THREE DIMENSIONAL PRINTING SURGICAL INSTRUMENTS: ARE WE THERE YET?

by

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Abstract:

Background: The applications for rapid prototyping have expanded dramatically over the last 20 years. In recent years, additive manufacturing has been intensely investigated for surgical implants, tissue scaffolds, and organs. There is, however, scant literature to date that has investigated the viability of 3D printing of surgical instruments.

Materials and Methods: Using a fused deposition manufacturing (FDM) printer, an army/ navy surgical retractor was replicated from polylactic acid (PLA) filament. The retractor was sterilized using standard FDA approved glutaraldehyde protocols, tested for bacteria by PCR, and stressed until fracture in order to determine if the printed instrument could tolerate force beyond the demands of an operating room.

Results: Printing required roughly 90 minutes. The instrument tolerated 13.6 kg of tangential force before failure, both before and after exposure to the sterilant. Freshly extruded PLA from the printer was sterile and produced no PCR product. Each instrument weighed 16g and required only $0.46 of PLA.

Conclusions: Our estimates place the cost per unit of a 3D printed retractor to be roughly 1/10th the cost of a stainless steel instrument. The PLA Army/ Navy is strong enough for the demands of the operating room. Freshly extruded PLA in a clean environment, such as an OR, would produce a sterile, ready to use instrument. Due to the unprecedented accessibility of 3D printing technology world wide, and the cost efficiency of these instruments, there are far reaching implications for surgery in some underserved and less developed parts of the world.

Introduction:

Additive Manufacturing, or 3D printing has recently shown itself to have some immediate utility in medicine and surgery. [1, 2] Surgeons are using patient CT derived 3D prints in order to plan surgical approaches.[3] 3D models of patient specific anatomy such as dental crowns and biological scaffolds are already being used for human implants.[4-6] However, there is scant literature discussing the production of surgical instruments with a 3D printer.[7]

The first 3D print was reported by Hideo Kodama in 1982. Since the additive manufacturing/ 3D printing of simple shapes, 3D printers have become much more accessible and are now able to print with a multitude of materials including metals, wood products, and thermoplastics such as polylactic acid (PLA). Additionally there are various techniques for printing solid materials in 3D, including Electron beam freeform fabrication (EBF^3), Direct metal laser sintering (DMLS), and Fused deposition modeling (FDM), among others.

Within the surgical realm, PLA and polyglycolic acids have been intensely investigated for biodegradable implants and suture material, such as Vicryl (Ethicon, New Brunswick, NJ).[5] As PLA has been proven to be safe for surgical implantation, we selected it as a cost effective, safe, and environmentally suitable material for printing a surgical instrument.

An instrument, though defined by its form, must also be functional. We sought to produce an instrument capable of tolerating the demands of the operating room on a commercially available 3D printer. An Army/Navy retractor is simple in shape and ubiquitous in all surgical specialties. The retractor must be strong enough to retract

human tissue, hypoallergenic, and it must tolerate repeat sterilization. Finally, it must be at least equivalent in cost, strength, and accessibility when compared to a standard stainless steel Army/Navy in order to be considered as a substitute.

The ability to sterilize a 3D printed instrument is paramount to its application. PLA is extruded at temperatures well above the 121^{o} C recommended for steam sterilization or even the 170^{o} C recommended for dry heat sterilization.[6] However, research has found that autoclaving compromises the structural integrity of PLA.[5, 8] Minimal degradation of PLA polymers has even been shown in vitro, when physiological conditions are simulated for days to weeks.[9, 10] Although lower temperature methods of sterilization such as Ethylene oxide “gas” sterilization did not impact PLA strength, harmful levels of ethylene oxide residue are a serious concern. Alternatively, glutaraldehyde, an effective sterilant at room temperature, has been shown to retain the greatest PLA strength when compared to other chemical sterilants.[11] As we are unaware of works in the medical literature specifically focusing on this area, the purpose of this pilot study was to determine if printed surgical instruments would tolerate chemical sterilization and tension of an operation.

