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Dental Science - Review

Recent Advances in Material and Geometrical Modelling in Dental Applications

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Abstract

This article touched, in brief, the recent advances in dental materials and geometric modelling in dental applications. Most common categories of dental materials as metallic alloys, composites, ceramics and nanomaterials were briefly demonstrated. Nanotechnology improved the quality of dental biomaterials. This new technology improves many existing materials properties, also, to introduce new materials with superior properties that covered a wide range of applications in dentistry. Geometric modelling was discussed as a concept and examples within this article. The geometric modelling with engineering Computer-Aided-Design (CAD) system(s) is highly satisfactory for further analysis or Computer-Aided-Manufacturing (CAM) processes. The geometric modelling extracted from Computed-Tomography (CT) images (or its similar techniques) for the sake of CAM also reached a sufficient level of accuracy, while, obtaining efficient solid modelling without huge efforts on body surfaces, faces, and gaps healing is still doubtable. This article is merely a compilation of knowledge learned from lectures, workshops, books, and journal articles, articles from the internet, dental forum, and scientific groups' discussions.

Introduction

Dental sciences started thousands of years ago in ancient Egypt by using precious materials like gold for restorations. By the time new materials were utilised in dentistry as new treatment methods appeared. Also, new technologies help dentists to introduce new treatment techniques.

The new imaging, modelling, and analysis methods lead to great improvement in treatments quality and success rates.

Therefore, dental materials are considered the cornerstone of all advances in oral and dental medicine. Furthermore, geometric modelling and stress analysis of the restorative materials, prosthesis, and new dental tools are used as a preliminary step before commercial usage.

Dental materials

Rigid polymers, elastomers, metals, alloys, ceramics, inorganic salts and composite materials are commonly used within a variety of dental materials as demonstrated in Figure 1.

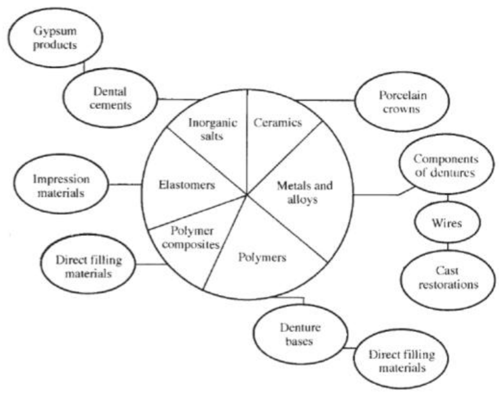

Figure 1: Variety of materials used in dentistry and some of their applications [1]

The physical properties and biocompatibility govern the dental material selection. Some dental materials should be sufficiently strong to withstand biting forces without fracture. Others should be rigid enough to maintain their shape under load, while these materials' properties are typically characterised by the stress-strain relationship. Additionally, chemical and electrical tests may be required for more properties as corrosion and conductivity.

Optimal dental material selection based on Finite Element Analysis

Stress analysis by finite element packages might be necessary due to its accuracy, low cost, and less time-consuming than experimental research. In many dental applications, Finite Element Analysis (FEA) can provide information would be difficult or impossible to be obtained by experimental observations, while, FEA cannot be performed without experimental inputs and validation [2]. The following examples demonstrate validated FEAs that focus on material selection:

1. The effect of post materials on stress distribution on endodontically treated lower first premolar was studied by FEA [3], and resulted in criteria for post material selection. Where, stiffer post materials are preferred to transfer less stresses to the root dentine with less displacement.

2. Reciprocating endodontic files material were investigated by FEA [4], that resulted in using stainless steel, is not suitable for manufacturing rotary or reciprocating instruments. NiTi is suitable for reciprocating instruments although it has short lifespan, thus one file per tooth is usually recommended.

3. Crown and implant-abutment materials combinations were studied [5] in details by FEA to find that using more rigid material for implant-abutment complex is preferred for low density bones to have better stress distributions. Using crown material with lower modulus of elasticity reduces the stresses generated on mandible, that it absorbs more energy from the applied load, and transfers less energy to the following parts.

4. Luting cement material type and its layer thickness were also studied [6] to conclude that increasing the cement layer thickness (ranged 20-60μm) ensures a longer lifetime of the restoration, and slightly increase the total deformation induced on the cement layer. Regardless of the cement type, thicker cement layer is preferred to reduce cortical bone stresses by about 6.5%. While spongy bone is insensitive to cement type or its layer thickness.

