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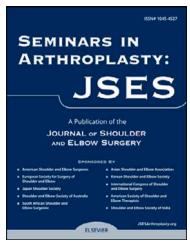

# Osseointegration in reverse total shoulder arthroplasty: a review of implant biomaterials and surface technology

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## ABSTRACT

Implant fixation failure remains a leading cause of revision in reverse total shoulder arthroplasty (rTSA), yet the role of biomaterials in supporting osseointegration has received comparatively less focus than implant geometry or surgical technique. Achieving durable biological fixation requires a careful balance of surface roughness, porosity, and material composition, all factors that have evolved significantly over the past 2 null decades. This review takes a historical approach to the development and progression of biomaterials in rTSA, detailing the transition from smooth machined titanium to advanced porous structures designed to enhance bone integration. Key surface technologies are reviewed chronologically, including grit-blasted titanium, sintered beads, titanium plasma spray, hydroxyapatite coatings, diffusion bonding, trabecular metal, and modern 3D-printed architectures. For each, we outline the manufacturing methods, decision-making rationale, and clinical relevance. By mapping how fixation strategies have changed over time, this review provides a structured understanding of how biomaterials contribute to implant stability and highlights where gaps in evidence remain. As new technologies emerge, the future of rTSA fixation will depend on integrating innovation with material designs that have proven long-term performance. This review offers a framework for understanding current options and guiding material selection in clinical practice.

***Level of evidence:*** Level V; Review Article; Expert Opinion

***Keywords:*** Shoulder arthroplasty; Osseointegration; Biomaterials; Implant fixation; 3D-printing; Hydroxyapatite



Implant design and fixation techniques in reverse total shoulder arthroplasty (rTSA) have been extensively studied and refined since the first rTSA became available in the US in 2003. On the glenoid, design features such as the central compression screw or post with surrounding peripheral screws have been optimized to maximize initial fixation, reduce micromotion, and help with bone attachment.[36,53,62] On the humerus, fixation with porous coatings have emerged as the market has shifted from cemented to press-fit components.[42] These design developments have optimized fixation and expanded the indications for rTSA, including complex conditions previously deemed inoperable. Despite these

Institutional review board approval was not required for this review article.

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https://doi.org/10.1016/j.sart.2026.151553

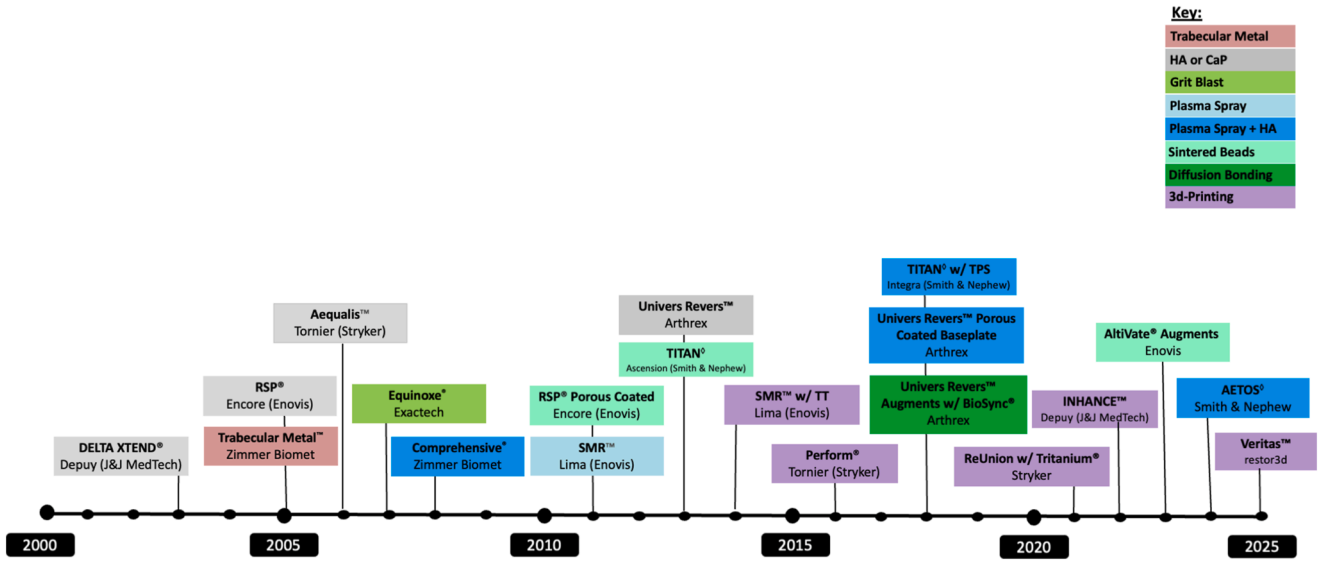


**Figure 1** – Evolution of materials used in reverse total shoulder glenoid baseplates in USA. *HA*, hydroxyapatite; CaP, calcium phosphate.

