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Review

Centralised 3D printing in the NHS: a radiological review

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In recent years, three-dimensional (3D) printing has seen an explosion of interest fuelled by improvements in technology and associated reduction in costs. The literature is replete with novel medical applications of custom anatomical models, prostheses, and surgical guides. Although the fundamental core of 3D printing lies in image manipulation, the driving force in many National Health Service (NHS) trusts has come from individual surgical specialties with 3D printers independently run and confined to respective departments. In this review of 3D printing, experience of establishing a new centralised 3D-printing service within an NHS hospital trust is reported, focusing on the requirements and challenges of such an endeavour.

Introduction

The term rapid prototyping (RP) was coined in the 1980s to describe new technologies that produce physical models directly from a three-dimensional (3D) computer-aided design of an object. In medicine, this equates to the manufacture of dimensionally accurate models of human anatomy derived from medical imaging.[1]

RP developments in the 1980s paralleled advances in medical imaging, namely 3D reconstructed computed tomography (3D-CT).[2] 3D-CT was particularly welcomed by the craniomaxillofacial community, becoming part of routine clinical care, and the imaging soon used to produce physical models.[3,4] The benefits were clear: with physical models providing superior visualisation of complex anatomy over both axial and static 3D rendered images, with better surgical planning capabilities and resultant improvements in patient outcomes.[5] Evolving technology saw computer numeric controlled (CNC) milling gradually replaced by the additive layer processes that are in widespread use today.

In recent years, 3D printing has seen an explosion of interest driven by improvements and capabilities of the technology and associated reduction in costs. Although the fundamental core of 3D printing lies in image manipulation the driving force in many National Health Service (NHS) trusts has come from individual surgical specialties. As a result, many 3D printers are independently run and confined to respective departments. Recently, there has been a drive to increase the involvement of radiology in such endeavours, with 3D printing featuring heavily in radiological scientific meetings.

In this review of 3D printing, experience of establishing a new centralised 3D-printing service within an NHS hospital trust is reported, focusing on the requirements and challenges of such an endeavour.

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RP technology

The initial “subtractive” methods of producing models using technology, such as CNC milling, whereby a starting block of material is gradually shaped into a model, have largely been replaced with additive processes, where a model is built up in layers. The additive manufacturing methods most frequently used include[1] fused deposition modelling (FDM)[2]; stereolithography (SLA)[3]; ink-jet based 3D printing; and[4] selective laser sintering (SLS).

FDM was developed and patented by Crump in 1989 and was commercialised in 1990 by the company he co-founded, Stratasys, which in 2012 merged with another market leader, Objet, to become one of today’s largest manufacturers of 3D printers and materials.[6] FDM uses plastic filament, which is extruded through a heated nozzle, allowing it to flow freely. Each layer cools and hardens providing the foundation for the subsequent layer. The most commonly used filaments are biodegradable plastic PLA (polylactic acid), or ABS (acrylonitrile butadiene styrene) polymer, which melt at around 170–250°C. FDM printers can be acquired cheaply and have low running costs with filament materials costing as little as £20 per 1 kg (approximately 110 m in length). The build envelope of the lower-end machines is typically small (20×20×20cm). A resolution of 0.6 mm can now be achieved, but in view of the necessary supporting structures, complex shapes can be challenging to produce. This technology is also used at the other end of the market where larger build sizes, full colour, and improved resolution models are achievable, and are reflected in machine costs.

SLA uses an ultraviolet beam at the surface of a pool of photosensitive resin, which leads to local polymerisation of the liquid resin layer by layer.[7] This technology was developed and patented in 1986 by Hull, who founded the company 3D Systems. Acquiring a number of smaller companies, 3D Systems has grown to become the main market contender to Stratasys.

In 1993, ink-jet based 3D printing technology was developed at the Massachusetts Institute of Technology. This technology was manufactured by the Z-Corporation, with the company being acquired by 3D Systems in 2012. Models are produced by printing binder solution onto a thin layer of powder in a similar manner to an ink-jet printer, with the model gradually built up layer by layer. The powder acts as the support structure for the developing model, which is easily removed with a fine jet of air, and recycled into the machine. Using colour binders, models can be printed in a full array of multi-colour. As the plaster models are brittle, they require finishing with a coating of cyanoacrylate. Such printers offer a resolution of 0.1 mm.

Finally, in SLS a high-power laser (carbon dioxide) is used to fuse a fine powder made from plastic, metal (e.g., titanium), or ceramic.[7] The laser sweeps the powder bed, tracing out the shape of each two-dimensional (2D) slice, thus melting and fusing areas of the powder to form the geometry of each layer.[8] Such technology offers the highest degree of accuracy, but with high start-up costs these printers are currently largely confined to industry.

RP is now possible in a range of materials, from plastics and powders, to ceramics, metals, PEEK (polyether ether ketone), and silicone. Newer 3D printers are also able to print in multiple materials simultaneously significantly expanding the capabilities for model complexity. Recent expansion of 3D printing technologies has benefited from expired patents, the open-source movement, and free sharing of digital files via the internet.[6] The terms 3D printing, RP and additive manufacturing are now used interchangeably.

Accuracy

The limiting factor in the resolution of RP models has become image acquisition, with many machines achieving levels superior to what medical scanners are currently capable of. Frühwald *et al.*[16] examined the accuracy of stereolithographic models produced from CT data in nine children with craniofacial abnormalities. Fourteen landmarks were identified with a digitiser on models, with corresponding measurements made on the planar CT reformats, and 3D CT reconstruction. They found that there was no significant difference between the sets of measurements obtained for one of the most reliable distances (spina nasalis anterior to nasion). Similar results were reported by Silva *et al.*[17] who also used dry skulls, with a mean dimensional error of 0.89 mm for SLS and 1.07 mm for ink-jet based 3D printing. Although many manufacturers specify a resolution of <0.1 mm for their machines, most CT scanners are limited to a slice thickness of 0.625 mm.

Although less routinely used, pilot studies of 3D models produced from “black bone” MRI data have demonstrated a similar level of accuracy to CT when comparable voxel size is used.[20]

With FDM technology consideration needs to be given to the small amount of shrinkage that occurs with plastics when they cool to room temperature, of around 0.5%, which can be overcome by pre-emptive scaling of the model.[6]

Medical uses of RP

The benefits and novel applications of RP have been widely reported in the literature. In their review, Malik *et al.*[8] subdivided the medical applications of RP into anatomical models, surgical instruments, and implants/prostheses. They found that maxillofacial, cardiothoracic, and orthopaedic disciplines are the greatest innovators in the use of RP. A systematic review by Martelli *et al.*[9] revealed that of 158 studies, 71% reported applications of RP to produce anatomical models, with the remainder distributed across surgical guides and templates, and customised implants. In terms of anatomical models, the greatest use appears to be in preoperative planning with reported intraoperative time saved ranging between 5.7 to 63 minutes, and associated reduction in blood loss and morbidity.[2,9,10] Erickson *et al.*[5] sought the opinions of surgeons on the use

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