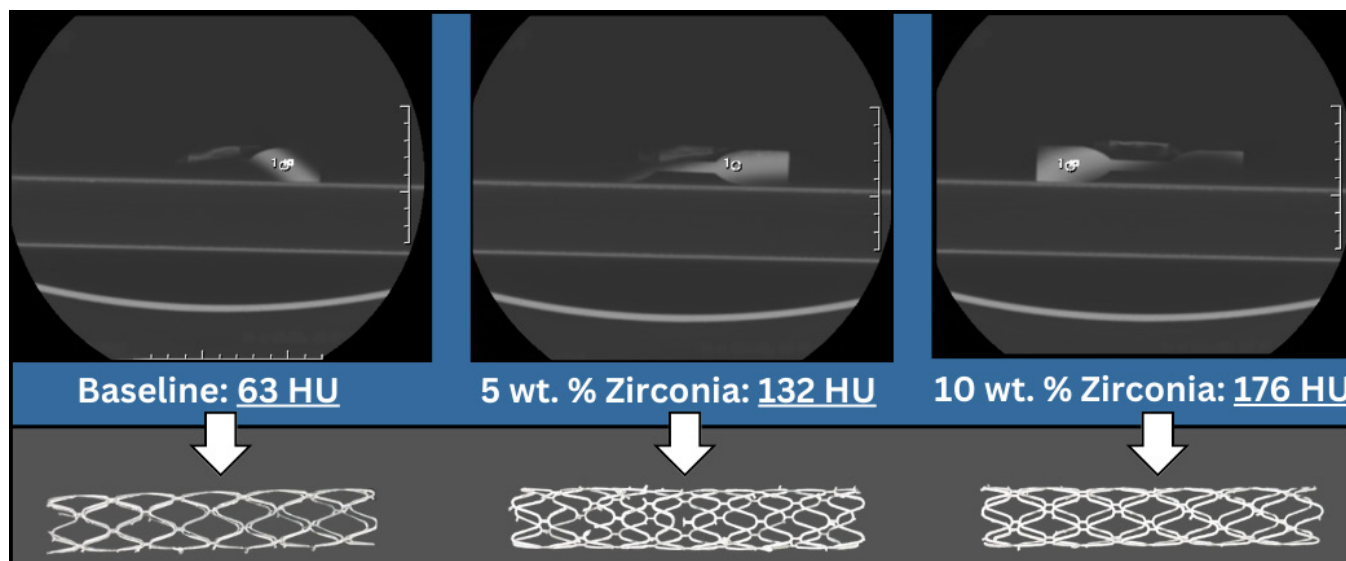


Figure 2: Computed Tomography (CT) imaging reveals increased radiopacity with zirconia nanoparticle reinforcement. Stents containing 0 wt.%, 5 wt.%, and 10 wt.% zirconia nanoparticles were imaged using CT software, and radiopacity was measured in Hounsfield units (HU) ($n = 3$ per group). Statistical significance was assessed using one-way ANOVA ($p < 0.001$). The stent diagrams shown below each CT image are schematic representations provided for visual context, illustrating the intended stent structures at corresponding nanoparticle concentrations.

icates that the radiopacity of the stents can be significantly improved, which may allow for more accurate postoperative imaging and monitoring.

Clinically, flow diverter stents must withstand arterial pressures and be visible under imaging. Metallic stents typically exhibit tensile strengths of 800–1200 MPa and radiopacities of 200–400 HU, while polymeric and bioresorbable alternatives generally range from 20–100 MPa and under 100 HU (2, 9). The reinforced samples in this study demonstrated tensile strengths approaching the lower bounds of clinically relevant performance for polymer-based devices, reaching up to 25.56 MPa. Notably, the radiopacity of the 10 wt.% zirconia-reinforced samples (176 HU) exceeded the typical range for polymeric alternatives and approached the lower threshold of metallic stents (200–400 HU), suggesting that zirconia reinforcement can substantially close the imaging gap between polymeric and metallic devices. These results indicate that nanoparticle incorporation is a meaningful step toward matching the mechanical and imaging properties needed for safe human use, though further optimization is required for clinical deployment.

Previous studies have shown that silica nanoparticles enhance the tensile strength of composite resins and that zirconia fillers increase polymer radiopacity for improved CT visualization (5, 8). However, these studies focused on dental and general implant applications, respectively (5, 8). The present study extends these findings to SLA-printed photopolymer resins designed specifically for intracranial flow diverter stents, where printability, biocompatibility, and vascular mechanical demands introduce unique constraints. The consistency between our results and prior reports supports the potential of nanoparticle-modified bioresorbable stents for clinical translation.