design improvements, in indications of challenging deformity or bone loss, component loosening is still remaining a cause of rTSA failure.[65,70] Achieving integration of the native bone to the implant interface is critical to minimize the risk of loosening with a variety of factors contributing to this osseointegration, including both mechanical fixation and the biological response to implant material.[55] Implant design advancements have received significantly more attention than the role of material and surface technologies in promoting osseointegration.

Evolution in manufacturing processes has enabled the development of rTSA implants with diverse roughened surfaces and various pore geometries and sizes; however, limited research exists on the optimal characteristics for these components and surface technologies. Implant material selection and surface modifications significantly influence the bony ingrowth and fixation of metal implants through factors including porosity, surface roughness, and material stiffness.[27,55,63,66] This review examines the evolution of implant materials and surface technologies with a summarized timeline see in Figs.1 and 2, specifically for rTSA, to highlight the role of biomaterials in achieving component fixation.

## Material properties that influence osseointegration

Osseointegration is the process by which a surgical implant becomes firmly anchored to bone through the formation of bone tissue, which can occur through bony ongrowth and bony ingrowth, both of which are crucial to maximizing the long-term stability of an implant.[49] Bone ongrowth relies on surface geometry and biological environment to support bone formation on a roughened two-dimensional implant surface.[47] Bone ingrowth creates a mechanical interlock between the implant and bone through bone tissue formation inside three-dimensional pores on an implant. Several material properties significantly influence this attachment process, including biocompatibility, stiffness, porosity, roughness, and surface chemistry.[28] Table I provides a comparison of material properties to native bone, while Table II outlines the characteristics of osseointegrative materials commonly used in shoulder arthroplasty implants. It is important to remember that while promoting osseointegration allows for decreased loosening of implants, it also increases the risk of bone loss when removing components in the revision setting.

## Biomaterials and fixation in rTSA implants

### *Machined titanium*

Titanium alloys (most commonly Ti-6Al-4V) have been used since the 1950s for orthopedic implants due to their high biocompatibility and corrosion resistance. Titanium first gained prominence in hip and knee arthroplasty during the 1950s and 1960s, and success in these applications led to its adaptation for shoulder implants with the first being in the Grammont prosthesis and Kessel screws.[35] Traditional manufacturing of titanium relies on subtractive manufacturing methods such as forging, milling, or turning, where metal stock is shaped into the desired geometry. This results in a polished surface with minimal surface roughness.[22] Clinical outcomes and retrieval studies for Kessel screws ultimately revealed that smooth titanium surfaces did not facilitate adequate osseointegration, leading to frequent cases of implant loosening.[8] The absence of surface roughness or porosity limited bone cell attachment and proliferation.[17] Smooth titanium is no longer utilized for noncemented rTSA components due to these limitations, and