Geometric modelling in dental applications

Two major applications depend on geometric modelling: stress analysis, and production by computer-aided manufacturing (CAM). As the human teeth and bone have very complicated geometries, thus, it is extremely difficult to use conventional graphics and/or engineering modelling techniques in generating an accurate three dimensional (3D) geometric model(s) for bio-tissues.

Engineering CAD and graphics packages produce 2D and 3D geometric models in what is called "vector graphics/image" format. That, build a geometry with few numbers of points and correlate them by lines, areas, and …etc. Which generated by a set of mathematical equations. The resulting file size is relatively small (kilobytes) for huge or complicated geometry. On the other hand, the actual data from digitising (3D scanning like a laser, blue ray or contact probes ones), computed tomography (CT), cone-beam computed tomography (CBCT), Spiral Tomography, and other techniques can be taken as a base for the 3D geometric model(s). Such techniques produce set(s) of "raster graphics/image" formats. The resultant file size is very large (Mega/Gigabytes) that containing a huge number of points' coordinates (cloud of points). These points are not related to each other, but they are too close to each other and may be common in one coordinate as a result of fixed step by the scanning machine.

As, laser or blue ray, or contact probes scanners usually used for modelling inanimate objects. Laser and contact scanners (Figure 2) produce moderate file size that containing data of the outer surface only. The idea of how it works is to move the sensor within a certain domain steadily and in specific directions from an origin to record coordinates of any point are located on the scanned part when it interferes with the sensor movement.

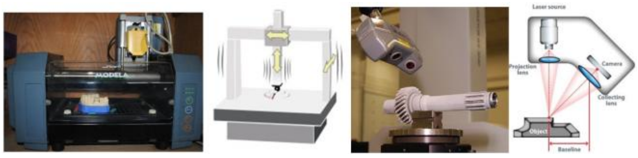

Figure 2: Contact probe and laser scanners pictures & schematics [8]

On the other hand, all other tomography systems are capable of producing images containing the entire body details, as schematic illustrates in Figure 3. The general idea of filming exploration of the human body, whether by X-ray or CT or other is a pass-ray window from the source and received on the other side which leads to a type of diffraction or absorption of part of the transmitted ray at the receiver, as a kind of change in the properties of radiation transmitted. Using mathematical analysis draw colourful 2D pictures or graded lighting for human body parts that had passed through these rays will be possible.

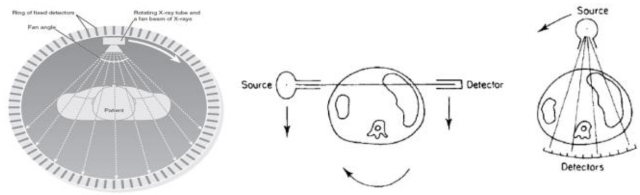

Figure 3: Schematics for CT imaging idea [8]

Changes in colour or lighting gradient unit's gives information about the type of material from which passed rays which can be specialists to determine the internal organs of the human body and its status (intact or a tumour or fragility ...etc.) as presented in Figure 4.

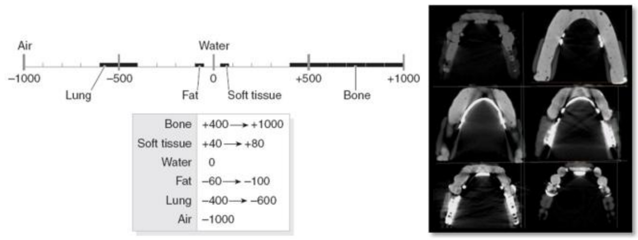

Figure 4: Brightness scale, and sample CT scan image [9]

Like any digital image, each point represents coordinates and information about the colour and intensity of light including resemble, with the presence of the tripartite scanners feature is the availability of these data for each holographic imaging under not only the outer surface. This result enables the user of some modern software(s) as Mimics, Amera, ...etc. To convert the CT scanner files (Dicom format) to form set of equally spaced 2D geometric forms, whether represented surface or volume in 3D. These programs select portions of the scanned body and using the “threshold” to select range of brightness values marking only one type of tissue (ex. bone), to create organ geometry. However, the further threshold on bone images removes also much of the cancellous bone tissue, since it is fewer dense than the cortical bone thus, leaving holes and openings on the required body mask. These opening were subsequently filled by software user, which results in a solid mask with all the bony tissues in the cloud. The mask was then added to the real image, yielding a segmented bone image only. Thus there is a high potential in dental researches to use CT-based image processing technique [8]. The stress shielding produced by numerous jawbone types might also be evaluated through the use of CT-scanned images at a set of intervals during the healing stage. This led to noticeably improved knowledge, for both the implant designer and implant surgeon, of how the jawbone will remodel. An alternative method to evaluate stress shielding within the jawbone experimentally through photoelastic stress analysis technique [9].