SEM imaging also revealed nanoparticle agglomeration at higher concentrations, particularly in the 2 wt.% silica and 10 wt.% zirconia samples. This clustering could reduce uni-

formity in local mechanical and radiopacity properties, which may affect stent performance in vivo. Improved dispersion strategies may be necessary to achieve more homogeneous composites at higher loading levels, which is critical for ensuring reliable clinical performance.

One limitation of this study is the lack of long-term degradation testing. Without degradation data, it is unclear how nanoparticle reinforcement affects mechanical and radiopacity performance as the resin resorbs over time, particularly if nanoparticle distribution is non-uniform. Additionally, CT imaging was performed on solid tensile specimens rather than fully formed stents, and thin stent struts may exhibit different attenuation characteristics than bulk samples, potentially limiting the applicability of these radiopacity measurements to clinical designs.

Although this study investigated silica and zirconia nanoparticle reinforcement independently, combining both within a single resin could yield synergistic benefits—silica enhancing mechanical durability through polymer matrix reinforcement, and zirconia improving radiopacity for postoperative imaging. However, such formulations may also introduce challenges including nanoparticle agglomeration, phase separation, or altered curing behavior during SLA printing. Future work should therefore assess the compatibility and stability of mixed composites under simulated physiological flow to evaluate mechanical integrity and degradation over time. In parallel, continued development should examine long-term bioresorption, in-vivo performance, and the mechanical behavior of fully printed stents under clinically relevant conditions such as radial expansion, crimping, and fatigue loading. These tests are critical to evaluating structural integrity and ensuring that bioresorbable stents can endure the mechanical demands of vascular environments. Ultimately, this approach could contribute to the next generation of patient-specific aneurysm treatment strategies that reduce complications associated with permanent metallic implants.

