Three-Dimensional Printing in Urology: History, Current Applications, and Future Directions

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Three-Dimensional Printing in Urology: History, Current Applications, and Future Directions

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Abstract:
To review the history, current applications, limitations, and future directions of three-dimensional (3D) printing within the field of urology. 3D printing is an additive manufacturing process in which a 3D model is created using a computer-generated image. This technology is applied by companies to create and test new drugs, design and manufacture instrument prototypes, and create patient-specific models of organs.
for surgical teaching and planning. A literature review was performed within the Web of Science and PubMed databases from January 2008 to May 2018 using keyword phrases “3D printing” and “urology.” A total of 46 relevant publications were included.

*Key Words:* three-dimensional; urology; printing; technology
Introduction:

Three-dimensional (3D) printing (3DP) was invented by Charles Hull in 1986\(^1\). It is a form of additive printing in which layer after layer of selected materials are laid to form a designed object with computer-guided instructions using a specialized device or printer. The process involves building a solid, 3D object from a digital model using additive processes in which successive layers of material are assembled on top of one another to build the desired object. Items for the 3D object are assembled directly from the digital model, increasing precision and removing room for error. This results in high-quality, low-cost products that can be created and diffused on a large scale. While various fields from the automotive industry to the aerospace industry have embraced this technology, healthcare has been slow to adopt this technology even though an excess of $155 billion is spent on medical devices yearly. 3DP was initially met with tremendous enthusiasm in the 1990s with great excitability about its potential uses in healthcare. The enthusiasm faltered somewhat at the turn of the millennium with resurgence in recent years.

The potential applications of 3DP in clinical medicine are numerous\(^2\). It can allow physicians to create patient-specific models of pathology with such precise anatomic detail that it facilitates pre-procedural planning prior to treatments. For example, patient-specific models of diseased or cancerous organs could be constructed to help better plan for surgical procedures to improve efficiency, minimize blood loss, and ultimately translate into better patient outcomes. 3DP can also play a role in the development of personalized prosthetics for amputees or artificial organs for transplant candidates as acceptable donor organ numbers continue to dwindle. 3DP can also
serve as an important teaching tool and training adjunct in medical education not only for medical students and residents, but also in the counseling of patients and their families with regards to disease management and procedural description\textsuperscript{3}. Finally, 3DP can allow for the creation of bioprinted cells for the testing and development of novel medications or targeted agents to better replicate its potential use and efficacy in actual patients\textsuperscript{4}. Various medical subspecialties have already extensively studied the application of 3DP into their clinical practice. Orthopedic surgeons have evaluated its clinical utility in joint replacement, otolaryngologists have examined its potential use for implantation in the external ear, cardiologists have looked into its ability to create implantable artificial heart valves, and trauma surgeons have been able to grow skin cells using 3DP for grafting and coverage of severe burns and wounds. The field of urology is just beginning to realize the potential impact of 3DP in pre-surgical planning, medical education, as well as the creation of personalized prosthetics or other devices in the treatment of patients\textsuperscript{5}. The following review examines the technology behind 3DP, its current utilization in the field of urology, its limitations, and potential future applications.

**Methods:**

A comprehensive literature review was performed within the Web of Science and PubMed databases from January 2008 to May 2018 using keyword phrases “3D printing” and “urology.” Initially, 76 relevant peer-reviewed publications were identified using our search criteria with 64 found within PubMed and 10 found within the Web of Science. Preferred Reporting Items for Systematic Reviews and Meta-Analyses
(PRISMA) was used as an evidence-based criterion to select publications for analysis (Appendix A). After the exclusion of 10 editorial comments or author responses, 8 non-urological publications, and 2 publications with no clinical relevance or patient-related data, a total of 46 publications were included for review.

**Background of 3DP:**

*Model Design and Creation*

The first step in the process of 3DP is designing the prototype or the model. Data for designs can be collected from various sources of advanced imaging such as high-definition ultrasound, computed tomography (CT) scan, magnetic resonance imaging (MRI), or angiography. Using compatible 3DP software, data from two-dimensional (2D) digital images can be fed into a 3D printer and converted to a 3D geometric model.

Many 3D printers are currently available for commercial use using different technologies and materials to create physical objects *(Table 1)*. Fused Deposition Modeling (FDM) is one of the most common printing methods in which a filament is heated and extruded via a head onto the printer. Liquid plastic is then deposited as per x and y coordinates onto the building platform in the desired shape. Another method, called stereolithography (SLA), uses a light-emitting device such as a laser to selectively illuminate the transparent bottom of a tank filled with a liquid photo-polymerizing resin. The solidified resin is then progressively dragged up by a lifting platform to create the desired shape. Finally, laser sintering techniques such as
electron beam melting (EBM) manufacture parts by melting powdered materials such as metal layer by layer with an electron beam in a high vacuum.

