SYSTEMATIC REVIEW

Fabrication of dental implants by the additive manufacturing method: A systematic review

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Implant dentistry has improved the rehabilitation of edentulous patients, especially those with alveolar bone resorption and poor retention and stability of conventional complete dentures.[1-4] A variety of dental implants are available, but limitations on design, length, and width can sometimes necessitate graft surgery.[3,5,6]

To achieve a high-quality rehabilitation with fewer clinical steps, less invasive procedures, and maximum tissue preservation, devices of innovative design and produced from more resistant materials and better surface treatment are required.[3,5,7,8] Thus, individualized dental implants offer benefits and are becoming a trend in dentistry.[3]

Additive manufacturing has allowed for the fabrication of custom implants with microscale resolution and is a potential technique for dental implant manufacturing.[9] The technique uses data obtained from computed tomography or magnetic resonance imaging.[10] The method, known as rapid prototyping or 3D printing, builds a structure by adding the material layer by layer[11] and is capable of building complex structures in a variety of geometries without using specific molds.[3] Additive manufacturing reduces wasting of material and time when compared with the milling technique and is an economical manufacturing method.[9] Metal implants are typically manufactured by electron beam melting (EBM) or selective laser melting (SLM).[12-24]

EBM and SLM, also known as direct metal laser sintering or selective laser sintering, build solid components layer by layer by melting metal powder and

ABSTRACT

Statement of problem. Placement of dental implants depends, among other factors, on anatomic conditions such as sufficient bone height and thickness. Thus, individualized dental implants seem to offer benefits for patients with alveolar bone resorption. Additive manufacturing has allowed for the fabrication of custom implants with microscale resolution and, although the efficiency of the process is unclear, is a potential process for manufacturing dental implants.

Purpose. The purpose of this systematic review was to evaluate the current situation of additive manufacturing techniques for fabricating dental implants.

Material and methods. An electronic search was performed in the databases PubMed, Lilacs, Cochrane Library, and Science Direct, with the terms "additive manufacturing" AND "dental implants," "rapid prototyping" AND "dental implants," "3 D printing" AND "dental implants," "electron beam melting" AND "dental implants," "selective laser melting" AND "dental implants." The articles were screened, and the final selection of articles was obtained by using the inclusion and exclusion criteria.

Results. The database search resulted in 1322 articles, which were screened for title and/or summary according to the inclusion criteria. From the selected 38 articles, 30 remained after applying the exclusion criteria. These were read completely, resulting in a selection of 13 articles for this systematic review. Owing to the great variety of articles with different objectives, the results were based on a descriptive analysis of the following topics: additive manufacturing technique and material, printed structure and implant design, implant characteristics, mechanical analysis, surface treatment, and osseointegration.

Conclusions. Additive manufacturing is a new technology that may solve many problems in diverse fields. In dentistry, however, further studies are needed to improve the method for manufacturing custom dental implants because no standard methodology is available. Moreover, the advantages and disadvantages of the process are not yet clearly defined. (J Prosthet Dent 2019;122:270-4)

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Clinical Implications

Additive manufacturing is a technique that can be used to fabricate individualized dental implants that can address specific patient challenges in a personalized and expeditious manner.

following a 3D computer-aided design (CAD) file. The metal-melting process of these 2 methods is different; EBM uses an electron beam, whereas SLM uses a high-energy laser.[11] The laser technique can provide total (in SLM) or partial melting of the particles (in selective laser sintering).

The metallurgical processes involved in solidification during the additive manufacturing processes are complex and produce fine-scale alloy microstructures with excellent mechanical properties, including high strength. Such characteristics occur due to the rapid solidification conditions of the alloy. In addition, the structures produced are porous, an important feature in reducing effective stiffness and, thus, concerns related to stress induction. Another beneficial feature of the porous structures fabricated by additive manufacturing is the possibility of providing anchor sites to the bone tissue and promoting accelerated osseointegration.[25] With such characteristics, the implants obtained by additive manufacturing could adequately transfer the stresses between bone and implant, increasing the life of an implant-supported restoration.[25]

However, challenges in this manufacturing method remain, such as obtaining a high-quality surface, dimensional accuracy, and adequate mechanical properties of the final object, not to mention the cost of running and the need for postprocessing.[26-28] As the technique has only recently been introduced into dentistry, questions about its efficiency in obtaining dental implants, as well as its advantages, disadvantages, and indications, are still unanswered. Therefore, the purpose of this systematic review was to search the literature for current information on the additive manufacturing of dental implants.