Methods:

In this project we used a MakerBot Replicator 2 (MakerBot, Brooklyn, NY), MakerBot MakerWare software to generate g-code by means of slicing via MakerBot Slicer (software products of MakerBot industries), and a Poly Lactic Acid (PLA) substrate to print a prototype replica of a common Army/Navy retractor. The instrument measured 17cm x 1.5cm x 4mm and was printed with 75% infill (the density with which the instrument is printed), 6 shells of perimeter laid axially, and 100 micron layer height with a hexagonal infill pattern. The Replicator 2 printer extruded material at 240^{o} C with a 90 mm/s speed while extruding.

In order to confirm sterility of the instrument, 5 replicate samples were taken of each of the following items: the printing environment (desk, keyboard, etc.); the freshly printed retractor; a “clean catch” 5cm string of PLA collected upon extrusion; 5cm pieces of PLA prior to printing; and printed retractor after exposure to sterilant. Sterilization entailed submersion in a 2.4% glutaraldehyde solution with a pH of 7.5 for 20 minutes at 25^{o} C in accordance with CDC guidelines for critical medical devices.[6] All samples were tested for bacterial load using polymerase chain reaction (PCR) amplification of the V1-V2 region of the 16s rRNA gene as a measure of intact bacterial DNA. Briefly, 200 microliters sterile phosphate buffered saline were added to each sample and vortexed. Two microliters of buffer was used as template in a PCR reaction consisting of 4 minutes at 98 °C followed by 30 cycles of 98°C for 10 seconds, 68.8 °C for 30 seconds, 72 °C for 30 seconds. PCR reagents were from the Applied Biosystems (Grand Island, NY) real time PCR Master mix with 2 units of Phusion polymerase (Ipswich, MA). The forward primer sequence was: AGAGTTTGATCMTGGCTCAG and

the reverse primer sequence was: CYIACTGCTGCCTCCCGTAG. Two microliters of the resulting PCR product from each reaction was analyzed on an agarose gel to determine if a PCR product had been formed of anticipated size. Negative controls consisting of purified water were included to control for contamination of the reagents. A positive control containing E. coli genomic DNA was included to demonstrate success of the procedure.

In order to test the strength of the instrument, weights were suspended by a 1.5cm webbing and sequentially hung from the retracting surface of the instrument while it was held perpendicular to the ground by an investigator. 5 printed retractors of the same measurements and infill were tested, and a one retractor was tested after sterilization with glutaraldehyde.

Results:

Printing of the Army/ Navy required just under 90 minutes in order to print. Print times were consistent for all instruments and dependent on g-code generated by the slicing profile settings as well as the printer's capabilities.

The form accurately represented an Army/Navy retractor. This is due in part to accurate computer aided-design (CAD), and the 100 micron resolution of our chosen printer.(Figure 1)

All specimens collected from the environment, the freshly printed instrument, the raw PLA and the gluteraldehyde-processed instrument contained bacterial gene products. The clean catch samples that were collected immediately upon extrusion revealed no viable bacterial product.

Strength testing proved that the printed retractor tolerated 11.3 kg + 0.57 of tangential force, began to visually deform at 13.6 kg + 0.68, and fractured at 15.9 kg + 0.8. The glutaraldehyde- processed retractor showed no significant difference in tolerances ($p = 0.96$).

Our 3D printer was purchased for $2,199 and 1kg of PLA is available for $27.99 including shipping. Each retractor weighed 16g. We can make 61 custom retractors per kilogram which calculates to $0.46 of PLA per instrument with our settings applied in g-code generation.