**Software and Hardware Integration**

Computer-aided design programs are the source of information and instruction behind the function of 3DP\(^1\). There are multiple file formats utilized with 3DP. The most commonly used format is the Standard Tessellation Language or Standard Triangle Language (STL) extension. STL files describe only the surface geometry of a 3D object without any representation of color or texture. Other file formats include object (OBJ), which incorporates color and texture, and polygon (PLY), which can store a variety of properties about scanned models including color, transparency, surface normals, texture coordinates, and data confidence values.

The main goal of the software is to code surface geometry of 3D objects, adopting the principles of tessellation\(^1\). Tessellation is a process in which different geometric shapes, usually triangles, are combined without leaving any gaps or overlaps. These coordinates of vertices and parts of the normal vector of the triangle are stored in the file formats discussed above as binary codes. The file format extension is then used with a 3D slicer, an intermediary that allows a computer to communicate with 3D printer hardware\(^1\). The file format must be opened in the slicer, which converts digital 3D information into instructions for the printer to create the intended object. The slicer conveys file information, including how much material must be deposited, to the printer in a bundle called the G-Code, the printer's language. The G-Code file is transmitted to the printer, and the 2D image is reassembled into a 3D model on the print bed. With
successive addition of multiple layers of different extruded material, an object is created one layer at a time.

**Parts**

The basic parts of the 3D printer include the print bed, heated surface, bed surface, filament, and extruder (Figure 1). The frame holds the entire machine. Similar to a 2D paper printer, a 3D printer’s head moves as per instructions in all directions, and the nozzle on the print head deposits layers onto a platform or bed where the object is printed. The motor controls the movement of the head and manages its position. The temperatures at the extruder nozzle and the motor are controlled by the internal electronic components.

**Materials**

There are a number of different types of compatible 3DP materials available to create a desired object (Table 2). Each material has specific properties and layer thickness requirements to impart strength and give shape. The most commonly used 3DP materials in healthcare include metals, resins, and wax.

**3DP in Urology:**

3DP technology with fabricated models have found many applications within urological surgery. Generated replicas can be used in preoperative surgical planning and can enhance medical education, serving as a platform for the teaching of surgical
techniques and the counseling of procedures to patients and their families. Applications for 3DP in urology are summarized below based on organ type.

**Kidney:**

*Renal Masses*

The use of 3DP in the clinical care of renal disease seems to be most highly utilized and studied in the treatment of renal masses. 3D kidney and kidney tumor models have been created with silicone, wax, or polymers most commonly using CT and MRI as the standard 2D source images. These materials reproduce the shape and elasticity of the living organ with similar mechanical strength. Smektala et al. evaluated the workflow of preparation of low-cost individual silicone replicas of kidneys for laparoscopic training and surgical simulation of complex nephron-sparing surgeries. The workflow consisted of four steps: 1. image segmentation, 2. casting mold design, 3. manufacturing of the casting mold, and 4. silicone replica casting. The authors prepared 5 silicone kidney models for 5 consecutive patients undergoing laparoscopic partial nephrectomy due to suspected renal cell carcinoma. Average times for image segmentation, casting mold design, casting mold printing, and pouring of silicone replicas were 94 minutes, 22 minutes, 14 hours, and 30 minutes, respectively. The average costs of casting mold printing and casting of silicone replicas were only $14.4 and $7.4, respectively, although this study was performed in Poland where costs run lower. Dwivedi et al. also created patient-specific, 3D-printed renal tumor molds based on volumetric segmentation of 6 renal masses from multi-parametric MRI findings. Adequate fitting of the tumor specimens from surgery
within the 3D molds created preoperatively was achieved in all patients, proving accuracy of the technology. The average cost of printing each mold in this United States study was $160 (range: $20 – $350).