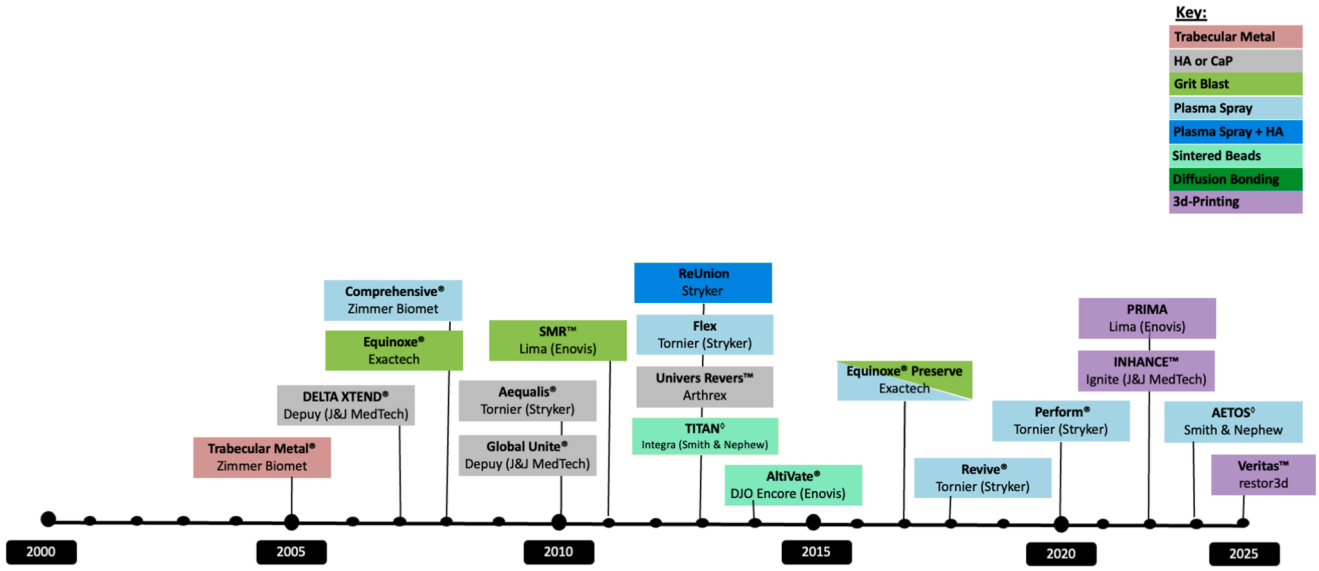


**Figure 2** – Evolution of materials used in short and standard uncemented humeral stems in USA. *HA*, hydroxyapatite; CaP, calcium phosphate.

**Table I – Osseointegrative surface characteristics. Summary of biomaterial properties and surface modifications designed to enhance osseointegration.**

| Surface property | Definition | Impact on osseointegration | Comparison to native bone |
|---|---|---|---|
| Biocompatibility | Biocompatibility is the fundamental requirement for any implant material, ensuring that it does not elicit an adverse immune response and supports cellular activities necessary for tissue integration.[45] | The oxide layer on titanium surfaces not only prevents ion release into surrounding tissues but also enhances the adsorption of proteins that facilitate cell adhesion.[21,23] | N/A |
| Roughness (Ra) | Micro- and nanoscale surface irregularities define the surface environment for osteoblast activity. | Microscale roughness can stimulate osteoblast activity, leading to increased bone matrix production and faster bony ongrowth.[25] | Cortical bone: 1-3 μm[15]<br>Trabecular bone: 10 nm[15] |
| Porosity (%, pore size) | The interconnected channels within an implant that provides space for bone ingrowth and vascularization.[31] | Provides space for bone ingrowth and vascularization, leading to a stronger mechanical interlock. Allows for ingrowth rather than ongrowth. New research suggests that larger pores up to 600 μm may facilitate stronger integration between implant and bone.[34] | Trabecular bone: 78%-92%, 300-500 μm[22] |
| Stiffness | The elastic modulus of the implant, which defines how load is absorbed or distributed relative to the surrounding bone. | Stress shielding is a phenomenon in which bone resorption occurs due to a mismatch in stiffness between the implant and bone. By optimizing stiffness, implants can achieve a balance between mechanical support and biological compatibility.[5] | Cortical bone: 18-25 GPa[66]<br>Trabecular bone: 1-5 GPa[71] |
| Surface chemistry | The charge and wettability of a surface, which affects protein adsorption and subsequent cell attachment. | Hydrophilic surfaces can promote osteoinduction, encouraging undifferentiated cells to develop into bone-forming osteoblasts.[60] | Calcium phosphate, which is found in the form of nanocrystalline hydroxyapatite (HA) |

*N/A*, not applicable; *GPa*, Gigapascal; *μm*; micrometer; *nm*, nanometer.

modern reverse total shoulder implants have adopted surface modifications to enhance osseointegration.

### *Grit-blasted titanium*

As a solution to limitations of machined smooth titanium, grit-blasted titanium implants gained prominence in the 1980s, initially used for acetabular cups in total hip arthroplasty (THA). Producing these implants involves subjecting implant surfaces to high-velocity streams of abrasive particles, such as aluminum oxide or titanium oxide, creating microscopic pits and peaks that enhance mechanical interlock between the bone and implant.[9,44] The resulting surface roughness includes divots ranging between 3 and 8 μm, which