MATERIAL AND METHODS

An electronic search was performed in the databases PubMed, Lilacs, Cochrane Library, and Science Direct, with the terms "additive manufacturing" AND "dental implants," "rapid prototyping" AND "dental implants," "3 D printing" AND "dental implants," "electron beam melting" AND "dental implants," and "selective laser melting" AND "dental implants."

The inclusion criteria were that articles should be about fabricating implants by additive manufacturing, be published between 1998 and 2018, be published in English, and be research articles. The exclusion criterion was articles on 3D printing of components other than dental implants.

The database search resulted in 1322 articles, which were screened for title and/or summary according to the inclusion criteria. From the selected 38 articles, 30 remained after applying the exclusion criteria. After selecting the 30 articles, some referred to devices other than dental implants; however, this information was not clear in the abstract, and a complete reading was needed, which resulted in the selection of 13 relevant articles (Fig. 1).

Analyzing the data statistically by performing a meta-analysis was not possible because the articles had very different objectives. Thus, the results were based on a descriptive analysis of the technique and material of additive manufacturing, printed structure, implant design, implant characteristics, mechanical analysis, and osseointegration.

RESULTS

The studies evaluated used titanium for the manufacture of implants; however, Mounir et al[12] used polyetheretherketone in addition to titanium for printing implants with the same design. Most articles used the laser technique (direct metal laser sintering, SLM, or direct laser metal forming).[14-22,24] The EBM technique was used in 2 studies,[12,13] and Mommaerts[23] reported using the CADskills technique.

Different implant models, such as endosteal implants[13-19,21,24] and subperiosteal implants,[12,20,22,24] were obtained by the additive manufacturing technique. Of the endosteal implants, threaded,[13,14,19,21] smooth,[16,18] threaded and smooth,[15] solid and porous,[24] and a highly porous multiradicular design implants were fabricated.[17] Printing of threaded implants similar to those found on the market was reported in some of the articles.[13,14,19,21]

Chen et al[15] reported that the implants obtained by additive manufacturing had a granular surface; were free of distortion, pores, and cracks; and had good accuracy, reproducing the threads without apparent defects. The diameter and length of the implants were about 1% to 1.5% higher than those of the control.

Peng et al,[17] Shaoki et al,[19] Ramakrishnaiah et al,[13] Cohen et al,[24] and Hyzy et al[14] found porous surfaces with peaks and valleys of varied geometries, with a total and open porosity of 68.6% reported by Cohen et al[24]; Shaoki et al[19] and Hyzy et al[14] reported similar or increased roughness compared with that of the milled surface.

Regarding the quality of the process, Ramakrishnaiah et al[13] reported that the implant stems were well formed, continuous, and with few internal pores, although they
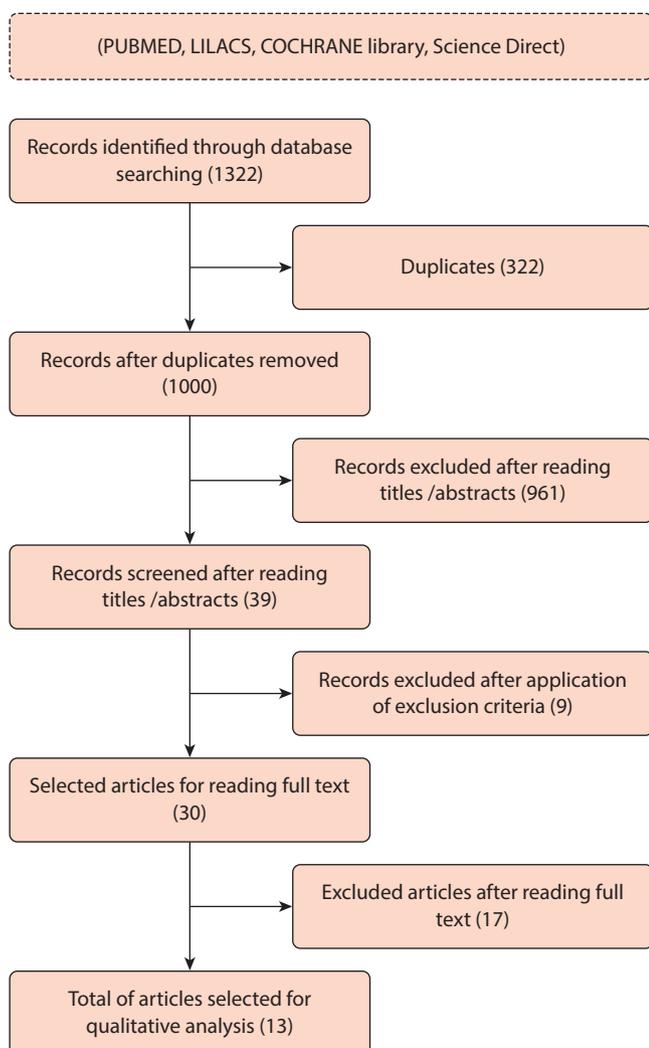
Figure 1. Flow diagram summarizing selection process.