Nephron-sparing surgery in the primary treatment of small renal masses with suspected renal cell carcinoma can be challenging due to variable renal hilar anatomy and unclear depth of invasion of renal tumors into the cortex and sinus fat. One of the most important advantages of 3DP is its ability to provide increased knowledge of anatomic detail before surgery as well as tactile feedback. Zhang et al. reported an effectiveness score of 7.8 and realism score of 6.0 (on a scale of 1 – 10) using 3D-printed models of kidneys with small renal masses in preparation for tumor excision. This increase in anatomical knowledge preoperatively can help improve surgical outcomes by allowing urologists to rehearse planned procedures with a patient-specific 3D model of the kidney and its accompanying renal mass. This can be especially useful in complex partial nephrectomy cases with higher nephrometry scores where the incidence of complications is greater. Westernman et al. reported that 3D stereolithographic kidney models provided tactile and anatomic information that offered advantages over digital 3D reconstructions alone with the potential to alter preoperative surgical planning and significantly enhance successful performance of complex nephron-sparing surgery. By rehearsing operative procedures with a 3D model of the patient’s anatomy, surgical approaches along with their risks and limitations become more evident and can be realized beforehand. This may cause a change in the surgical approach, improve precision, and thus improve patient outcomes. Wake et al. generated 3D-printed models using MRI of 10 renal mass
cases with a nephrometry score greater than 5 (range 6 – 10) and evaluated surgical approach from three experienced urologic oncology surgeons with and without the models through questionnaires. There was a change in the planned approach with the 3D-printed model seen in 30% – 50% of cases with the largest impact seen regarding decisions on transperitoneal or retroperitoneal approach and hilar clamping. The 3D-printed models helped increase confidence regarding the chosen operative procedure in all cases.

3DP has also been shown to improve surgical outcomes such as operative time, blood loss, and warm ischemia time during partial nephrectomy. Golab et al. created 3D-printed silicone kidney models from digital 2D CT scan images from three patients with complex renal masses\textsuperscript{17}. The patient’s surgery was preceded by a laparoscopic simulation of the operation on their respective silicone model in which the tumor was excised and renorrhaphy was performed. The average time of the live partial nephrectomy on the patient was slightly shorter than that of the silicone model (16 versus 17 minutes) and warm ischemia time was reduced (less than 9 minutes). The authors concluded that training with the silicone model helped improve operative efficiency during the live case.

3DP with modeling can enhance planned communication among physicians of different specializations in complex renal tumor cases where multiple teams are required. For example, Golab et al. used 3DP with tumor modeling from a digital image to plan for a rare, complicated surgery involving removal of a malignant renal cell carcinoma with tumor thrombus extending to the right atrium requiring coordination from vascular and cardiothoracic surgery\textsuperscript{18}. The printed kidney tumor
model, the authors reported, was an essential element of communication between physician groups both preoperatively and intraoperatively.

Medical education of students, residents, and patients as well as their families serves as another important application of 3DP with regards to the anatomy and pathology of renal masses. The Center for Research in Education and Simulation Technologies (CREST) teaching methodology supports the use of 3DP to benefit the education of residents with use of anatomical models and surgical simulation. 3D-printed kidney models can also enhance the understanding of patients and their families with regards to the goals of their surgery, pre- and post-operative kidney anatomy, and overall change in renal function. Bernhard et al. reported that in patients with a primary diagnosis of a renal mass who were being considered for partial nephrectomy, real-time demonstration and patient counseling with a life-sized, patient-specific 3D-printed kidney replica led to an increase in patient satisfaction during their visit. After viewing their personal 3D kidney model, patients demonstrated an improvement in understanding of basic kidney physiology by 16.7%, kidney anatomy by 50%, tumor characteristics by 39.3%, and the planned surgical procedure by 44.6% compared to patients without this visual aid.

Nephrolithiasis

Another area of potential utilization of 3DP in the kidney is in the management of nephrolithiasis as well as the introduction of novel therapies in the treatment of this disease. The renal collecting system can be constructed with 3DP based on CT or MRI imaging using a water-soluble mold in a silicone bed. The mold is then washed away,
leaving a replica of the collecting system. This process, however, is currently expensive and time consuming, limiting its routine application. Adams et al., however, reported the construction of soft 3D-printed phantoms of the human kidney with collecting system by using a novel technique that combines 3D wax printing and polymer molding at a much more cost-effective price point\textsuperscript{24}. Anatomical details and material properties of the phantoms were validated in detail by CT scan, ultrasound, and endoscopy. Finally, Ghazi et al. created models of the renal pelvicalyceal system (PCS) using polyvinyl alcohol hydrogels and 3D-printed injection molds\textsuperscript{25}. Five experts (>100 cases annually) and 10 novices (<20 cases annually) completed simulations of percutaneous nephrolithotomy (PCNL) with excellent face and content validity with an average score of 4.5 and 4.6 (out of 5), respectively.