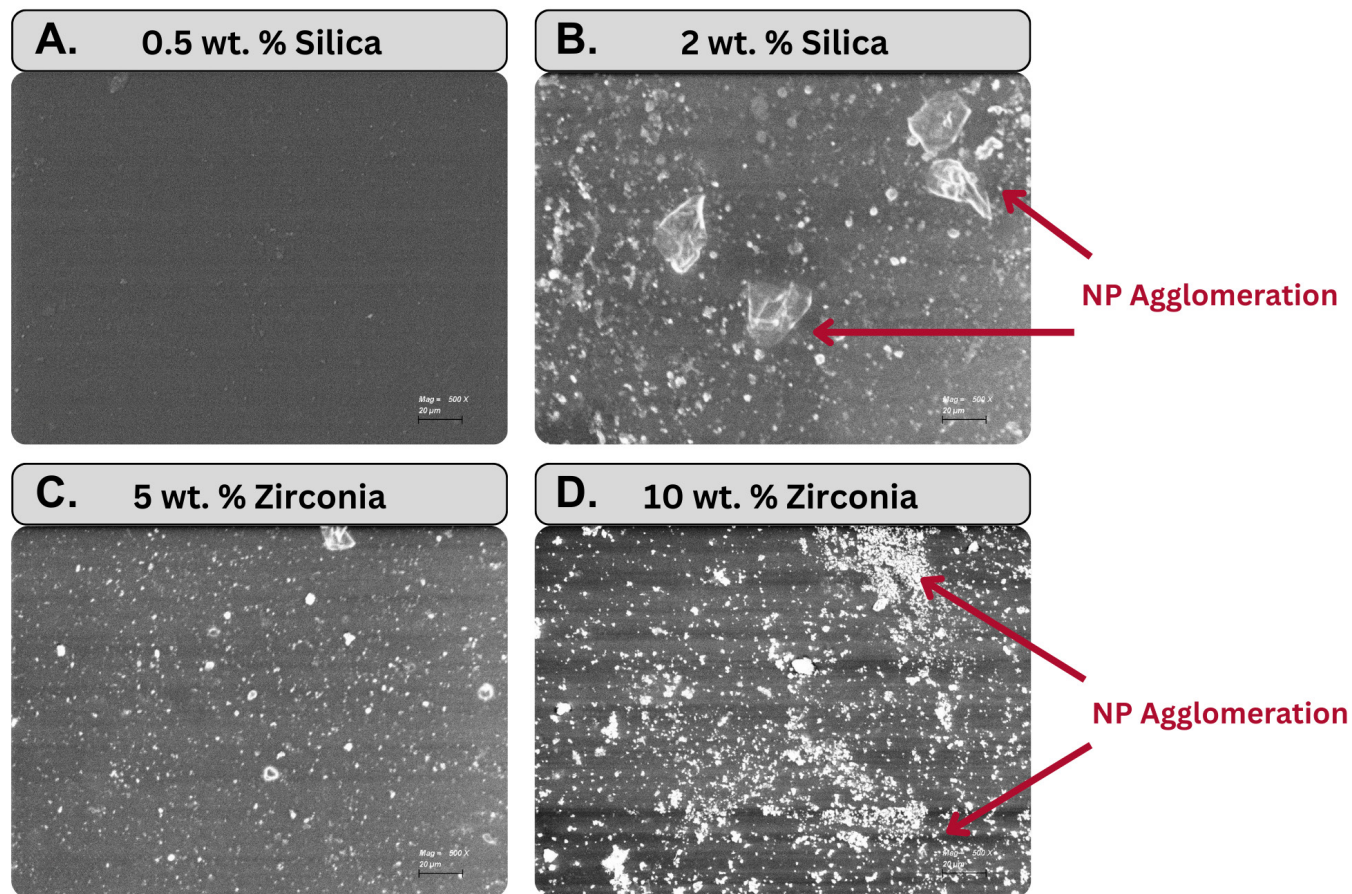


Figure 3: Scanning Electron Microscopy (SEM) images showing nanoparticle dispersion in silica- and zirconia-reinforced stent resin. Cross-sectional SEM micrographs at 500× magnification of resin samples reinforced with 0.5 wt.% and 2 wt.% silica and 5 wt.% and 10 wt.% zirconia. Brighter regions represent nanoparticles, while darker regions correspond to the base resin. Arrows indicate regions of nanoparticle agglomeration and surface defects within the composite matrix.

MATERIALS AND METHODS

Specimen fabrication and resin preparation

A commercially available biocompatible photopolymer resin (Liqcreate Biomed Clear) was used due to its ISO-tested cytocompatibility. To enhance bioresorbable characteristics, poly(ϵ -caprolactone-co-glycolide) (PCGL) was blended into the resin. Five resin compositions were evaluated: a control with no nanoparticle addition, two silica-reinforced formulations (0.5 wt.% and 2 wt.%), and two zirconia-reinforced formulations (5 wt.% and 10 wt.%). Silica and zirconia nanoparticles were sourced from XFNANO. Each mixture was magnetically stirred for 10 minutes to ensure even dispersion of the PCGL and nanoparticles. The resulting composite resins were poured into the vat of an Elegoo Mars 5 SLA printer. Stent and test specimen geometries were designed using Autodesk Fusion and exported as STL files for printing. Stent prototypes were designed with an outer diameter of 10mm and a length of 65mm. All prints were fabricated on an Elegoo Mars 5 SLA printer using a 50 μ m layer height and 8-second exposure time per layer. Printed parts were rinsed for 5 min in isopropyl alcohol to remove uncured excess resin, then post-cured for 8 min under 405 nm UV light to fully polymerize and harden the resin.

Mechanical testing

Mechanical testing was conducted to assess the tensile strength and modulus of resin specimens with and without silica nanoparticle reinforcement. Dumbbell-shaped tensile specimens ($n = 3$ per composition) were printed according to ASTM D638 Type V dimensions. Prior to testing, gauge lengths were marked using a digital caliper, and specimens were mounted in the grips of an electromechanical test system (Instron) equipped with a 1 kN load cell. A clip-on extensometer was attached at the gauge length to record displacement. Testing was performed in load-control mode at a crosshead speed of 5.08 mm/min using Instron control software. Load-displacement data was collected for all samples, and tensile strength was calculated from the resulting stress-strain curves.

CT imaging and radiopacity

Stents containing 0 wt.%, 5 wt.%, and 10 wt.% zirconia nanoparticles were scanned using a standard clinical CT machine. Average HU were calculated using the scanner's software by selecting multiple regions of interest across each stent. HU values were compared across formulations to evaluate the effect of zirconia concentration on radiopacity.

SEM imaging

SEM was used to visualize nanoparticle distribution within the resin matrix. Cross-sectional samples were prepared by fracturing dumbbell-shaped tensile specimens to expose the internal resin matrix. Three images per sample were captured using backscattered electron mode at 500× magnification to distinguish between the polymer base and embedded nanoparticles based on compositional contrast. Bright regions in the images corresponded to the higher atomic number nanoparticles (silica or zirconia), while darker regions represented the base resin. The images were analyzed qualitatively to assess particle dispersion and agglomeration across different reinforcement levels.

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