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Additive manufacturing applications in medical cases: A literature based review

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ABSTRACT

Background: A significant number of the research paper on Medical cases using Additive manufacturing studied. Different applications of additive manufacturing technologies in the medical area analysed for providing the state of the art and direction of the development.
The aim of work: To illustrate the Additive Manufacturing technology as being used in medical and its benefits along-with contemporary and future applications.
Materials and methods: Literature Review based study on Additive Manufacturing that are helpful in various ways to address medical problems along with bibliometric analysis been done.
Result: Briefly described the review of forty primary applications of AM as used for medical purposes along with their significant achievement. Process chain development in the application of AM is identified and tabulated for every process chain member, its achievement and limitations for various references.
There are five criteria which one can achieve through medical model when made through AM technology. To support the achievements and limitations of every criterion proper references are provided. The ongoing research is also classified according to the application of AM in medical with criteria, achievement and references. Eight major medical areas where AM is implemented have been identified along with primary references, objectives and advantages.
Conclusion: Paper deals with the literature review of the Medical application of Additive Manufacturing and its future. Medical models which are customised and sourced from data of an individual patient, which vary from patient to patient can well be modified and printed. Medical AM involves resources of human from the field of reverse engineering, medicine and biomaterial, design and manufacturing of bones, implants, etc. Additive Manufacturing can help solve medical problems with extensive benefit to humanity.

Contents

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1. Introduction

Additive Manufacturing (AM) provides extensive customisation as per the individual patient data and requirements for Medical applications. Individual patient models are in three-dimensional (3D) sections developed through customised software. These include implants, soft tissue, foreign bodies, vascular structures, etc.[14] Magnetic Resonances Imaging (MRI) technology or Computerised Tomography (CT) are usually used for capturing model data. Many other methods such as laser scanning, Ultrasound, Positron emission tomography are also used for obtaining patient data. The data so obtained shows cross-sections of the patient, with similar brightness area representing regions of similar material or specific tissue types as cortical bone.

For the generation of the reconstructed virtual model, an exact material is identified for the patient image, corresponding to the regions of interest. Each slice contours are interpolated and joined to form a complete representation of 3-D objects. By using AM, models created show colours, textures, and shapes that may sometimes not be the exact reproductions of the final design and thus we need better features for building these models. It is credible to use AM for the production of different types of the parts including the buildings and the medical applications.[97]

The patient-particular product is customised, designed and fabricated with the help of AM technology. This technology creates ideal fit of the implant, saves time as well as cost.[9] The models are processed using 3-D Computer Aided Design to incorporate other objects, such as implants and fixation devices. When the virtual model is complete, the data is further translated into a Standard Triangulate (STL) format, which is used for Rapid Prototyping through machines.[31] In the current scenario, additive manufacturing technology is used significantly in medical fields, such as printing of medical model, biomaterial.[60] Rapid technology is used in various medical applications such as new orthopaedic products, Fabrication of customised maxillo-facial prosthesis; it also has suitable applications in dentistry.[98] Additive manufacturing creates a satisfactory result for skeleton models which provides basic idea related to medical work.[50] Tuomi[107] has classified the Additive Manufacturing application in medical into five major areas:

I. Medical models
II. Surgical implant
III. Surgical guides
IV. External aids
V. Bio-manufacturing.

Medical Rapid prototyping technology is used in many areas such as biomedical modelling.

AM help for printing organs, produces cells, cell-laden biomaterials, biomaterials individually.[87] The process used for bio printing organs are:

i Vascular architecture creates blueprint of organ
ii Bioprinting process plan creation
iii Isolate stem cells
iv Differentiate of stem cell into organ-specific cells
v Preparation of bio ink reservoirs with the help of blood vessel cells, organ-specific cells and support medium
vi Bioprint
vii Bioprinted organs placed in bioreactor before transplantation.

Medical RP involves resources of human from the field of reverse engineering, medicine and biomaterial, design and manufacturing of bones, implants, etc. For treatment and diagnosis, this technology plays a significant role in designing and development of different surgical tools.[40] AM is replacing the wax pattern for skull fabricating skull model.[3] With progress in various Medical Rapid Prototyping techniques like fused deposition modelling (FDM), stereolithography (SLA) and Inkjet 3D printing. Today, recently advanced techniques like Direct Metal Laser Sintering (DMLS), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM) are being used to manufacture implant with sufficient dense in metallic form. Medical Rapid Prototyping is overtaking the traditional techniques of machining and casting for the designing and manufacturing of implants because it is produced in lesser time with better specifications quickly at lower cost.[58,61]

Additive Manufacturing plays a significant role in product development. It helps in reducing the cost of product development and cycle time and is a valuable tool for rapid product development.[49] Rapid Prototyping used automatic generation of a physical object with the help of computer model. Rapid prototyping methods need STL format which is export from the CAD model for producing the part. The software is then used to slice the CAD Model into thin cross-sections for building the part layer by layer.[35]

Earlier AM was used in the manufacturing industry for increasing the speed of prototype. Nowadays, it explores different applications in the medical field.[8] Medical AM is used for new organ development, custom fit mask, operation practice, etc.[59] Additive Manufacturing is growing in many fields including those in education, medical, design and manufacturing of prototype before starting the full production.[48,62]

2. Research status of application of Additive manufacturing in medical

Additive manufacturing applications in medical, research are on the continuous increase. We have taken data from Scopus which

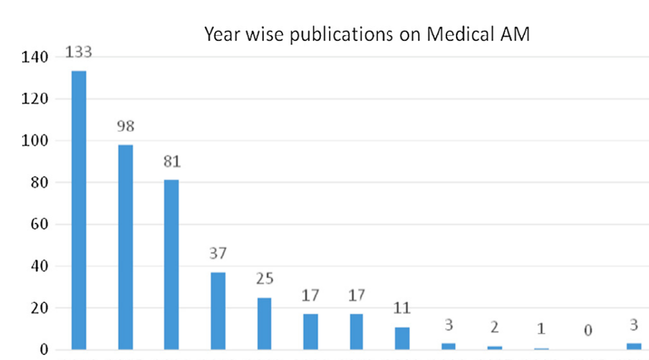

Fig. 1. Medical applications of Additive Manufacturing: Year wise Publication. *Source:* Scopus.

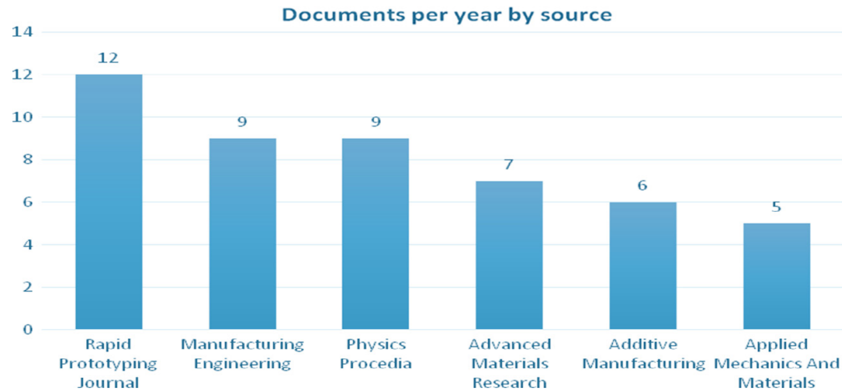

Fig. 2. Medical applications of Additive Manufacturing: Top Five journals in which documents are published. *Source:* Scopus.