Designing and creation of the renal PCS with 3DP can help facilitate the implementation of novel devices in the treatment of nephrolithiasis. Antonelli et al. evaluated a novel device to prevent stone fragment migration during percutaneous lithotripsy in a human collecting system model created on a 3D printer\textsuperscript{26}. This polyethylene sack stone entrapment device (the PercSac), which fit over the shaft of a rigid nephroscope, resulted in more efficient PCNL in an in vitro 3D-printed kidney model with a shorter median time for stone fragmentation and a shorter total time for stone clearance.

3D-printed models of the renal PCS, similar to literature seen with renal masses, have also shown great promise in medical education and provide an excellent teaching tool to train residents, especially in the context of work hour requirements. Currently, training for percutaneous renal access for PCNL procedures involves the use of
anesthetized pigs or training in the simulation lab, but 3DP with kidney replicas could serve as a supplement or substitute to other educational methods although there is lack of consensus regarding the best teaching tool. Atalay et al. investigated the impact of 3D-printed PCS models on residents’ understanding of anatomy prior to PCNL in five patients. After examination of the 3D models, residents were 86% and 88% better at determining the number of anterior and posterior calices, respectively, 60% better at understanding stone location, and 64% better at determining the optimal calyx for entry into the collecting system. These same set of authors then evaluated the utility of these 3D models in patient education and counseling the day before planned PCNL surgery. Based on questionnaire forms administered and completed by the patients before and after presentation of the 3D model, understanding of basic kidney anatomy increased by 60%, kidney stone position by 50%, the planned surgical procedure by 60%, possible surgical complications by 64%, and overall satisfaction by 50%.

**Transplantation**

Minimal research has been performed with 3DP in the area of renal transplantation although it is a promising area of future application. Kusaka et al. reported on the creation of a 3D model of a patient’s donor kidney and pelvic cavity using stereolithographic 3DP techniques to help facilitate education and surgical planning. The objective of this study was to help surgeons reduce cross-clamp time and the amount of blood loss with the end goal of reducing perioperative morbidity and mortality for the included patients. The 3D-printed model was created to help determine
factors such as placement of the transplant kidney within the pelvis and vessel length to help create a more personalized surgical approach and improve outcomes.

**Prostate:**

The vast majority of studies examining 3DP of the prostate gland deal with the management and treatment of prostate cancer. They examine optimization of diagnosis with MRI and ultrasound-guided fusion technologies or improvement of outcomes after radical prostatectomy.

Combining prostate MRI and 3D-printed prostate models has been shown to improve the histological correlation rate for prostate adenocarcinoma. Wang et al. explored the effect of 3D-printed prostate modeling in assisting with prostate biopsy using cognitive fusion in 16 patients with suspected lesions on 3-Tesla (3T) MRI. 3D printing-assisted cognitive fusion improved the detection of prostate cancer from 22.4% with systematic biopsies to 46.2% with targeted biopsies.

Similar to partial nephrectomy, 3DP of the prostate gland can assist with surgical planning, physician education/training, and patient counseling. The identification of the anterior pudendal artery and the dorsolateral neurovascular bundles (NVBs) that control erectile function are extremely important when performing robotic-assisted radical prostatectomy (RARP). The preservation of the dorsolateral NVBs is essential in decreasing the incidence of permanent post-prostatectomy erectile dysfunction and maintaining quality of life after surgery. It is often difficult to identify these structures secondary to the inherent, deep location of the prostate behind the pubic bone.

Combining the input of magnetic resonance angiography with 3DP to create a patient-
specific replica of prostate anatomy can help increase the rate of identification of these structures intraoperatively. Inspecting 3D models before and during surgery can also allow for tactile feedback and interaction that robotic-assisted technology currently lacks in real time.

Shin et al. evaluated 5 patients with clinically localized prostate cancer with a dominant lesion visible on pre-biopsy multi-parametric 3T MRI rated as Prostate Imaging Reporting and Data System (PI-RADS) 4 or 5 with a high probability of microscopic extracapsular extension. Manual segmentation of the entire prostate gland, the biopsy-proven index lesion, and the bilateral NVBs was performed to create life-sized, 3D-printed prostate models demonstrating all three key anatomic aspects. The authors reported that this detailed preoperative knowledge of the prostate, cancer anatomy, and distance or proximity of the index cancer lesion to the prostatic capsule and NVBs enhanced intraoperative precision and confidence of the surgeon during RARP. The cost of creating the 3D-printed prostate models was approximately $500 per case.