**Table II – Characteristics of osseointegrative materials in reverse total shoulder implants. Material properties and surface technologies for enhanced osseointegration.**

| Material | Roughness (Ra) | Pore size | Porosity | Thickness | Stiffness | Surface chemistry |
|---|---|---|---|---|---|---|
| Machined titanium | 0.15 μm[69] | X | X | X | 120 GPa[17] | None |
| Grit-blasted titanium | 0.5-2 μm[70] | X | X | X | 120 GPa[17] | None |
| Sintered beads (SBS) | 50-100 μm[4] | 250-450 μm[4] | 30%-50%[51] | 0.5 mm-1.5 mm[51] | 1-10 GPa[51] | None |
| Titanium plasma spray (TPS) | 20-55 μm[28] | 100-250 μm[39] | 30%-60%[41] | 1 mm[41] | 120 GPa[17] | None |
| Hydroxyapatite coating (HA) | 30-50 μm[25] | 200-500 μm[25] | 10%-30%[64] | 60-150 μm[64] | 70 GPa[68] | Calcium phosphate |
| Trabecular metal (TM) | 53 μm[7] | 450 μm ± 300 μm[7] | 75%-80%[7] | 750 μm[7] | 3 GPa[7] | None |
| Diffusion bonding (DB) | NR | 523 μm[72] | 58.8%[72] | 1 mm[72] | 3.2 GPa[72] | None |
| 3D-printed implants* | 9 μm[34] | 400-1200 μm[34] | 55%-75%[34] | Varied | 1-6 GPa[34] | None |

*NR*, not reported; X, not applicable; *GPa*, gigapascal; *μm*; micrometer; mm, millimeter.
* 3D-printing is a manufacturing modality and implants can feature a variety of osseointegrative structures. Values shown here reflect the range on reverse total shoulder implants commercially available in the US, today.

leads to bony ongrowth but not bony ingrowth due to the shallow two-dimensional nature of the texture.[5,74]

Studies comparing grit-blasted surfaces to polished titanium have demonstrated increased bony contact and improved cell attachment in vitro, as well as higher pull-out strength and enhanced initial stability in animal models.[9,44,52] However, clinical data on rTSA suggest grit-blasted humeral stems still carry a risk of loosening. In a multicenter study of short humeral stems made of grit-blasted titanium without ingrowth coating, 12.5% of patients presented with potential humeral loosening and 7.11% underwent revision surgery where a loose stem was confirmed. While these data are relatively short-term, grit-blasting alone may not allow for sufficient bone ingrowth to prevent component loosening in shoulder arthroplasty but more research is needed.[1]

In modern rTSA systems, grit-blasted surfaces have been incorporated into some components, but it is not the most used surface coating by the major market players (Figs. 1 and 2). Specifically, the Equinoxe (Exactech) glenoid baseplate features a grit-blasted porous cage and current standard length humeral stems have a grit-blasted proximal finish. Oftentimes, grit-blasting is used in combination with other coatings, enhancing adhesion and providing a base roughness that supports osseointegration.[48]

### *Sintered beads (SBS)*

Sintered bead technology emerged in the late 1970s and early 1980s, offering a new approach to porous coatings for orthopedic implants. Sintered beads were first applied to femoral stems in hip arthroplasty, laying the groundwork for their adaptation in rTSA decades later.[13] The introduction of sintered beads in rTSA coincided with a broader shift away from cemented implants toward cementless designs, emphasizing biological integration overall mechanical fixation.[16] This manufacturing process involves applying a layer of metallic beads onto a machined implant surface through sintering, wherein the beads are heated just below their melting point to form a cohesive layer to the surface of the implant.[38] Materials with similar melting points must be used for sintering (eg, titanium alloy), and spherical or nonspherical beads can be used as the substrate, but nonspherical, smaller beads are more commonly used in contemporary implants. The resulting surface has beads sized between 200 and 800 μm, creating interconnected pores that support bone ingrowth and vascularization. These coatings are typically limited in thickness from 0.5 mm to 1.5 mm, and volumetric porosity can range from only 30%-50%.[4,41] As shown in Figs. 1 and 2, sintered beads are only featured on a few rTSA systems from the major market players. These are the Titan System (Smith & Nephew) and AltiVate (Enovis), including the legacy RSP baseplate, glenoid augments, and short and standard length humeral stems.[54]

While there have been several reports of bead debonding or delamination from the acetabular component in THA, especially when cobalt-chromium beads are used, the majority of animal studies have shown that sintered bead surfaces can improve initial implant stability and reduce micromotion.[14,28] In rTSA, a 5-year case report of 94 patients who received the DJO system with sintered beads showed no evidence of glenoid loosening and 3% of patients with humeral loosening.[11]