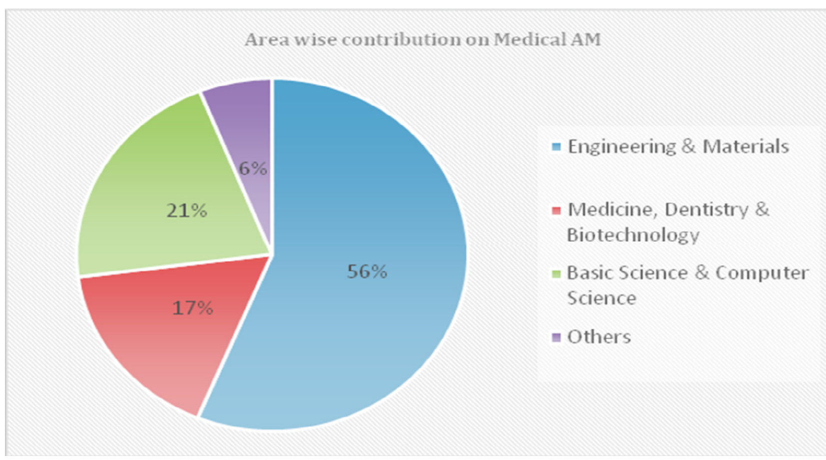

Fig. 3. Medical applications of Additive Manufacturing: Area wise contribution. *Source:* Scopus.

shows that the use of AM in medical is growing. Total 426 research papers published in this useful area from 2004 2016. In the year 2004, there were only three articles published in this area, and it increased to 426 till 2016. Last year in 2016, 133 articles were published shown in Fig. 1.

The specific details of publications by different journals on Additive manufacturing in medical applications shown in Fig. 2. There are many publications done in this particular, but in this paper top, 5 Journals shown. Out of top five, Rapid Prototyping Journal has highest publications, Manufacturing engineering and physics procedia on the second position. Advance material research is in the third place; Additive Manufacturing Journal is in the fourth position, and Applied Mechanics and Materials Journal is in the Fifth position.

Area wise research on using Additive Manufacturing in Medical Applications is shown in Fig. 3. Engineering and Materials have significant contribution in this area which is 56%. Medicine, Dentistry and Biotechnology have 17%, Basic Science and Computer Science have 21%, and Other Fields have 6% contribution in this particular area.

It indicates that engineering and materials areas have demonstrated a great potential in this field, this is tool-less production which produces complex shapes quickly, in lesser time.

3. Additive manufacturing in Medical: A Brief review

A brief Review related to medical Additive Manufacturing is discussed in the following Table 1.

Development in Medical Additive Manufacturing: - The significant developments made by Additive Manufacturing in the medical area is given below:

a. Creation of physical model, which gives better idea to doctors before performing procedures that helps surgeon
b. Substitute's bones fabricated by using Additive Manufacturing Technology and these substitutes' bones replaced defects areas
c. Improve strength of implants
d. Designing and development of medical implants
e. For achieving more accurate result
f. Reduction of operating time
g. Providing pre-surgical planning and also help medical students and surgeons
h. Producing lightweight implant
i. Reconstruction of skull/nose
j. Used in improving quality of implants
k. Quickly created models in low cost
l. Exact fitting of various parts of human body with the help of model manufactured by AM technologies
m. Excellent surface quality
n. Reconstructive surgery and aesthetic surgery.

4. Process chain development in medical applications

In medical process chain development, scores of steps of processes are involved. Medical applications are linking process when we need design and manufacturing of customising medical

Table 1
Brief review of the primary applications of Additive Manufacturing as used for medical purposes, chronologically arranged.

S. no.	Authors	Description	Achievement
1	Jamieson et al.[47]	Suggested that additive manufacturing is an attractive market in the field of orthopaedics. Bone geometry also examined and allows to the construction of implant prototype with the help of machining process and compared the development and manufacturing of surgical tool with the aid of machining process and Rapid prototyping technology	Comparative analysis to show that AM help in reduction of time in product development phase
2	James et al.[46]	The medical practice is done with the help of prototype. The broken bone of the patient replaced with the help of additive manufacturing. Scanning and production of the broken bones physical model made with the help of additive manufacturing	The physical model, of the bone, gave a better idea to doctors to perform the procedure, which saved time and cost
3	Hutmacher[43]	There is an essential requirement of strong bone and reconstruction of osteochondral approaches which take into account morphological, biochemical, anatomical factors. We can take substitute bone to replace the defects area	Substituted bone manufactured with the help of AM. These bones replaced the defect area
4	Sanghera et al.[95]	Additive manufacturing technology now introduced in the non-engineering field. It explores great potential in the area of medicine which creates the best significant effect in this field which has its potential and various medical applications	Helpful for the surgeon and achieve vast improvement in this field
5	Gibson et al.[32]	Consider various characteristics of multiple transplants, such as density, pore size and shape. It has an important parameter which will manipulate growth in tissue and implant bone mechanical properties	The implant mechanical strength is approximately three to five times higher than the implant made from processes
6	Ng et al.[82]	Rapid Prototyping (RP) technology utilised for the development of prosthetics CAM system. The socket manufactured in four hours instead of a day with the help of RP technology. Both biomechanical and clinical studies are conducted and evaluate fit and comfort level of new socket during giant. Investigated the functional characteristics of the new socket done which show very similar functional characteristics as in traditional socket	Reduce manufacturing time of socket by using AM. It evaluates fit and comfort as compared to the traditional socket which is manufactured by other processes
7	Hieu et al.[39]	Presented design methods of cranioplasty implant using medical rapid prototyping technology. The skull formed with the help of CT data and reverse engineering is used to construct the 3D model. It is based upon two types of data first is Stereo Lithography files (STL) and bone slice contours (Strata Sys Layer files (SSL) and Initial Graphics Exchange Specification (IGES)). These data generated during processing of the medical image	CT data and reverse engineering used for the easy construction of the 3D model. It is more beneficial for designing and development of medical implants
8	Harrysson et al.[36]	Take a case of one-year-old German Shepherd dog which has bilateral multifocal pelvic limb deformities. Computed tomography (CT) scans used for scanning. The prototype is manufactured by Stereolithography patterns using Quick Cast build style on an SLA-190	The AM technology gives an accurate result
9	Yaxiong et al.[116]	Substitute bone match the shape of a patient's bone quickly, the technology based on rapid prototyping (RP) and reverse engineering (RE)are put forward for substitute of designing and fabricating a customised bone. Reverse engineering technique is used to create the substitute customised bone according to the computed tomography (CT) sectional pictures, and the bone is manufactured with RP technology and inserted in the patient's body at the right position	The result shows matching of substitute bone in the patient body
10	Hieu et al.[40]	Reviewed additive manufacturing in medical and methods which based on medical imaging data and reverse engineering. 3D models for anatomical has constructed. These methods are successful for design and manufacturing of medical devices, surgical aid tools, implant and bio-models	Since 1999, in Europe and Asia, approximately 40 different types of medical Rapid prototyping applications were implemented
11	Naing et al.[80]	Detailed the mathematical formulae derivation of a novel system for designing and fabricating tissue engineering scaffolds. Computer-aided design with rapid prototyping techniques and imaging software for customised scaffolds the designing and fabrication	The result shows that these methods are suitable for producing viable scaffolds and also appropriate for individual patients
12	Singare et al.[99]	Improved the aesthetic outcome in surgery, in which computer-assisted prefabricated design of implant and manufacturing system. For creating a usefully dimensional model of the deficient mandible, a helical CT data is used	The result of this approach showed significant results in chin augmentation. It is fit as compared to traditional methods; the operating time also reduced
13	Ahn et al.[1]	Before physical model fabrication, first virtual phase come in medical imaging technologies such as MRI, CT images and laser digitising prepare a CAD file	Improve accuracy and precision of orthopaedics surgery
14	He et al.[37]	Presented a Hemi-knee joint custom design and fabrication method substitute composed of porous bioceramics and titanium alloy which based on Additive manufacturing technology. With the help of CT image via reverse engineering the reconstruction of the 3D model of a femur bone was done and accurately evaluated. Maximum deviation is 0.206 mm from the 3D reconstructed freeform model as compared to original anatomy	The result shows that the substitute bone matches well and has good mechanical strength
15	Hollister[41]	In dentistry, additive manufacturing is an important tool because plaster model of patient's mouth or teeth replacement can be built quickly	Easy replacement of patient damaged mouth and teeth