Advances in dental materials

The advances in four major categories of dental materials will be discussed, that covers most of the dental branches applications.

Dental composites in restorative dentistry

Amalgam restorations had been used for a long time, without enough attention to its mercury content toxicity [10]. Another major issue is the colour of amalgam for aesthetic considerations, and alternative materials are being sought to replace [11].

Restorations using composite materials have promising aesthetics however these materials are very technique sensitive, and its mechanical properties are not as good as of amalgams [12].

Bowen developed the Bisphenol A-Glycidyl Dimethacrylate (Bis-GMA) resins and used silane couplers, which composite fillings became an essential component of the restorative armamentarium. The last decade has witnessed rapid advances in dental restorative materials including the resin-based composites [13]. As dental composites are based on resin polymer enforced by other materials. Distribution of nano-filler particles as "homogenous", or "non-homogenous" and presence of nanoclusters results in composites with different bulk and surface properties that can be tailor-made according to the site of application [14].

Non-Metallic Dental Implants PEEK

Recent studies reported that Poly-Ether-Ether-Ketone (PEEK) as an alternative material for Titanium dental implants. PEEK is a biocompatible material with Young's modulus of 3.6GPa, which can be modified by reinforcing it with carbon fibres "CFR-PEEK", to reach 18GPa, similar to that of cortical bone [15].

Nowadays, orthopaedic applications PEEK implants are manufactured with a variety of physical, mechanical, and surface properties, and in different shapes to fit a wide range of dental clinical cases [16]. That, the reinforced PEEK by suitable fillers are prepared in simple sequence (known as compression moulding) [17].

Sarot et al., [18] compared the stress distribution in the peri-implant support bone of 30% CFR-PEEK or titanium, using FEA. Assuming perfect osseointegration, the results of PEEK showed high-stress concentration in the implant neck and the adjacent bone. However, PEEK implants is widely used nowadays to support complete overdentures as its performance is considerably improved when distributed adequately along the jawbone [17][19].

Nano-materials

Enamel, dentin and cementum as dental hard tissues are naturally composed of nanoscale structural units [20], and their mechanical properties may vary from one point to the other [21][22]. Nanomaterials have numerous advantages like superior properties as hardness, flexural strength, modulus of elasticity, translucency, durability in comparison to traditional materials. Currently, nano-technology embedded in many applications including bone/tissue regeneration, implantology, restorative materials, and biomarkers to detect diseases as demonstrated in Figure 5.

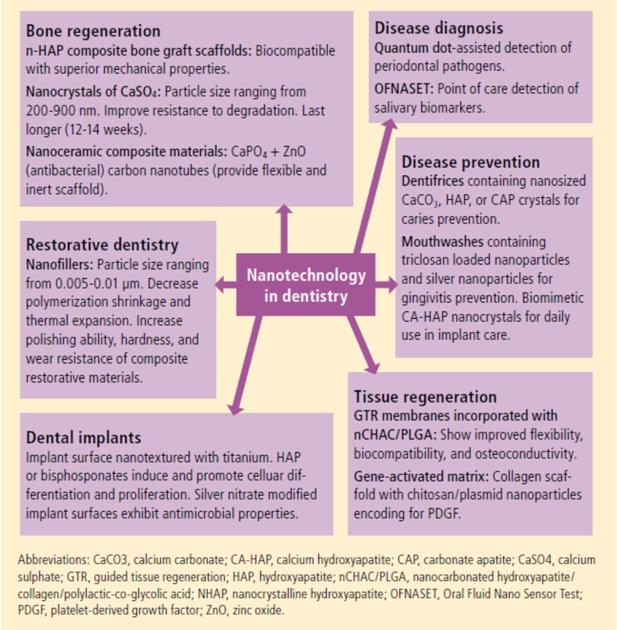

Figure 5: Current applications of nanotechnology in dentistry [25]

Dental ceramics

Classification of ceramics in dentistry is an impossible task due to vast improvements made in the compositions. Thus many classifications can be found for dental ceramics. One example classification according to the chemical composition as Alumina based, Leucite reinforced based, …etc. While another classification is based on processing technique (sintered, castable, slip cast, machinable and pressable). Most of dental ceramics are used in the prosthesis, while recent researches on immediate loading tend to use ceramics as part of implant-abutment or replacing the tooth. In previous studies tended too, bioceramic implants generate fewer stresses to surrounding bones than Titanium one, while its osseointegration behaviour is much better [6].