### *Titanium plasma spray (TPS)*

Titanium plasma spray (TPS) coatings emerged in the 1990s as a method to combine roughness and porosity for enhanced osseointegration. TPS involves coating the implant surface with titanium particles using a thermal spray with a high-temperature plasma flame, where it melts and is projected onto the implant surface. A high voltage ionizes an inert gas, such as helium, to create the plasma and the molten particles rapidly solidify, forming a porous coating with micro- and macro-level roughness and some porosity. Plasma spray creates an asymmetric lattice with a porosity is between 30% and 60%, a thickness that can range from 0.05 mm to 0.2 mm, and roughness that can be an order of magnitude higher than grit-blasted surfaces, ranging between 3 and 5μm.[32] Many major market rTSA systems utilize TPS, especially on the humeral side (Fig. 2). Specifically, the Comprehensive (Zimmer Biomet) and Flex, Perform, and Revive (Stryker) all feature TPS on short- and standard-length humeral stems (Fig. 2). On the glenoid side (Fig. 1), TPS is often used in conjunction with hydroxyapatite (HA), such as on the Comprehensive (Zimmer Biomet) baseplate.

Compared to grit-blasted surfaces, plasma-sprayed implants have exhibited stronger integration to bone in animal models.[67] Implants with plasma spray coatings have shown better response to micromotion and resistance to microfractures

in vivo.[21] The interlocking of bone within the porous structure helps distribute stress, reducing the risk of implant loosening due to micromotion. In clinical usage, a study of 33 patients with short-stem Ascend Flex implants, no cases of radiographic loosening were observed at 27 months. In addition, in a 15-year study of the Norwegian Shoulder Registry there were no cases of humeral loosening with the 369 Ascend Flex implants.

### *Hydroxyapatite coating*

HA coating is often used in combination with titanium plasma spray and was introduced commercially in the early 1990s for femoral stems in hip arthroplasty. HA is a bioactive layer composed of a naturally occurring calcium phosphate material, $Ca_{10}(PO4)_6(OH)_2$, that is applied to increase the osseointegrative properties. The calcium-to-phosphate ratio of these coatings is 1.65, which is very close to the ratio found in native bone (1.67).[3] Similar to titanium coating, HA coating is typically applied by plasma spray, in which the powder is melted in a plasma flame and projected onto the implant surface. When combined with titanium plasma spray, each implant surface has a dual-layer coating.[51] Even without titanium plasma spray coatings, HA coatings can be porous themselves, with a lattice structure and roughness with a porosity of about 30% due to the crystalline structure of the material.[19] One limitation, however, is that some studies in THA have reported delamination of HA coatings, particularly where coating thickness exceeds 1 μm.[58]

HA coating is widespread in reverse total shoulder implants. Early-generation systems, including DELTA XTEND Reverse Shoulder (DePuy Synthes), ReUnion RSA System (Stryker), and Aequalis Reversed Shoulder System (Stryker), feature HA coatings (Fig. 1). In newer systems, HA coating is typically combined with titanium plasma spray. These systems include SMR Shoulder System (Lima) and the ReUnion Shoulder System (Stryker). Some other reverse total shoulder implants, such as the Univers Shoulder System (Arthrex) humerus, use an alternative calcium phosphate coating with slightly different chemical structures but that serve the same purpose as HA in enhancing bone bonding and osseointegration.

Animal studies have demonstrated that HA-coated implants can be osteoinductive and promote bone ingrowth by inducing the expression of key osteogenic genes such as alkaline phosphatase, osteocalcin, and collagen.[7] Animal studies using canine tibias have shown that HA-coated implants tend to perform better than TPS implants when subjected to micromotion.[61] Several clinical studies have explored the efficacy of cementless fixation with plasma-sprayed titanium and HA in the setting of rTSA. A randomized controlled trial involving 20 patients using the SMR glenoid baseplate found greater motion was observed for non-HA coated implants, but no significant differences in clinical outcomes were seen between TPS baseplates with and without HA coatings.[37] In a longer-term study for TPS + HA stems in THA, similar positive results were achieved at 10-year follow-up study, where 301 THA surgeries reported no stem revisions due to aseptic loosening.[34] In addition, in a 15-year study of the Norwegian Shoulder Registry, there were only 4 cases of humeral loosening with the 3,865 HA coated implants.