Table 1 (*continued*)

S. no.	Authors	Description	Achievement
16	Liu et al.[65]	Additive manufacturing played a significant role in the medical field. It can fabricate anatomical parts which are complex in shape directly from the different scanning process, such as CT images	For human anatomy AM provide the best illustration with the help of these models used to provide precise pre-surgical planning and also help medical students and surgeons
17	Singare et al.[100]	This technology used for maxillofacial implant fabrication. Methods of designing of Rapid medical prototyping used. CT data create the 3D model of the Patient skull. CAD environment creates the design of the individual shape of the implant	Results show that the defect is fit well by the custom made implant. The patient can eat. The operating time also reduced
18	Chen[12]	Nowadays additive manufacturing is becoming an essential building tool used in all field such as manufacturing industry. In this technology, the challenge is that the model produced is matches with original product geometry and specification and also light weight problem of product	Has tremendous potential for the light weight of product and performance achieving is also good
19	Willis et al.[114]	AM become necessary which can generate 3D shapes with the help of CAD model. The 3D scanner is used for capture the object shape in digital form and manufactured prototype with the support of AM system	A manufactured complex object with deep concavities with high accuracy
20	Poukens et al.[92]	Repair of bone defects done by inert implants which are caused by different diseases and traumas. Traditionally these implants are produced by handcrafting method; This has been done intra operatively or preoperatively by taking help of pre operative models. However, this manual process is costly and labour intensive. In the current scenario, it is possible to create the custom made patient specific implants with the help of additive manufacturing methods, 3D modelling software and by combining these with both medical imaging and clinical applications	The potential of this process is accurate and implants which are cost effective. Nowadays additive manufacturing and digital design successfully performed the reconstruction of skull with implants
21	Azari et al.[5]	Presented that the AM technology is used to create 3D parts directly from computer-aided design models quickly and fabricate complex-shaped. This technique decomposes the 3D computer model's data into thin cross-sectional layers, which built layer by layer. This new modelling method is more suitable in dentistry especially in the field of implantology and surgery	This technology has potential to build 3D complex models in dentistry. In future, this method develops fast and could change traditional dental practices. Dental students will take benefits of this novel technology. RP technology gives optimum safety, simplicity, and reliability in dentistry
22	Hutchinson[42]	The demand increase for fabricating joints and bone with the help of additive manufacturing technology such as osteoporosis, arthritis, spinal injuries, traumatic musculoskeletal injuries, and spinal deformities	Joint fabricated by AM is increasingly used in various field of medical
23	Makovec[67]	Transplants of bones done with the help of Additive manufacturing technology. This technology makes transplant which is like as original. AM creating a precise transplant	More and more products manufactured by using AM technology
24	Melchels et al.[74]	In biomedical applications, SLA has strong perspective such as anatomically shaped implant manufacturing, biomedical devices and speed up surgical procedure especially complex surgeries and implant placement	Improving the quality of surgical items, such as implant placements. SLA is the best technique used for biomedical engineering purpose
25	Wang et al.[111]	The applications of stereolithography used for creating CT image and converted into Rapid prototyping model by using standard triangulate language format method and fabricated layer by layers	Reconstruction has been done easily by using stereolithography
26	Dhakshyani et al.[23]	Additive manufacturing technology model is for customised implants and plays communication tool functions between patients and surgeons	This technology gives the best way for enhancing orthopaedic surgeon knowledge and skill
27	Esses et al.[26]	Physical models produced from CT data using additive manufacturing technology. It has various clinical applications like surgical planning and communication	The physical model created can be used in surgical planning, prosthesis and patient communication
28	Salmi et al.[94]	Developed a workflow for additive manufacturing (AM) and 3D modelling of patient-specific medical implants. Work is done in four steps: First step is medical imaging; second is 3D modelling; third is additive manufacturing; finally, clinical application. Defect facial bone reconstructs from Patient-specific implant which designed digitally	This method shows exact fitting of the implant. Operation time is also reduced, improves accuracy, enhance the quality of surgery and decrease patient morbidity
29	van Noort[108]	Additive manufacturing technology makes operations faster, cost-efficient and accurate than the manual process	Quickly fabricate model at low cost
30	Wong and Hernandez[115]	Transforming the practice of medicine is done by additive manufacturing and makes work easier. The strength of part also improved by using this technology	It creates accurate transplant and these models manufactured by this technology has the highest level of precision
31	DeBeer and van der Merwe[20]	Studied have proposed a process chain which helps in customised intervertebral disc implants designing and manufacturing using medical scanning, CAD software, simulation and rapid prototyping technologies	Intervertebral, disc endplate, designed successfully and fabricated with the help of AM technology using biocompatible material. The accuracy achieved is good, i.e., 0.37 mm
32	Wang et al.[112]	In recent year 3D printers become more popular for custom object fabrication for the home user. The primary purpose is reducing the material cost of skin- frame structure	Methods show cost effective as compared to other manufacturing processes in skin frame structure
33	Evila et al.[27]	Focused on designing and fabrication of new customised tracheal stents by FDM machine. The developed method and strategy provide an automatic and novel system to fabricate customised tracheal stents with overall manufacturing efficiency	Achieved excellent surface quality and reduced costs
34	Lu et al.[66]	The low-cost 3D printer used for new geometric problems investigation. A method is presented to reduce weight and material	A novel optimisation algorithm method used for reducing weight and cost of material

(*continued on next page*)

Table 1 (*continued*)

S. no.	Authors	Description	Achievement
		cost	
35	Negi et al.[81]	Made an overview of Additive manufacturing technology and show how much it is beneficial in medical by review various papers of the journal. In this article study is conducted by two Indian institutions, there is the absence of right ear of a 19-year-old male patient. The ear designed by using this RP technology	The result shows the studies are so exact and cheaper as well at operates much faster. So, that rapid prototyping technique is suitable and beneficial in medical
36	Domanski et al.[25]	New lumbar intervertebral disc implants presented the methodology of a design process off with specific emphasis on the use of rapid prototyping technologies. The design process based on the computed tomography (CT) scan data, the lumbar spine bone tissue anatomical parameters achieved, which were the basis for the design and manufacturing process carried out with the use of computer-aided designing/computer-aided manufacturing systems/computer-aided engineering	For solving problems related to the reconstruction of geometry and the functionality of disc three rapid prototyping technologies FDM, 3DP and SLM used
37	Jiménez et al.[51]	Presented an optimal Additive manufacturing technology for the production of occlusal splints, and compare the model by fabrication which different techniques of prototyping. They analyse the most important variable such as geometry accuracy, prototype material, costs and surface finish	They found that rapid prototyping technologies are essential for the production of the model used in transforming of correction splints
38	Farouk[30]	A great role playing for human interaction is faced feature. In which centre point of the face is the nose, it is a significant contributor of the human face shape	Result show satisfactory for the patient in accepting the appearance of the nose
39	Ibrahiem et al.[45]	AM manufactured all human parts. The structural fat graft now considered by many plastics surgeons	Achieved that both reconstructive surgery and aesthetic surgery is accomplished easily. It is a valuable tool for soft tissue augmentation
40	O'Malley et al.[85]	AM technology is best suited for the fabricated implant of complex geometry and produced accurately	Additive Manufacturing technology is suitable for medical devices and clinical environment

implants. Process chain has been divided into eight major steps. These eight major steps in this process chain are show in Fig. 4.