Discussion:

The utility of a surgical instrument is defined by its application, but its form, strength, sterility and safety are key components. The MakerBot Replicator 2 represents one of the many FDM machine builds that is capable of 100 micron resolution. Although our CAD generated instrument was made to replicate common Army/Navy instruments, it did represent some customization and practical alterations to optimize the FDM, such as a solid handle body design. The force required to retract human tissue typically requires only a few pounds. Our instrument with 75% infill was capable of supporting 13.6 kg prior to fracture. Fracture was defined as nucleation, propagation and separation of the retracting surface from the handle. Given the common utility of an Army/Navy as a skin retractor, 13.6 kg of tolerance is more than adequate.[7] Exceptions to this are typically larger retractors, designed to retract the abdominal wall or large skin flaps, such as a Richardson retractor. Additionally, all 5 retractors broke under the same stress and at the same position; at the junction of the handle and retracting surface. This shows consistency across printed instruments. Another benefit discovered while maximally stressing these instruments is that they fracture in a clean, predictable manner, without comminution, which might otherwise result in foreign body contamination of the wound.

PCR was chosen as the method for testing sterility in this trial due to its superb sensitivity. For this particular task, it was overly sensitive, as we believe that the discovery of bacterial product on the sterilized instrument was due to remnant DNA from dead bacteria.[12] Given that the glutaraldehyde protocol we used is approved for critical medical devices, it is likely that the glutaraldehyde satisfactorily sterilized our instrument

but did not remove all nucleic acids. A benefit of glutaraldehyde sterilization is its simplicity, cost efficiency, brief time requirement and reusability without impacting the strength or form of PLA.[8] Additional testing will also need to be performed with FDA approved variations of the glutaraldehyde protocol, including 5 minute submersion at 35^{o} C. As a thermoplastic, PLA is temperature sensitive, but literature has shown minimal degradation of PLA polymers under physiologic temperatures only after 3-4 weeks of in vitro simulation. It is unlikely that the PLA would be weakened by such brief, modest increases in temperature. Futhermore, this rapid protocol could overcome some of the time concerns addressed in the literature.[7]

As anticipated due to the high temperature required to extrude PLA, the “clean catch” samples were completely sterile and free of all remnant DNA as evidenced by the lack of product seen after PCR. Therefore, if an instrument were printed onto a sterile surface in a clean environment, such as an OR, that device would be ready for surgical application as soon as printing was complete. Another report of printed instruments showed that 92% of printed instruments were sterile and ready for use after printing.[7] The combination of printing into a clean environment and the use of a sterilant would certainly improve the rate of sterility.

PLA is relatively hypoallergenic and safe, such that it has been FDA approved as a semi-permanent dermal filler.[13] Though not completely inert, PLA has an excellent safety profile and does not incite hypersensitivity reactions. We believe the approval of PLA for implantation is adequate to deem PLA safe for transient human contact during an operation.

Our experiment and analysis are admittedly limited due to a small number of instruments and a single printer, however, our FDM printer processes and executes G-code language. This is a fundamental print method which has been in existence for several years and is utilized by hundreds of machine makers and open source builds. Although no two machines are identical in performance, our methods would be reproducible with the specifications we've provided.

The growing accessibility of this technology is unprecedented. Many companies are manufacturing 3D printers for the professional and amateur consumer market alike, with nearly global availability. For the adept enthusiast, instructions for building a 3D printer are freely accessible on the internet, and possible with common machine parts and tools. Several commercial and open source software solutions, required to render a 3D model, are available on multiple operating systems. The standardization of these file formats also allows iterative derivation and modifications of shared designs as well as generation of g-code machine instructions, which is compatible with a variety of 3D printing technology.

This technology works very well in the developed world where we have the infrastructure to support 3D printing and the exchange of information, and other investigators have shown this technology is ready for military application.[7] The penetration of these manufacturing means continues in underserved areas of the world. As of June 2012, 34% of the world's population had ready access to the Internet. That number had grown by over 500% in the 12 years preceding those published statistics.[14] Even 43% of Latin Americans/ Caribs, and 15% of Africans were using the Internet.