### *Trabecular metal*

The success of coatings like HA inspired the development of trabecular metal (TM), which attempts to mimic the random structure of trabecular bone. TM implants, which gained commercial use in the early 2000s, are porous foams primarily manufactured from tantalum.[33] The process begins with a piece of polyurethane foam, a lightweight and flexible material with an open-cell structure that serves as a template for the porous structure.[69] The polyurethane foam undergoes pyrolysis, a thermal decomposition process, leaving behind a low-density vitreous carbon skeleton. The carbon skeleton retains the foam's original porous structure which is then placed in a chamber where tantalum is vaporized and infiltrates the carbon structure and coating both the interior and exterior surfaces of the carbon skeleton. In this process, tantalum is used due to its low reactivity and stability in vapor deposition and this results in a high porosity of approximately 75% to 80%. The pore sizes, ranging from 450 μm ± 300 μm, are larger than those created with sintered beads or plasma spray techniques.[6] The elastic modulus of the material is 3 GPa, closely aligning with the mechanical properties of cancellous bone. The Trabecular Metal Reverse Shoulder (Zimmer) is the primary example of TM in rTSA.[20]

TM is designed to more closely mimic cancellous bone's porous architecture and a modulus of elasticity similar to bone, thereby reducing stress shielding.[31] In animal models, trabecular titanium (TT) has demonstrated significantly more bone ingrowth when compared to sintered beads and plasma-sprayed alternatives.[6] When implanted in a canine pushout model, the amount of bone ingrowth was comparable to alternative materials, but the strength of bone–implant attachment was higher due to the larger pore size. Because trabecular metal's elastic modulus is closer to that of natural bone than titanium, it may offer superior stress distribution in implants for rTSA.[18,56]

In clinical applications, TM has been used in acetabular cups for THA since the mid-2000s. Three-year outcomes of TM acetabular components demonstrated similar revision rates compared to other uncemented THA components in a cohort of over than 5,000 surgeries.[30] Specifically, in rTSA, 5-year outcomes of rTSA using TM glenoid components have been found to be comparable to other baseplates in study involving 243 patients.[24,64]

### *Diffusion bonding*

The development of advanced orthopedic implants has led to the creation of diffusion-bonded porous metal structures, which, like TM, attempts to mimic the architecture of cancellous bone but are manufactured using a different method. Diffusion bonding involves the creation of a solid-state bond between 2 or more metal components (one solid and one porous) without melting them. In this manufacturing method, a powder or fiber is used as substrate and then is aligned and clamped into the desired lattice structure. Once aligned, a uniaxial pressure is applied along with heat below the material melting point to create atomic diffusion across the components.[15] This combination of heat and pressure

allows for the mechanical bond to be created while maintaining the aligned lattice structure. The resulting bonds are strong, retaining up to 90% of the tensile strength of the initial material.[15] Diffusion bonded materials have existed in orthopedics for decades primarily in the setting of THA.[45] In rTSA, diffusion bonding is used in the Arthrex BioSync porous structure, which is found in the current generation Univers Reverse (Arthrex) baseplate design. This porous structure closely matches the material properties of native cancellous bone, with a porosity of 58.8% and a mean pore size of 523 mm.[72]

In animal studies, BioSync has been compared to other porous scaffolds. For example, in a dynamic canine hip model, it showed negligible stem subsidence and achieved 75.4% bone ingrowth in 12 weeks, surpassing the results of sintered beads and TM. In addition, a static canine long-bone model revealed significantly higher push-out strengths than polyetheretherketone (PEEK), anodized titanium, and allograft controls, with nearly complete cortical bone integration (90%-100%) and excellent trabecular infiltration (>75%) within six weeks.[73] While these results are promising, there are relatively few clinical studies focusing on integration into BioSync implants in the setting of rTSA. In a multicenter study of 187 patients who received the Arthrex Universe Reverse Implant, there was no evidence of radiographic loosening or implant migration at 2 years.[59]

### *3D-printed (3DP)*

The most recent innovation is 3D-printed orthopedic implants, which were introduced commercially in the mid-2010s. Additive manufacturing technologies utilize electron beam melting (EBM) or selective laser melting (SLM) to build the implant from metal powder. The metal powder is selectively melted using a laser or electron beam in a layer-by-layer fashion, allowing precise control over geometry and porosity and seamless integrations between the solid and porous regions of an implant and improvement in mechanical properties. SLM occurs with a 20-100 μm laser beam at relative lower temperatures around 100°-300°C in the setting of inert gas, which allows for high-resolution parts with a smoother surface finish.[12] Because of the relatively low overall temperature, some impurities can be present, so a hot isostatic pressing is a post-treatment process in which the parts are subjected to increased heat and pressure to remove impurities.[23]

In EBM printing, a larger diameter high-energy electron beam is used to melt and fuse metal powder in a vacuum chamber. This process operates at much higher temperatures often exceeding 1,000°C, making it only suited for select materials such as titanium and cobalt-chromium.[12] The high heat causes full melting of the powder leading to denser parts when compared with SLM and higher surface roughness and decreased part resolution when compared to SLM.