In Table 2, Process chain members development in medical applications of AM are discussed with their achievements and limitations.

The process chain starts from diagnosis and ends at surgery. Data varies from patient to the patient. We need imaging and scanning, which is produced through various scanning procedure such as CT convert data in the 3D digital form. AM helps to transform the original design of the customised implant to the physical model. There is the importance of biomechanical simulation how much strength exerted, all simulation has done, regulatory approval is must before manufacturing. After building the model, post processing is compulsory for increasing strength, surface finish and finally, surgery is done.

5. Advances in additive manufacturing systems

According to PC magazine, a Belgian woman approximately 83-year-old the first person who got her jawbone transplanted with the help of a 3D printer. The benefit is that patient surgery time and recovery time is reduced. The shape of bone differs from person to person, which the help of AM technology, one can fabricate best-fit transplant which is easy to insert and time for the procedure get reduced with the better cosmetic result.[79] Prosthetic sockets manufactured by Stereolithography. Socket manufactured by this technology is cost-effective and better for the patient as compared to machine or hand method.[38] Not only the bone or any other hard part produced, but it is also possible to print cell.[76,16]

In modern research, surgical guides evaluate maxillofacial surgery field. Thus engage with additive manufacturing technology and use appropriate materials.[69] The tissue lost by accidents and by other reason of patient recover faster and with improved cosmetic results with the help of AM technology. The 3D printing technology which also prints cell possible for printing artificial blood vessels which have applications in coronary bypass surgery or other diseases like medical therapy and cardiovascular defects.[17]

With globalisation, the designing and manufacturing companies in current scenario are moving towards the international trade, where they have to compete internationally. Thus, it is important for the companies themselves to distinguish among the pool of competitors, and time-to-market fastly is one of the deciding factors.[53]

Manufacturing industry, productivity is measured by cost effectively a product developed and how quickly it produced from initial concept to the end-market. The high percentage of production costs spent on designing a product which has analysed.[103]

A vast amount of work has done in materials research and manufacturing methodologies in this field. Specifically in constructing bone substitutes for load bearing applications; however, there is still a gap in understanding the ideal relationship between the scaffold morphology (pore size, shape, and interconnectivity), transient biochemical interactions, and mechanical properties.[10,11]

6. Additive manufacturing parameters for medical models development

In the current scenario, there is no doubt that medical models help in solving complex surgical problems, Rapid Prototyping technology has numerous efficiencies which are used to generate the models. Key issues that change this perspective include as shown in Table 3. Additive manufacturing is used to create everything according to patient's requirement, i.e., the customised implant builds quickly and with high accuracy at a reasonable cost according to required strength which is ease of use. There are five criteria which we achieve through medical model when made through AM technology; they are speed, cost, accuracy, material and ease of use.

7. Applications of additive manufacturing in medical

The medical technology aims to assist, maintain or restore a person's mobility. In many cases, doctors need custom-made

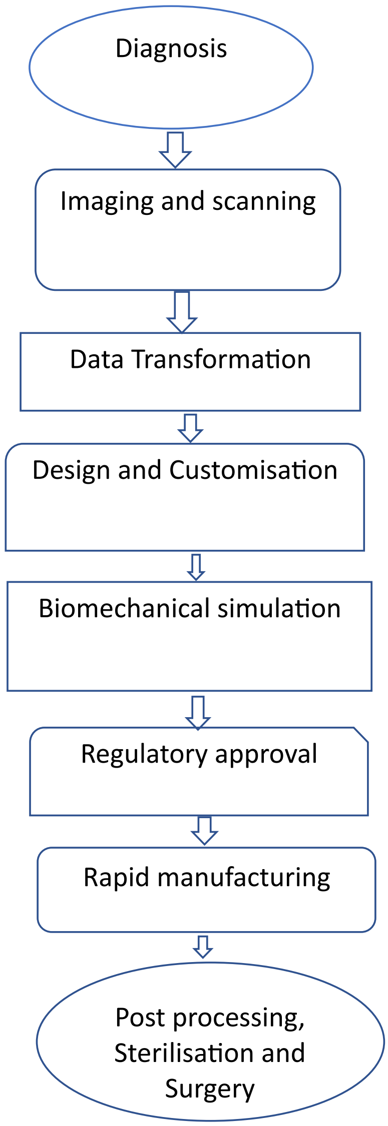

Fig. 4. Process chain development in medical application of Additive Manufacturing.

designs implant used for patients which are less in number and differ from patient to patient. Additive manufacturing fulfils the need and products are quickly available and produced at an economical price. Various applications of Additive manufacturing are discussed in following Table 4.

8. Implementing additive manufacturing in medical areas

Additive manufacturing is implemented in various applications and recently introduced in the medical field. Various researchers reported this influence of technology in the different areas. There are eight major areas of medical applications as follows and shown in Table 5. Here we are presenting the objectives and main advantages of these eight medical application areas.

9. Major contribution of the study

Additive Manufacturing has contributed increasable in the medical field. From designing phase to the production of an implant, it plays an important role which is under:

I. The direct contact of the patient with the medical application is growing with the help of additive manufacturing technology. The Additive Manufacturing Technologies which use medically scanned data to produce an accurate implant.
II. AM vastly fabricated the physical object directly from virtual 3D- CAD data. Additive manufacturing can align the need for medical device segment producing cost effect implants.
III. Additive Manufacturing used in various medical application such as Patient-custom manufacturing, mass fabrication of primary femoral implants, Fabrication of customised maxillo-facial prosthesis, Pre-surgical planning, new orthopaedic products, and suitable applications in dentistry.
IV. AM has significant contribution in designing and fabrication of implants, medical tools designing and development process, training, diagnosis, surgical simulation. In fields of prosthetics and implantation, it plays an important role.
V. Additive Manufacturing technologies now a day used in the medical field because Additive manufacturing technologies especially help surgeons and in previous generation doctors used this technology for imagination. Now a day it is successfully implanted by using this Additive Manufacturing technology.

A major review has been under taken for the primary applications of AM as used for medical purposes. Process chain development in the use of AM has been identified, and explained for every process chain member, its achievement and limitations for various references. The main criteria that we achieve through medical model when made through AM technology have been analysed. A classification of the application of AM in medical with criteria, achievement and references have been provided.

10. Research direction and future scope

In future Additive manufacturing will have a better capability of enhancing product customisation and usage with reasonable cost. AM has disrupted all the traditional fabrication of medical models. This technology fabricates implant with its specific geometrical dimensions, and it replaces conventional scaffold fabrication methods. This technology is beneficial in surgical planning; the models provide surgical and physician team with a visual aid to make surgery planning better. It has potential to fabricate customised fixtures and implants; complex geometry is also fabricated in short time. This is needed for designing and manufacturing of surgical aid tools, bio-models, implants, various scaffolds for tissue engineering and development of multiple medical devices and surgical training models. In future medical will have to work in close collaboration with AM researchers and commercial with AM researchers and commercial product developers.

11. Conclusion

Additive Manufacturing technology is used to create 3D parts directly from CAD models and quickly fabricate complex-shapes. Additive Manufacturing application in the case of medical applications model is useful for surgical planning. This technology plays a significant role in reverse engineering applications, E-manufacturing Processes, Rapid Tooling, Product design and development, Medical Field, etc. Medical education and training, Designing and development of medical devices, designing of the customised implant, scaffolding and tissue engineering, prosthesis and orthotics, mechanical bone replica, forensics, various problems are solved in dentistry by implementing this Additive Manufacturing technology. AM system provide extensive support in medical applications, providing better accuracy and speed, product visual-

Table 2
Process chain development in medical application of Additive Manufacturing.