Electricity is another commodity that is not available the world over. Our Makerbot replicator can receive AC 100-240V, 2 amps, and 50-60Hz making it internationally applicable. The power requirements are 24V DC at 6.25 amps, making this particular unit compatible with a small gas generator or even an automobile DC converter run off of a cigarette lighter.

The above geographical locations represent the vast majority and focus of medical mission trips. Estimates put total U.S. based mission groups at 543, with an average of 10 trips/ year/ group, and a total annual expenditure of $250 million. Much of these expenses are attributable to transportation of materials and supplies. Remote treatment facilities are often lacking in the variety of instrumentation and materials to accommodate the wide range of surgical and clinical treatment specialists which perform procedures. This disconnect requires that campaigns travel with required instruments or substitute alternative tools. Additional logistical factors are not accounted for but are familiar to campaign veterans, which include the potential for damage and theft of instruments. The ability to reduce traveling payload and generate on-demand, custom tools could benefit these efforts immensely.

Although the costs of medical mission work is significant, and largely the inspiration for the authors of this manuscript, this is a large sum that still pales in comparison to the 111 billion spent annually in the United States on medical devices.[15] With these figures, the implications of functional, low cost surgical equipment are substantial.

In many instances, the cost of new technology is prohibitive to widespread use. On the contrary, rapid prototyping technology by means of FDM is nearly a quarter-

century old. Current means of 3D printing with PLA is quite inexpensive and offers an impressive degree of sophistication for many common uses. For example, A new set of 2 stainless steel army navy retractors are available online for a retail price of $46.96, which makes the unit cost $23.48. Our 3D printer is available for $2,199 and 1kg of PLA is available for $27.99 including shipping. Since each retractor weighs 16g, we can make 61 retractors per kilogram, which calculates to $0.46 of PLA per instrument. We would need to print 95 retractors in order to cover the cost of the printer and make each unit cost the same as the stainless steel version, $23.48. If our printer were to run at 95% efficiency for the next week (168 hours), the printer would pay for itself. Even if these instruments were utilized as a one time use, they are still less expensive than the cost of damage or theft of steel instruments.

Additionally, 3D printers are quite durable. Our printer has completed a moderate 2000 hours of printing without significant hardware failure and regular, standard maintenance. If we spent the last 2.7 months, roughly 2000 hours, printing retractors at 95% efficiency, we would have 950 retractors with a unit cost of $2.77. Not only does the low cost of this new technology make it accessible, but the potential cost savings may make it fiscally responsible.

Low cost single unit manufacturing with 3D printing is changing the nature in which innovation and prototyping can be performed. This technology is beginning to revolutionize medical and surgical possibilities. This expansion of applications will likewise penetrate medical and surgical services in underdeveloped nations. Even within the borders of our country, we face natural disasters where access to instruments in the face of damaged infrastructure could be life saving.

Single unit manufacturing of surgical instruments could complement open source ecology, an idea presented by Marcin Jakubowski. He has created a modular, do-it-yourself, low cost platform for building industrial machines needed to establish a civilization. As an open source project, the designs and information are freely accessible on the Internet. Advanced additive manufacturing capabilities would likely play a crucial role in the development of an open source medical infrastructure.

The advancements of 3D printing improve with each generation of the technology. The open source adoption of expired patent technology, lags. As a consequence, certain instruments, with extremely fine moving parts or high physical demand, would still present a challenge with the current generation of FDM. As patented properties continue to expire, the capabilities of open source will improve as well. Additionally, the logistical application of 3D printing surgical instruments “on demand” would still need to be demonstrated in a more real world setting. The possibility of this is quite feasible from a theoretical standpoint, and merits further investigation, as well as adoption by care facilities.

Figure 1:

Figure Legend:

Figure 1: Two printed replicas of the poly lactic acid surgical prototypes after being printed.

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