Compared with conventional machining, in both EBM and SLM printing, the as-printed surface of titanium without any porosity is very rough, making this modality suitable for bone growth. In animal models, printed parts with no added porosity have even shown superior osseointegration strength compared to machined and grit-blasted titanium implants with HA coatings. Much like TM, this technology can produce implants that mimic trabecular bone, promoting vascularization and bone ingrowth; however, the versatility of 3D-printing allows structures that are even better optimized for bony ingrowth.[26] For example, 3D-printed titanium is the market standard for acetabular cups, and as of 2020, there are seventeen 3D-printed acetabular cups on the market dating back to 2007.[12]

The 2 major categories of 3D-printed structures are strut-based and sheet-based structures. In strut-based structures, beams or rods (struts) form an open, lattice-like architecture that is strong and stiff for its weight and perform well under static loads, with lower surface areas compared to sheet-based designs. Sheet-based structures, such as triply periodic minimal surfaces, consist of continuous, thin surfaces that have a higher surface area and are less stiff, providing greater flexibility and energy absorption capacity compared to strut-based structures.[2]

Several different 3D-printed structures are used in rTSA implants on the market today. TT used on the SMR (Enovis) glenoid baseplate was the first 3D-printed structure to the US rTSA market, cleared in 2014 (Fig. 1). TT is a strut-based design manufactured with EBM printing, with a porosity between 65% and 72%, a pore size of 600 μm, and an elastic modulus of 1 GPa.[10] Clinically, In a 5-year follow-up study of TT acetabular cups in primary THA patients, 99.3% of acetabular components were radiologically stable at the last follow-up.[40,50] With the SMR (Enovis) system, a case series of 16 consecutive patients treated with a TT glenoid implant in the context of bone loss reported all patients had successful graft integration with no component loosening.[39] In another prospective study with a 2-year follow-up, 5 of 41 patients treated with a TT glenoid and bone graft for severe bone loss exhibited radiolucent lines.[57] Beyond TT, other 3D-printed structures have been developed for reverse total shoulder implants, each with unique design features and biomechanical properties. Table III summarizes the key characteristics of 3D-printed structures currently available.

ADAPTIS technology, introduced in 2016, is a strut-based titanium lattice created through a laser melting process. This structure is currently featured on the Perform Reversed Baseplates (Stryker) and the ShoulderID baseplate (Stryker). There is limited published data specifically assessing this structure, but internal data at Stryker indicates increased bone ingrowth at 4 weeks and 12 weeks compared to a plasma-sprayed alternative. Augmented baseplates with this printed structure have been analyzed in a sample of 44 patients at 1 year post-operatively, with no evidence of glenoid loosening.[29] Tritanium is another 3D-printed porous structure used on the glenoid baseplate of the ReUnion RSA (Stryker). Similar to ADAPTIS, this structure is strut-based and manufactured via SLM printing, with an average pore size is 400-500 μm, mean porosity of 55%-65%, and elastic modulus of 6.2 GPa.[43] While there are limited data available on the use of Tritanium in shoulder, it is used on the tibial component on the Trialathon Knee (Stryker), and a review of the American Joint Replacement Registry over 28,000 tibial components showed that the Tritanium components had increased survivorship.[46] UNITI titanium porous structure, featured on both

**Table III – Characteristics of 3D-printed structures available in reverse total shoulder implants.**

| Structure name | Structure type | Printing method | Roughness | Pore size | Porosity | Stiffness |
|---|---|---|---|---|---|---|
| As-printed titanium | None | SLM | 9 μm[35] | N/A | N/A | 105-115 GPa[34] |
| Trabecular titanium (TT) | Strut | EBM | 20-50 μm[12] | 600 μm[12] | 65%-72%[12] | 1 GPa[12] |
| ADAPTIS™ technology | Strut | SLM | NR | NR | NR | NR |
| Tritanium | Strut | SLM | NR | 400-500 μm[13] | 55%-65%[13] | 6.2 GPa[13] |
| UNITI™ (JnJ/INHANCE™) | Strut | SLM | NR | 500-600 μm[75] | 66%[75] | NR |
| TIDAL (restor3d) | Sheet | SLM | 9 μm[34] | 1200 μm[34] | 60%-70%[34] | 5 GPa[34] |

*NR*, not reported; *SLM*, selective laser melting; *EBM*, electron beam melting; *GPa*, gigapascal; μm; micrometer; *N/A*, not applicable.

the humeral and glenoid components, was introduced in 2021 as part of the INHANCE Shoulder System (Johnson & Johnson MedTech, Warsaw, IN, USA) with a strut-based selective laser melting process. UNITI has a 66% porosity and 500-600 μm average pore size for effective biologic fixation. However, there are minimal published data on this porous structure.[75]