had a high degree of surface roughness, which may have resulted from the powder of the raw material. However, Peng et al[17] reported the presence of collapsed structures and contamination at some sites, and Hyzy et al[14] found residues of Ti, O, and C on the implant surfaces.

Wettability tests were performed using disks[14,19] and implants[24] produced by additive manufacturing. Hyzy et al[14] found a contact angle less than 20 degrees, suggesting a hydrophilic surface, which is a desired characteristic in dental implants (greater wettability). However, Cohen et al[24] reported a contact angle of 85 degrees, and Shaoki et al[19] reported a contact angle less than 90 degrees, suggesting that even with larger contact angles, the property of the wetting presented would be similar to that found in the machined implants, implying adequate wettability.

Moin et al[18] assessed the accuracy of 3D printed implants shaped as tooth roots by optical scanning and observed differences between the printed implant and the original model, especially at the apex and cementum-enamel junction areas on the buccal and lingual sides. A decrease of 6.33% in the general surface area of the printed implant was found compared with the original tooth, and an increase of 0.27%, when comparing the optical examination of the 3D model with the original tooth; this showed that this technique could produce printed implants analogous to natural teeth.

Chen et al[15] evaluated the tensions generated in the smooth and threaded implants by simulation in the CAD system and mechanical tests, obtaining solid and high-strength implants with flexural strength that are comparable to commercially available implants. They reported that the threaded implants had better tension distribution and primary stability than the smooth root-like implant.[15] Gellrich et al[20] analyzed stress with the finite element method before installing subperiosteal implants, concluding that the method was appropriate.

Several studies reported the performance of post-processed implants fabricated by additive manufacturing.[12-14,16,17,21,22,24] However, Chen et al,[15] Mommaerts,[23] Shaoki et al,[19] Moin et al,[18] and Gellrich et al[20] did not report any type of postprocessing on the 3D printed implants.

Osseointegration was evaluated in the studies through in vitro or in vivo testing,[14,17,19,21,22,24] with an analysis of cell interaction with the printed structures, new bone formation, and the amount and quality of the bone formed. Microcomputed tomography,[14,17,19,22,24] histological analysis,[14,17,19,21,24] and cell culture[14,19,24] were used, as well as mechanical tests such as maximum insertion torque,[17] pullout test,[14,17,22,24] and pullout torque.[19] From these analyses, Peng et al,[17] Hyzy et al,[14] and Shaoki et al[19] found that printed implants with threaded design[14,19] and multiroot porous implants had similar or better performance than the machined commercial models used as control.[17]

Peng et al,[17] Hyzy et al,[14] and Cohen et al[22,24] reported on the growth of osteoblasts and new bone formation around implants printed in 3D, indicating that the bone can grow and cover the entire porous surface of the implant, with bone penetration into the pores and osseointegration.[14,17,22,24] This was in agreement with the study by Shaoki et al[19] who reported improvements in cell differentiation in implants fabricated by additive manufacturing. However, the commercially available control had better osseointegration, evident in the measured withdrawal torque.

Case reports demonstrated the success of treatments by using implants obtained by additive manufacturing, with follow-ups of 2 months,[23] 8 months,[22] 1 year,[12,16] and 5 years.[21] Mangano et al[21] reported consistent bone adherence to the surface of 3D printed implants, with osseointegration and continuous bone remodeling, concluding that the surface of these implants can provide

excellent bone growth after long-term functional load; however, they also reported fractures of two 3D printed implants in clinical use for 5 years without mentioning the reason for the fractures.