S. no.	Process chain member	Achievement	Limitation	Refs.
1	Diagnosis	• Medical diagnosis process help for deciding patient signs and symptoms for condition or diseases • AM used for reverse engineering	• Hard for obtaining accurate and reliable data	Marchelli et al.[71], McGann[72], Dobransky[24]
2	Imaging and scanning	• Medical imaging and scanning technology used for scanning and find diseases earlier • Imaging and scanning used for top development from no of years • These used for determining broken bone as well as diseases in human body	• Financial burden for the patients	Connolly[18], Sedghi et al. [96], John et al. [52]
3	Data transformation	• Preparing a data from computing which derived from the original value • Before statistical analysis the data transformation is necessary	• Need high level of skill in data analysis	Vestal and Massey[110]
4	Design and customisation	• Medical Rapid Prototyping can design and fabricate customised implants according to required • Shape and size which vary from patient to patient	• Need high-end designing and AM technology is costly	Eyers and Dotchev[28]
5	Biomechanical simulation	• The biomechanical simulation used to improve human body parts injury • They replace defective bones, skull, etc. • With the help of AM technology, we achieve models, which used for adapting the user or patient needs • It also contributes to analyse and describe the spines internal dynamics.	• Create more problem for patient if exact analysis of spine not available	Sun et al.[104], DeJong et al.[21], Perestrelo et al.[91], Timothy et al.[106]
6	Regulatory approval	• Regulatory Approval is critical either of the patient or any other concern or health authorities	• Need authorisation whether it is feasible or not • Safety and precautions are also needed	William[113]
7	Rapid manufacturing	• Medical Rapid manufacturing is used to produce medical model according to geometric accuracy in required time.	• Create problem if there is poor surface finish	Arrieta et al.[4]
8	Post processing, sterilisation and surgery	• Post processing increase strength, accuracy • The surface finishing of medical model and improve safety during operation • It is last steps of process chain in medical. After surgery patient may feel relax as various cases discussed in different papers	• Increase in overall cost of medical implant	Ah-sung et al.[2], Bibb et al.[9]

Table 3
Criteria for medical models when made using Additive Manufacturing.

S. no.	Criteria	Achievements	Limitation	Refs.
1	Speed	• Additive manufacturing has fast built speed • Surface finish, accuracy and mechanical strength of the part are also good • This technology typically used for producing the conceptual model for manufacturing as well as medical	• Not suitable for batch production system	Kochan[57]
2	Cost	• Additive manufacturing technologies used for the low-cost production of the customised medical model • Medical models differ from patient to patient; this model suitably produces by it at low cost	• Suitable only in case of customisation	Ostuzzi et al.[86]
3	Accuracy	• The medical model produced by this technology has good accuracy and surface finish	• Accuracy is good but not as good as compared to some other machining process	Mallepree and Bergers[68], Salmi et al.[93]
4	Materials	• There is a change of material option in this technology • We can change the material properties for increasing property of medical implant • The accuracy of the model is varying from material to material	• Material changing options are limited	Salmi et al.[94], Lei et al.[63]
5	Ease of use	• This technology has exponential growth of Computer Aided Design • The model produced by this technology is fast and ease of use • No tooling and fixtures are required	• Need highly skilled person	Gibson[31]

Table 4
Applications of Additive Manufacturing in medical: Criteria and achievements.

S. no.	Criteria	Achievements	Refs.
1	Designing and manufacturing of surgical aid tools, bio-models and implants	• Play a useful role for design and production of surgical support tools, bio-models and implants • Also used for the surgical tools up gradation	Singare et al.[99], Song et al.[102]
2	Designing and manufacturing of various scaffolds for tissue engineering	• An AM characteristic is to Design and manufacture the different scaffolds for the restoration of tissues • It replaces conventional scaffold fabrication methods • AM help for printing organs, produced cells, cell-laden biomaterials, biomaterials individually	Bang Pham et al.[7], Cheng and Lee[13], Ozbolat[87], Gibson and Li[105], Li et al.[64],Vasireddi and Basu[109]
3	Development of various medical devices and surgical training models	• Used for developing various medical models, surgical training models which are used in medical education	Sanghera et al.[95], Chimento[15], Dahake et al.[19]
4	Individualization	• AM is used for individualisation, as data differs from patient to patient • Used for customised implant fabrication	Yaxiong et al.[116], Deshmukh et al.[22]
5	Complex geometries	• This technology has great potential for fabrication of complex geometries implant	Dahake et al.[19]
6	Functional integration	• The medical models are in functional integration • It works like an original one	Mallepree and Bergers[68], Deshmukh et al.[22]
7	Reduced costs	• AM technology helps for reducing cost of medical implant as compared to other manufacturing processes	Evila et al.[27]
8	Rapid availability	• AM has availability for producing medical model in short time	Kochan[56], Graham[33]
9	Improved patient care	• This technology is used for development and improve patient care through the customised model	AhnSung et al.[2]
10	Cost-effectiveness for the hospital	• AM technology makes possible to manufacture customised implants which comfortably fit the patient with reasonable cost	Milovanovic and Trajanovic[75]
11	Weight reduction	• Reduction of weight done with the help of this technology by changing material	Eyers and Dotchev[28]

Table 5
Major medical areas where Additive Manufacturing has been implemented.

S. no.	Area of medical application	Objectives	Major benefits	Refs.
1	Surgical planning	• The main objective is how AM become more beneficial in surgical planning • These models provide surgical and physician team a visual aid used to become surgery planning better • Bone structure of patient is studied before surgery, which reduced operation time, cost as well as risk	• With the help of this technology during operation, we predicted the problem cause and obtained diagnostic quality • AM models are better understood the complex anomaly and complicated procedure • These models especially help in surgeries where there are deformities or anatomical abnormalities, in surgery of heart surgery of spine maxillofacial and craniofacial surgery	Kai et al.[54], Faber et al.[29], Liu et al.[65], Sodian et al.[101], Guarino et al.[34], Paiva et al.[88], Mizutani et al.[77], Poukens et al.[92], Maravelakis et al.[70], Zenha et al.[118], Mehra et al.[73], Peltola et al.[89]
2	Medical education and training	• The primary purpose is that how this technology provides better demonstration of internal and external human anatomy structure • It consists of many colours, so these models are used in teaching as well as in research purpose in medical education	• AM models used for better illustration in school and museums • These models are used by young doctors or medical students to understand surgical procedure and problem without causing patient in discomfort	Nyaluke et al.[84], Liu et al.[65], Mori et al.[78]
3	Design and development of devices and instrumentation used in medical	• The purpose of this technology is how this helps for design and development of devices and instrumentation used in medical	• For fabrication of medical devices and instrumentation AM is used because this technique design the model, develop and then produced required medical equipment or instruments • It includes hearing aid, dental devices and surgical tools	Van Noort[108]
4	Customised implant design	• The purpose of this technology has potential to fabricate customised fixtures and implants • Complex geometry is also built in short time	• CAD and AM technology make possible to manufacture customised implants which comfortably fit the patient with reasonable cost • AM create accurate implant for patient rather than standard-sized implants such as knee joints, spinal implant and dental implant which is significantly beneficial for patient Surgical implant become more precise by using AM	Noorani[83], Liu et al.[65], Balazic et al.[6], Milovanovic and Trajanovic[75]

(continued on next page)

Table 5 (*continued*)