3D-printed prostate models have also been reported to assist with emerging technologies such as cryotherapy or high intensity focused ultrasound (HIFU) that perform focal ablation of prostate tumors as well as with radioactive seed implantation during treatment with brachytherapy. They may assist in the measurement of quantitative transrectal shear wave elastography, which has shown a sensitivity of 77% and specificity of 82% in predicting radiorecurrent disease within the prostate gland based on salvage RARP specimens.
Other:

In addition to the above, 3DP has been effectively used for urological surgeries involving the adrenal gland, ureter, tunica albuginea, and urethra\textsuperscript{38-44}. Srougi et al. used a preoperative 3D-printed model of an adrenal gland to successfully preserve hormone-secreting function in a patient undergoing concomitant total adrenalectomy and contralateral partial adrenalectomy with the end goal of avoiding long-term hormonal replacement\textsuperscript{42}. Cheung et al. also implemented 3DP in an obstructed ureteropelvic junction model as a laparoscopic simulator in the surgical training for pediatric pyeloplasty\textsuperscript{45}. The model’s usability and realistic feel gave it promise as an educational tool.

Limitations:

As can be seen from the multiple references above, most studies in urology dealing with 3DP have very small sample sizes, making it difficult to make generalized conclusions about the effects of 3DP on surgical outcomes as well as extrapolate these results to other patients. The costs and time of hardware, software, and material creation is also a concern especially in the current healthcare climate where resources are already over-priced and inefficient. Other issues such as material biocompatibility, regulatory compliances, ethical implications, and the potential for abuse of pharmaceutical bioprinting remain significant hurdles to the commonplace use of this technology in clinical medicine.

Future Directions:
As 3DP develops, customization, on demand manufacturing, and ease of production will continue to improve. Drug development and customization with 3DP will allow for more personalized medications at lower production costs due to the ease with which 3DP allows for molecular change. Spritam, an FDA-approved antiepileptic medication, is the first drug manufactured using 3DP and is already available in the marketplace.

Medical device development is another area of future promise with regards to 3DP in healthcare and urology\textsuperscript{46}. Del Junco et al. created 3D-printed ureteral stents and examined its flow characteristics compared to contemporary stents in an ex vivo porcine model with antegrade irrigation of saline\textsuperscript{38, 39}. Mean intraluminal flow rates for the 3D-printed ureteral stents were significantly higher than the 6 French (F), 7F, and 8.5F stents, and mean extraluminal flow rates were lower compared to 6F and 8.5F stents. Total flow rates were comparable in all groups. Park et al. also successfully designed and fabricated an anti-refluxing ureteral stent with a polymeric flap valve that prevented backward flow using a 3D printer in vitro\textsuperscript{41}. Backward flow rates were decreased by 8.3 and 4.0 times in uncoated and coated stents, respectively, at applied pressures of 50 cm H\textsubscript{2}O. Finally, Cui et al. used 3DP to develop a novel guiding device for electrode implantation in sacral neuromodulation procedures. The customized 3D-printed guiding device facilitated quick and precise implantation of the electrode into the target sacral foramen and could be used in the future to improve surgical efficiency\textsuperscript{47}.

A final area of potential impact for 3DP in clinical medicine and urology is the bioengineering of tissue or even full-scale organs for possible implantation\textsuperscript{48-50}. Yu et al. explored the feasibility of 3DP of polycaprolactone (PCL) scaffolds for tissue
engineering applications of tunica albuginea.\textsuperscript{43} Zhang et al. was the first to utilize 3D bioprinting technology to fabricate tubular and spiral scaffolds using PCL polymers laden with urothelial and smooth muscle cells in a hydrogel to replicate the native urethra in rabbits. The 3D-bioprinted tissue demonstrated similar mechanical properties and cell bioactivity compared to the animal models. Huang et al. also evaluated the effects of urethral reconstruction with a 3D porous bacterial cellulose scaffold seeded with lingual keratinocytes in a rabbit model. This bioengineered tissue was then used to successfully repair rabbit ventral urethral defects measuring up to 2 cm.