TiDAL technology (restor3d) is a sheet-based triply periodic minimal surface structure, commonly known as a "gyroid," that is used in patient-specific baseplates. It consists of titanium alloy with fully interconnected pores and 60%-70% porosity. TiDAL provides a large surface area for bone ingrowth while maintaining an elastic modulus of 5 GPa.[25] In an ovine cortical model, pushout testing revealed that porosity levels of 60%-70% providing the highest shear strength at the bone–implant interface.[27] When TiDAL was tested in the same ovine lumbar fusion model used to develop Tritanium, the TiDAL cage outperformed all other porous structures and autograft in fusion of flexion and extension.[43]

The technology is promising in cases for massive bone loss. A review article demonstrated a 64% improvement in failures in tibiocalcaneal arthrodesis rates in diabetics at an average 2-year follow-up with a TiDAL fusion cage.[76] Currently, there are no published results of TiDAL technology's use in rTSA.

## Discussion

The biomaterials used in rTSA implants have evolved significantly over the last 2 null decades (Figs. 1, 2). The evolution of implant technology has addressed critical issues such as osseointegration, implant stability, and fixation failures. Early rTSA implant designs relied on smooth machined titanium, providing limited or no capacity for osseointegration and often leading to implant loosening and the need for revision surgeries. Studies have shown that the overall rate of glenoid loosening ranges from 0.7% to 3% but can be as high as 17% in revision settings.[1–3] On the humeral side, loosening is relatively less common and seen in 0.7%-1.4% of cases and up to 2.8% of revisions.[1,2] Surface treatments and manufacturing techniques, including TPS, sintered bead surfaces and HA coatings, have become widely adopted in clinical settings to provide improve osseointegration and long-term implant stability. Although there is still limited validation in clinical research in shoulder arthroplasty, there is evidence these techniques promote osteointegration, reduce micromotion, and provide durable fixation.

Newer advancements, particularly in 3D-printing, have introduced new possibilities for optimizing implant designs. Technologies developed through additive manufacturing, offer superior control over porosity, surface structure, and mechanical properties. By providing more explicit control of porosity, these 3D-printed implants may promote improved osseointegration and load distribution. However, despite these promising features, the clinical use of 3D-printed implants in RSA is still relatively recent, and there is a lack of clinical data to substantiate their effectiveness. Older manufacturing methods, such as HA coatings and sintered beads, have been effective for a broad range of patients and remain used in many legacy systems. Essentially all new RSA are 3D-printed, and as 3D-printing technology continues to evolve, further research and long-term clinical studies will be necessary to validate its potential superiority over older legacy implant surfaces and materials.

## Conclusion

Biomaterials used in rTSA implants have evolved significantly over the last 2 null decades to address critical issues such as osseointegration, implant stability, and fixation failures. Over the last 20 years, there has been a rapid progression of implant innovation with evolution and use of an array of various biomaterials for both the glenoid and humeral sided implants (Figs. 1, 2). Traditional coatings like sintered beads, TPS, and HA have demonstrated consistent success over decades of clinical use and reliable performance in promoting osseointegration and long-term implant success. Although newer technologies such as 3D printing in rTSA offer more customization and enhanced bone integration, these technologies currently lack the extensive clinical track record of legacy methods. Notably, enhanced osseointegration of newer implants could prove more challenging for future revisions by creating further bone loss in removal.

The choice of implant technology must be guided by evidence-based practice with the goal of optimal performance and fixation. Established methods remain highly effective for most cases and are supported by a wealth of clinical data. Although 3D-printed implants hold great promise for addressing unique challenges in rTSA, such as complex anatomical requirements or poor bone quality, additional research is needed to validate their long-term outcomes compared to the relatively low rates of loosening seen today. As rTSA continues to evolve, the future lies in balancing innovation and evidence-based practice to optimize implant fixation and outcomes. Innovative material improvements will continue to develop with time, as ongoing research into methods, including biodegradable coatings and

bioactive materials, holds the potential to completely transform the approach to osseointegration in rTSA.

## Disclaimers:

Funding: No funding was disclosed by the authors.

Conflicts of interest: Benjamin Wesorick reports stock ownership in restor3d and serves as a consultant for the company. Ken Gall reports stock ownership in restor3d and serves as a consultant for the company. Vani J. Sabesan reports stock ownership in restor3d and serves as a consultant for the company. Any additional authors, their immediate families, or any research foundation with which they are affiliated have received financial payments or other benefits from any commercial entity related to the subject of this article.

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