S. no.	Area of medical application	Objectives	Major benefits	Refs.
			• With customised implant fabrication risk and surgery time is reduced	
5	Scaffoldings and tissue engineering	• The primary purpose is how this technology fabricates implant with its unique geometrical characteristics like scaffolds for the restoration of tissues • It replaces conventional scaffold fabrication methods	• The scaffold is supporting structure and provides support and guidance to defective patient bone or growing tissue which is damaged • AM techniques like FDM, SLS and 3D printing are suitable for fabricating controlled porous structures by using application of biomaterial contributing in the field of tissue engineering and scaffolding • AM technology increased the ability to produce complex geometry product with higher accuracy	Kim and Mooney[55], Hutmacher et al.[44], Yeong et al.[117], Peltola et al.[90]
6	Prosthetics and orthotics	• How this technology is beneficial in prosthetics and orthotics field of Medical which starts with particular patient anatomy	• Accurate alignment characteristics of patient also needed in this model, which allowing biomechanically correct geometry development and improves comfort, stability • AM fabricate custom prosthesis which fit precisely to patient at reasonable cost such as pattern of dental crowns	Noorani[83], Liu et al.[65]
7	Mechanical bone replicas	• How AM technology used for mechanical bone model fabrication • This technology replicates the material variation done easily	• SLA can create composite structure which has similar property of bone • These bones can be-be provided strength under various conditions • Also beneficial to recreate the stresses, fractures and different changes in bone, which give more helps to researcher and doctors	Noorani[83]
8	Forensics	• AM tool is more beneficial tool for investigation of criminal, such as homicide cases where crime scene for investigation reconstructed	• These models kept evidence for investigation of criminal and manufacture of different scaffolds investigator in finding some question answer • In many cases, it is used to create events and scene accurately which quickly help for solving cases	Liu et al.[65]

isation and customisation, customised tools, improved modelling and extensive assistance in decision making. Additive Manufacturing is opening up a new market to help the humanity.

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References

1. Ahn DG, Lee JY, Yang DY. Rapid prototyping and reverse engineering application for orthopaedic surgery planning. *J Mech Sci Technol*. 2006;20:19–28.
2. AhnSung H, Lee CS, Jeong W. Development of translucent FDM parts by post processing. *Rapid Prototyp J*. 2004;10:218–224.
3. Al-Sukhun J, Kontio R, Lindqvist C, Tornwall J. Use of a prefabricated titanium plate for accurate reconstruction of secondary orbital blow-out fracture. *Plast Reconstr Surg*. 2006;117:1648–1651.
4. Arrieta C, Uribe S, Ramos G, et al.. Quantitative assessments of geometric errors for rapid prototyping in medical applications. *Rapid Prototyp J*. 2012;18:431–442.
5. Azari A, Nikzad S. The evolution of rapid prototyping in dentistry: a review. *Rapid Prototyp J*. 2009;15:216–225.
6. Balazic M, Kopac J. Improvements of medical implants based on modern materials and new technologies. *J Achieve Mater Manuf Eng*. 2007;25:31–34.
7. Bang Pham C, Fai Leong K, Chiun Lim T, Sin Chian K. Rapid freeze prototyping technique in bio plotters for tissue scaffold fabrication. *Rapid Prototyp J*. 2008;14:246–253.
8. Beneke F, Metzen M, Bergers D. Study of a process chain for the use of medical graphic data in technical applications. *Materialise Archives Leuven*; 2003.
9. Bibb R, Eggbeer D, Evans P, Bocca A, Sugar A. Rapid manufacture of custom fitting surgical guides. *Rapid Prototyp J*. 2009;15:346–354.
10. Bohner M, Loosli Y, Baroud G, Lacroix D. Commentary: deciphering the link between architecture and biological response of a bone graft substitute. *Acta Biomater*. 2011;7:478–484.
11. Butscher A, Bohner M, Hofmann S, Gauckler L, Müller R. Structural and material approaches to bone tissue engineering in powder-based three-dimensional printing. *Acta Biomater*. 2011;7:907–920.
12. Chen Y. 3D texture mapping for rapid manufacturing. *Comput-Aided Des Appl*. 2007;4:761–771.
13. Cheng YL, Lee ML. Development of dynamic masking rapid prototyping system for application in tissue engineering. *Rapid Prototyp J*. 2009;15:29–41.
14. Cheung LK, Wong MCM, Wong LLS. Refinement of facial reconstructive surgery by stereo model planning. *Ann R Aust College Dent Surg*. 2002;129–132.
15. Chimento J, Jason Highsmith M, Crane N. 3D printed tooling for thermoforming of medical devices. *Rapid Prototyp J*. 2011;17:387–392.
16. Christensen B. New device prints human tissue; 2009. <http://www.livescience.com/5977-device-prints-human-tissue> [HTML].
17. Conner M. 3-D medical printer to print body parts. *EDN*. 2010;55:9–18.
18. Connolly C. Imaging developments benefit medical applications. *Sensor Rev*. 2005;25:246–248.
19. Dahake SW, Kuthe AM, Mawale MB, Bagde AD. Applications of medical rapid prototyping assisted customized surgical guides in complex surgeries. *Rapid Prototyp J*. 2016;22:934–946.
20. De Beer N, van der Merwe A. Patient specific intervertebral disc implants using rapid manufacturing technology. *Rapid Prototyp J*. 2013;19:126–139.
21. De Jongh CU, Basson AH, Scheffer C. Predictive modelling of cervical disc implant wear. *J Biomech*. 2008;41:3177–3183.
22. Deshmukh TR, Kuthe AM, Chaware SM, Vaibhav B, Ingole DS. Rapid prototyping assisted fabrication of the customised temporomandibular joint implant: a case report. *Rapid Prototyp J*. 2011;17:362–368.
23. Dhakshyani R, Nukman Y, Abu Osman N, Vijay C. Preliminary report: rapid prototyping models for Dysplastic hip surgery. *Open Med*. 2011;6:266–270.
24. Dobransky K. Labeling, looping, and social control: contextualizing diagnosis in mental health care. In: McGann PJ, Hutson David J, eds. *Sociology of diagnosis. Advances in medical sociology*, vol. 12:111–131.
25. Domanski J, Skalski K, Grygoruk R, Mróz A. Rapid prototyping in the intervertebral implant design process. *Rapid Prototyp J*. 2015;21:735–746.
26. Esses SJ, Berman P, Bloom AI, Sosna J. Clinical applications of physical 3D models derived from MDCT data and created by Rapid Prototyping. *Am J Roentgenol*. 2011;196:683–688.