**Conclusion:**

With reduction in cost, 3DP will become an indispensable tool with wider applications in patient care and urology. Its utility in pre-surgical planning and medical education is expanding, and its ability to efficiently design and create patient-specific instrumentation, prosthetics, pharmaceuticals, and even complex solid organs for transplantation could be revolutionary. Standardization and protocol development will continue to make this technology more user-friendly with time as hardware, software, and materials become more clinically integrated into healthcare systems. The field of urology has always been at the forefront of incorporating technological advances into clinical practice, and 3DP will likely not remain the exception.
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Figure Legends:

Figure 1: Parts of the 3D Printer for A) Stereolithography and B) Fused Deposition Modeling
### Table 1: 3DP Technologies and Materials

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder jetting (BJ)</td>
<td>Liquid binding agent is dispersed on powder material selectively binding it together</td>
<td>Ceramic, metal, sand, plastic</td>
</tr>
<tr>
<td>Bio-ink or ink jet printing</td>
<td>Droplets of stem cells or living cells are dispersed layer by layer (i.e. organ creation)</td>
<td>Stem cells</td>
</tr>
<tr>
<td>Digital laser sintering (DLS)</td>
<td>Direct metal laser melting ore</td>
<td>Metal</td>
</tr>
<tr>
<td>Digital light processing (DLP)</td>
<td>Traditional light source or laser used to harden photopolymer</td>
<td>Photopolymer</td>
</tr>
<tr>
<td>Direct metal deposition (DMD)</td>
<td>Laser used to melt metallic powder</td>
<td>Metal, titanium</td>
</tr>
<tr>
<td>Electron beam melting (EBM)</td>
<td>Election beam melts and fuses material in a vacuum with no air and free from gaps</td>
<td>Metal, steel, titanium</td>
</tr>
<tr>
<td>Fused deposition modeling (FDM) or fused filament fabrication (FFF)</td>
<td>Thermal energy used to fuse materials</td>
<td>Plastic, acrylonitrile butadiene styrene, polyactic acid</td>
</tr>
<tr>
<td>Laminated object manufacturing (LOM)</td>
<td>Material is layered (additive) and cut (subtractive) to shape using a laser or blade</td>
<td>Glass, metal, foil paper, plastic</td>
</tr>
<tr>
<td>Material jetting (MJ)</td>
<td>Printer head releases drops of material on platform</td>
<td>Wax, gels</td>
</tr>
<tr>
<td>Power bed fusion (PBF)</td>
<td>Laser sinters bed of metal powder</td>
<td>Metal</td>
</tr>
<tr>
<td>Selective laser melting (SLM)</td>
<td>Laser used as a heat source to melt materials into desired shapes</td>
<td>Metal, metal alloy, cobalt, aluminum</td>
</tr>
<tr>
<td>Selective laser sintering (SLS)</td>
<td>Laser sinters material, which is bound into solid objects (similar to welding)</td>
<td>Nylon, ceramic, glass, metal</td>
</tr>
<tr>
<td>Stereolithography (SLA)</td>
<td>Ultraviolet (UV) light source used to harden photopolymer</td>
<td>Photopolymer resin</td>
</tr>
</tbody>
</table>
Table 2: 3DP Materials and Their Characteristics

<table>
<thead>
<tr>
<th>Material</th>
<th>Strength</th>
<th>Color</th>
<th>Minimum Wall Thickness (Millimeters)</th>
<th>Layer Thickness Per Millimeter</th>
<th>Biocompatibility</th>
<th>Flexibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylonitrile butadiene styrene (ABS)</td>
<td>Strong</td>
<td>Many</td>
<td>1</td>
<td>3</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Ceramic</td>
<td>Delicate</td>
<td>White</td>
<td>3</td>
<td>6</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Cobalt chromium</td>
<td>Strong</td>
<td>Blue</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Gold or silver</td>
<td>Strong</td>
<td>Gold or silver</td>
<td>0.5</td>
<td>10</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Nylon (polyamide)</td>
<td>Strong</td>
<td>Optional</td>
<td>1</td>
<td>10</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Polyether ether ketone (PEEK)</td>
<td>Strong</td>
<td>Brown or grey</td>
<td>1</td>
<td>10</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Polyjet resin</td>
<td>Strong</td>
<td>Transparent</td>
<td>1</td>
<td>10</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Resin</td>
<td>Delicate</td>
<td>Transparent</td>
<td>1</td>
<td>10</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Stereolithography (SLA) resin</td>
<td>Strong</td>
<td>Transparent</td>
<td>1</td>
<td>10</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Very strong</td>
<td>Gold or bronze plating</td>
<td>3</td>
<td>6</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Titanium</td>
<td>Strongest</td>
<td>Silver</td>
<td>0.2</td>
<td>30</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Ultem (polyetherimide)</td>
<td>Strong</td>
<td>Tan, green, or black</td>
<td>N/A</td>
<td>N/A</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>