DISCUSSION

The relationship between biological or physiological response and implant-manufacturing methods was evaluated in this review; implants produced by additive manufacturing have properties such as well-controlled porosity and microroughness and nanoroughness that promote new bone formation and improve the osseointegration process.[14,17,19,21,22,24]

Features such as porosity and roughness, besides promoting new bone formation, also contribute to the distribution of tensions around the implants, thus promoting effective and rapid osseointegration.[28,29] In addition, clinical studies report the successful use of implants obtained by additive manufacturing for the oral rehabilitation of patients, with follow-up periods of up to 5 years.[12,16,21-23]

Three studies analyzed the additive and milling techniques,[14,17,19] but an objective comparison between the studies was not possible because they used different follow-up times and animal models. One study reported that both methods create implants that result in adequate bone volume and bone-to-implant contact,[19] and the other 2 studies reported better results for implants obtained through additive manufacturing.[14,17] This suggests that the additive manufacturing technique may be effective for fabricating dental implants, having promoting new bone formation and reducing the amount of material used in the confection and customization of the implant as benefits, supporting its indication in the rehabilitation of patients.

The analysis of the 13 included articles yielded no significant result when the effectiveness of additive manufacturing techniques and the relationship between the biological and physiological responses of dental implants were compared, which is important information for the understanding of the technique. The literature reports no significant difference in bone growth potential between the SLM and EBM techniques on the surfaces of implants produced with the same design.[29] This was similar to the findings of Wang et al[30] who evaluated biocompatibility and cytocompatibility and did not find significant differences between EBM and SLM specimens. Furthermore, all studies reported good results for all additive manufacturing methods used (EBM, SLM, DMLF, DLSM, and CADskills).

Regarding the quality of the implants produced by additive manufacturing, Chen et al[15] reported that the SLM method produced surfaces with macrorugosity and without distortions, cracks, or superficial pores. In addition, the implants also presented threads that were reproduced with precision and without apparent defects. Ramakrishnaiah et al[13] reported a surface with uniform and completely sintered particles and a metallurgical bond between the particles and alloy layers.

Concerning the diameter and length of the implants, Chen et al[15] reported an increase of 1% to 1.5% in the size of implants obtained by additive manufacturing compared with the control, which is in agreement with the study by Moin et al,[18] who also reported differences between the dimensions of the implant obtained by additive manufacturing and the control. However, the authors conclude that the implants had adequate dimensional accuracy with both the SLM and EBM methods.[13,15,18]

Some studies have reported on the deficiencies of implants fabricated by additive manufacturing.[13,17,19] In the SLM technique, a study reported defects such as collapsed structures and dross formation, the influence of the build direction on the quality of processing, and the overhanging structure of the pores.[17] Shaoki et al[19] reported a few melted particles of titanium on implants, and Ramakrishnaiah et al[13] reported that the lateral surfaces of implants produced by EBM had numerous unmelted and partially fused alloy particles. Partially fused particles create surface microporosity and are associated with improved bone growth and cell adhesion. Nevertheless, unmelted particles can increase the chances of failure due to fatigue.[31]

In this review, the different additive manufacturing techniques could not be compared because the included studies did not perform this comparison. According to the literature, EBM and SLM have peculiarities in relation to their benefits. Advantages of EBM over SLM are the high vacuum in the build chamber, which protects highly oxidizing materials such as Ti-6Al-4V, and maintenance of substantially high temperatures, which avoids residual stresses that may arise due to wide variations in temperature.[13]

Regarding the fabricated structures, Biemond et al[29] reported similar trabecular surface designs for both techniques, but the gross morphology and surface texture were different; in the EBM samples, but not in the SLM specimens, individual titanium granules were observed. In addition, the SLM specimens demonstrated a flatter macroscopic surface compared with those produced by EBM.

CONCLUSIONS

Based on the findings of this systematic review, the following conclusions were drawn:

1. Additive manufacturing is a new and effective alternative for the manufacture of custom implants.

2. Additive manufacturing of implants has advantages such as customization, flexibility, and freedom in implant design and the possibility of manipulating chemical and physical parameters.

3. Disadvantages of the additive manufacturing of dental implants are obtaining surface quality and dimensional accuracy and the cost of the equipment and materials.

4. Additive manufacturing is a technology that may solve many problems in diverse fields. In dentistry, however, further studies are needed to improve the method for manufacturing custom dental implants because no standard methodology is available. Moreover, the advantages and disadvantages of the process are not yet clearly defined.

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