27. Evila LM, Vallicrosa G, Serenó L, Ciurana J, Ciro AR. Rapid tooling using 3D printing system for manufacturing of customized tracheal stent. *Rapid Prototyp J*. 2014;20:2–12.
28. Eyers D, Dotchev K. Technology review for mass customisation using rapid manufacturing. *Assembly Automation*. 2010;30:39–46.
29. Faber J, Berto PM, Quaresma M. Rapid prototyping as a tool for diagnosis and treatment planning for maxillary canine impaction. *Am J Orthod Dentofac Orthop*. 2006;129:583–589.
30. Farouk A. Esthetic rhinoplasty as an adjunctive technique in nasal oncoplastic surgery. *Alex J Med*. 2016;52:347–352.
31. Gibson I, Cheung LK, Chow SP, et al.. The use of rapid prototyping to assist medical applications. *Rapid Prototyp J*. 2006;12:53–58.
32. Gibson I, Kvan T, WaiMing L. Rapid prototyping for architectural models. *Rapid Prototyp J*. 2002;8:91–95.
33. Graham S. Rapid prototyping: a key to fast-tracking design to manufacture. *Assembly Automation*. 2000;20:291–294.
34. Guarino J, Tennyson S, McCain G, Bond L, Shea K, King H. Rapid prototyping technology for surgeries of the pediatric spine and pelvis. *J Pediatr Orthopaedics*. 2007;27:955–960.
35. Haleem A, Khan A, Javaid M. Design and Development of Smart Landline Using 3D Printing Technique. *Int J Adv Res Innovation*. 2016;4:438–447.
36. Harrysson OLA, Cormier DR, Marcellin LJ, Jajal K. Rapid prototyping for treatment of canine limb deformities. *Rapid Prototyp J*. 2003;9:37–42.
37. He J, Li D, Lu B, Wang Z, Zhang T. Custom fabrication of a composite hemi knee joint based on rapid prototyping. *Rapid Prototyp J*. 2006;12:198–205.
38. Herbert N, Simpson D, Spence WD, Ion W. A preliminary investigation into the development of 3-D printing of prosthetic sockets. *J Rehabilitation Res Dev*. 2005;42:141–146.
39. Hieu LC, Bohez E, Vander Sloten J, et al.. Design for medical rapid prototyping of cranioplasty implants. *Rapid Prototyp J*. 2003;9:175–186.
40. Hieu LC, Zlatov N, VanderSloten J, et al.. Medical rapid prototyping applications and methods. *Assembly Automation*. 2005;25:284–292.
41. Hollister SJ. Porous scaffold design for tissue engineering. *Nat Mater*. 2006;5, pp. 590-590.
42. Hutchinson MR. The burden of musculoskeletal diseases in the United States: prevalence, societal and economic cost. *J Am College Surg*. 2009;208:e5–e6 [1st ed.].
43. Hutmacher DW. Scaffolds in tissue engineering bone and cartilage. *Biomaterials*. 2000;21:2529–2543.
44. Hutmacher DW, Sittinger M, Risbud MV. Scaffold-based tissue engineering: rationale for computer-aided design and solid free-form fabrication systems. *Trends Biotechnol*. 2004;22:354–362.
45. Ibrahiem SMS, Farouk A, Salem IL. Facial rejuvenation: serial fat graft transfer. *Alex J Med*. 2016;52:371–376.
46. James WJ, Slabbekoorn MA, Edgin WA, Hardin CK. Correction of congenital malar hypoplasia using stereolithography for presurgical planning. *J Oral Maxillofac Surg*. 1998;56:512–517.
47. Jamieson R, Holmer B, Ashby A. How rapid prototyping can assist in the development of new orthopaedic products: a case study. *Rapid Prototyp J*. 1995;1:38–41.
48. Javaid M, Haleem A, Shuaib M, Kumar L. Product design and development using combination of Steinbichler comet 3D scanner and projet 3D printer. In: *National conference on innovative trends in Mechanical Engineering-2017 held at Department of Mechanical Engineering, Shri Mata Vaishno Devi University Katra, Jammu, from 3–4 March 2017*.
49. Javaid M, Kumar L, Kumar V, Haleem A. Product design and development using polyjet rapid prototyping technology. *Int J Control Theory Inf*. 2015;5:12–19.
50. Jiang X, Cheng X, Peng Q, et al.. Models partition for 3D printing objects using skeleton. *Rapid Prototyp J*. 2017;23:54–64.
51. Jiménez M, Romero L, Domínguez M, Espinosa MM. Rapid prototyping model for the manufacturing by thermoforming of occlusal splints. *Rapid Prototyp J*. 2015;21:56–69.
52. John MF, Bradley AT. Brain imaging and political behavior. In: Peterson Steven , Somit Albert, eds. *Biology and politics*. *Research in biopolitics*, vol. 9:231–255.
53. Kai Chua C, Fai Leong K, Sing Lim C, Thien VT. Multimedia courseware for teaching of rapid prototyping systems. *Rapid Prototyp J*. 2010;16:80–89.
54. Kai CC, Meng CS, Ching LS, Hoe EK, Fah LK. Rapid prototyping assisted surgery planning. *Int J Adv Manuf Technol*. 1998;14:624–630.
55. Kim BS, Mooney DJ. Development of biocompatible synthetic extracellular matrices for tissue engineering. *Trends Biotechnol*. 1998;16:224–230.
56. Kochan A. Rapid developments in rapid prototyping. *Assembly Automation*. 1995;15:18–19.
57. Kochan A. Rapid prototyping gains speed, volume and precision. *Assembly Automation*. 2000;20:295–299.
58. Krishnan SP, Dawood A, Richards R, Henckel J, Hart AJ. A review of rapid prototyped surgical guides for patient-specific total knee replacement. *Bone Joint J*. 2012;94:1457–1461.
59. Kumar L, Haleem A, Tanveer Q, Javaid M, Shuaib M, Kumar V. Rapid manufacturing: classification and recent development. *Int J Adv Eng Res Sci (IJAERS)*. 2017;4:29–40.
60. Kumar L, Tanveer Q, Kumar V, Javaid M, Haleem A. Developing low cost 3D printer. *Int J Appl Sci Eng Res*. 2016;5:433–447.
61. Kumar V, Kumar L, Haleem A. Selection of rapid Prototyping technology using an ANP based approach. *IOSR J Mech Civ Eng*. 2016;13:71–78.
62. Kumar V, Kumar L, Rajesh M, Haleem A. Design and development of thermal rapid prototyping machine and its application. *Int J Emerg Technol Eng Res (IJETER)*. 2016;4:101–106.
63. Lei SC, Frank MD, Anderson D, Brown T. A method to represent heterogeneous materials for rapid prototyping: the matryoshka approach. *Rapid Prototyp J*. 2014;20:390–402.
64. Li Y, Li D, Lu B, Gao D, Zhou J. Current status of additive manufacturing for tissue engineering scaffold. *Rapid Prototyp J*. 2015;21:747–762.
65. Liu Q, Leu MC, Schmitt SM. Rapid prototyping in dentistry: technology and application. *Int J Adv Manuf Technol*. 2006;293:317–335.
66. Lu L, Chen B, Sharf A, et al.. Build-to-last. *ACM Trans Graphics*. 2014;33:1–10.
67. Makovec R. Digital technologies in dental laboratories. *Ann DAAAM Proc*. 2010;15–79.
68. Mallepree T, Bergers D. Accuracy of medical RP models. *Rapid Prototyp J*. 2009;15:325–332.
69. Malley OF. Research to inform the improved accuracy of zygomatic implants placed using computer design and additive manufactured surgical guides. In: *ADT 5th triennial congress Beijing, China 6th–8th September 2014*.
70. Maravelakis E, David K, Antoniadis A, Manios A, Bilalis N, Papaharilaou Y. Reverse engineering techniques for cranioplasty: a case study. *J Med Eng Technol*. 2009;32:115–121.
71. Marchelli G, Prabhakar R, Storti D, Ganter M. The guide to glass 3D printing: developments, methods, diagnostics and results. *Rapid Prototyp J*. 2011;17:187–194.
72. McGann PJ. Troubling diagnoses. In: McGann PJ, Hutson David J, eds. *Sociology of diagnosis*. *Advances in medical sociology*, vol. 12. Emerald Group Publishing Limited; 2011:331–362.
73. Mehra P, Miner J, D'Innocenzo R, Nadershah M. Use of 3-D stereolithographic models in oral and maxillofacial surgery. *J Maxillofac Oral Surg*. 2011;10:6–13.
74. Melchels FPW, Feijen J, Grijpma DW. A review of stereolithography and its applications in biomedical engineering. *Biomaterials*. 2010;31:6121–6130.
75. Milovanovic J, Trajanovic M. Medical applications of rapid prototyping. *Mech Eng*. 2007;5:79–85.
76. Mironov V, Reis N, Derby B. Review: bioprinting: a beginning. *Tissue Eng*. 2006;12:631–634.
77. Mizutani J, Matsubara T, Fukuoka M, et al.. Application of full-scale three-dimensional models in patients with rheumatoid cervical spine. *Eur Spine J*. 2008;17:644–649.
78. Mori K, Yamamoto T, Oyama K, Nakao Y. Modification of three-dimensional prototype temporal bone model for training in skull-base surgery. *Neurosurg Rev*. 2008;32:233–239.
79. Moscaritolo A. Woman receives 3D printer created transplant Jaw. PC Mag; 2012. <http://www.pcmag.com/article2/0,2817,2399887,00.asp>.
80. Naing MW, Chua CK, Leong KF, Wang Y. Fabrication of customised scaffolds using computer aided design and rapid prototyping techniques. *Rapid Prototyp J*. 2005;11:249–259.
81. Negi S, Dhiman S, Sharma RK. Basics and applications of rapid prototyping medical models. *Rapid Prototyp J*. 2014;20:256–267.
82. Ng P, Lee PSV, Goh JCH. Prosthetic sockets fabrication using rapid prototyping technology. *Rapid Prototyp J*. 2002;8:53–59.
83. Noorani R. *Rapid prototyping: principles and applications*. Hoboken (NJ): John Wiley and Sons Inc; 2006. ISBN: 978-0-471-73001-9.
84. Nyaluke AP, An D, Leep HR, Parsaei HR. Rapid prototyping: applications in academic institutions and industry. *Comput Ind Eng*. 1995;29:345–349.
85. O'Malley FL, Millward H, Eggbeer D, Williams R, Cooper R. The use of adenosine triphosphate bioluminescence for assessing the cleanliness of improve materials used in medical applications. *Addit Manuf*. 2016;9:25–29.
86. Ostuzzi F, Rognoli V, Saldien J, Levi M. +TUO project: low-cost 3D printers as helpful tool for small communities with rheumatic diseases. *Rapid Prototyp J*. 2015;21:491–505.
87. Ozbolat IT, Yu Y. Bioprinting toward organ fabrication: challenges and future trends. *IEEE Trans Biomed Eng*. 2013;60:691–699.
88. Paiva WS, Amorim R, Bezerra DAF, Masini M. Application of the stereolithography technique in complex spine surgery. *Arq Neuropsiquiatr*. 2007;65:443–445.
89. Peltola MJ, Vallittu PK, Vuorinen V, Aho AAJ, Puntala A, Aitasalo KMJ. Novel composite implant in craniofacial bone reconstruction. *Eur Arch Otorhinolaryngol*. 2011;269:623–628.
90. Peltola SM, Melchels FPW, Grijpma DW, Kellomäki M. A review of rapid prototyping techniques for tissue engineering purposes. *Ann Med*. 2008;40:268–280.
91. Perestrelo P, Bártolo P, Paranhos M, Noritomi P, Silva J. Cranial biomechanical simulation. *Proc CIRP*. 2013;5:305–309.
92. Poukens J, Laeven P, Beerens M, et al.. A classification of cranial implants based on the degree of difficulty in computer design and manufacture. *Int J Med Robotics Comput Assisted Surg*. 2008;4:46–50.
93. Salmi M, Paloheimo KS, Tuomi J, Wolff J, Mäkitie A. Accuracy of medical models made by additive manufacturing (rapid manufacturing. *J Cranio-Maxillofac Surg*. 2013;41:603–609.
94. Salmi M, Tuomi J, PaloheimoKaija S, et al.. Patient specific reconstruction with 3D modeling and DMLS additive manufacturing. *Rapid Prototyp J*. 2012;18:209–214.
95. Sanghera B, Naique S, Papaharilaou Y, Amis A. Preliminary study of rapid prototype medical models. *Rapid Prototyp J*. 2001;7:275–284.

96. Sedghi S, Sanderson M, Clough P. Medical image resources used by health care professionals. *Aslib Proc*. 2011;63:570–585.
97. Shuaib M, Javaid M, Kumar L, Haleem A. Using additive manufacturing for improving building services. In: *International conference and exhibition on building utilities organized by Department of Mechanical Engineering, Faculty of Engineering & Technology, Jamia Millia Islamia, New Delhi on Dec 2016*. p. 53–64.
98. Shuaib M, Kumar L, Javaid M, Haleem A, Khan MI. A comparison of additive manufacturing technologies. In: *International conference on advance production and industrial engineering held at DTU Delhi in Dec 2016*. p. 353–60.
99. Singare S, Dichen L, Bingheng L, Zhenyu G, Yaxiong L. Customized design and manufacturing of chin implant based on rapid prototyping. *Rapid Prototyp J*. 2005;11:113–118.
100. Singare S, Yaxiong L, Dichen L, Bingheng L, Sanhu H, Gang L. Fabrication of customised maxilla facial prosthesis using computer aided design and rapid prototyping techniques. *Rapid Prototyp J*. 2006;12:206–213.
101. Sodian R, Weber S, Markert M, et al.. Stereolithographic models for surgical planning in congenital heart surgery. *Ann Thorac Surg*. 2007;83:1854–1857.
102. Song C, Yang Y, Wang Y, Yu J, Wang D. Personalized femoral component design and its direct manufacturing by selective laser melting. *Rapid Prototyp J*. 2016;22:330–337.
103. Stier K, Brown R. Integrating rapid prototyping technology into the curriculum. *J Ind Technol*. 2000;17:1–6.
104. Sun LW, Lee RYW, Lu W, Luk LDK. Modelling and simulation of the intervertebral movements of the lumbar spine using an inverse kinematic algorithm. *Med Biol Eng Compu*. 2004;42:740–746.
105. Tarik AM, Gibson I, Li X. State of the art and future direction of additive manufactured scaffolds-based bone tissue engineering. *Rapid Prototyp J*. 2014;20:13–26.
106. Timothy J, Horn O, Harrysson LA, et al.. Development of a patient-specific bone analog for the biomechanical evaluation of custom implants. *Rapid Prototyp J*. 2014;20:41–49.
107. Tuomi J, Paloheimo KS, Vehviläinen J, et al.. A novel classification and online platform for planning and documentation of medical applications of additive manufacturing. *Surg Innovation*. 2014;21:553–559.
108. Van Noort R. The future of dental devices is digital. *Dent Mater*. 2012;28:3–12.
109. Vasireddi R, Basu B. Conceptual design of three-dimensional scaffolds of powder-based materials for bone tissue engineering applications. *Rapid Prototyp J*. 2015;21:716–724.
110. Vestal K, Massey R. Work transformation in health care. *Health Manpower Manage*. 1994;20:9–13.
111. Wang CS, Wang WHA, Lin MC. STL rapid prototyping bio-CAD model for CT medical image segmentation. *Comput Ind*. 2010;61:187–197.
112. Wang W, Wang TY, Yang Z, et al.. Cost-effective printing of 3D objects with skin-frame structures. *ACM Transon Graphics*. 2013;32:1–10.
113. Kitchens William H. FDA regulatory approval process for medical products. In: Thursby Marie C, ed. *Technological innovation: generating economic results. Advances in the study of entrepreneurship, innovation & economic growth*, vol. 26:201–229.
114. Willis A, Speicher J, Cooper DB. Rapid prototyping 3D objects from scanned measurement data. *Image Vis Comput*. 2007;25:1174–1184.
115. Wong KV, Hernandez A. A review of additive manufacturing. *ISRN Mech Eng*. 2012;1–10.
116. Yaxiong L, Dichen L, Bingheng L, Sanhu H, Gang L. The customised mandible substitute based on rapid prototyping. *Rapid Prototyp J*. 2003;9:167–174.
117. Yeong WY, Chua CK, Leong KF, Chandrasekaran M. Rapid prototyping in tissue engineering: challenges and potential. *Trends Biotechnol*. 2004;22:643–652.
118. Zenha H, Azevedo L, Rios L, et al.. The application of 3-D bio-modelling technology in complex mandibular reconstruction experience of 47 clinical cases. *Eur J Plast Surg*. 2010;34:257–265.