Recent researches formulated its failure stress by FEA as linearly related to Young's modulus differences (ceramic-substrate) and the square of the ceramic thickness. Great differences in Young's modulus between dentine, cement, and the ceramic crown is the responsible for the prosthesis expected failure [24]. This relation improved the understand of single crown failures, as a mechanism, which does not involve damage from wear facets but stresses on the cementation surface due to occlusal loading.

Metallic Alloys in Endodontics

Metals and alloys have many uses in dentistry. Steel alloys are commonly used for the construction of instruments for orthodontics. Gold alloys and alloys containing chromium are used for making crowns, inlays and denture bases while dental amalgam is the most widely used dental filling material.

Nickel-titanium (NiTi) has unique properties of shape memory and super-elasticity[25], that its endodontic instruments are three times more flexible than stainless steel instruments and have the ability to revert to their original shape after flexure, and more resistant to fracture [26]. NiTi (56% Nickel and 44% Titanium) is the favorable material for manufacturing continuous rotating and reciprocating endodontic instruments, that have three microstructural phases; austenite phase (ductile) exists at higher temperatures and lower stresses; the martensite phase (hard) exists at lower temperatures and higher stresses, whereas, R-phase is an intermediate phase that forms during the forward and reverses transformation between austenite and martensite [27][28].

In 2007, a new NiTi alloy termed "M-Wire" (Dentsply Tulsa-Dental Specialties, Tulsa, OK, USA) was developed through proprietary thermomechanical processing procedure. Manufacturer’s data for M-Wire indicated significantly improved fatigue resistance in comparison with conventional NiTi alloys. Currently, M-wire is used for the manufacture of GT series X instruments and Protaper Next (Dentsply Tulsa-Dental Specialties), Wave One (Dentsply Maillefer, Ballaigues, Switzerland), and Reciprocal (VDW, Munich, Germany). Many finite element studies [4][29][30][31] compared Stainless Steel, NiTi, and M-Wire endodontic instruments behaviours.

New trends in geometrical modelling in dentistry

Geometric modelling is essential to develop a database supporting engineering design. Figure 6 demonstrate the role of geometric modeling in CAD system(s). As it links the user interface and the mathematical representation (database). Additionally, any complete part representation should include both topological and geometrical data. That the geometric data offers shape and dimensions, and topology represent the connectivity and associativity of the object entities; it determines the relational information between object entities. Geometric modeling techniques for structures and assemblies contain many difficulties usually appeared with model(s) transfer between different packages.

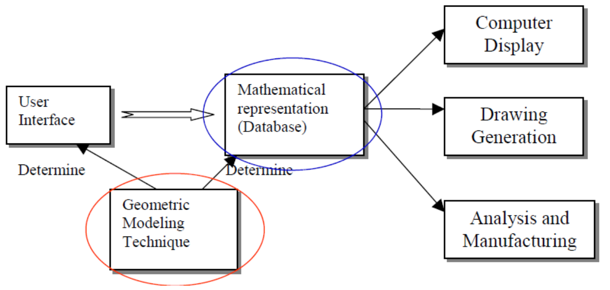

Figure 6: Role of geometric modelling in CAD system(s) [34]

Wireframe models (and 2D Projection) contain points, lines, and curves, that topological data are not included. On the other hand, surface models store topological information of the containing objects. However, surface models can't support a full range of engineering activities [32] such as stress analysis on the internal body. Solid models have complete, valid and unambiguous spatial addressability. Additionally, wireframe and surface models can be extracted from solid one(s), and reverse process is not valid [33]. Most of engineering CAD/CAM packages involve Constructive Solid Geometry (CSG) technique in representing solids using Boolean (like a union, intersection, ...etc.) combination of primitive solids (like cubes, cylinders, ...etc.).

On the other side, extracting 3D model(s) from digitisers (scanners, CT, MRI, micro-CT, CBCT, 3D Ultrasound, Confocal Microscopy) needs great effort to be recognised. Software(s) like Mimics (Materialise, Leuven, Belgium) can manipulate medical format pictures as brightness threshold and mask to separate the image parts (organs). That can generate models for a variety of engineering applications and directly export the 3D models and anatomical landmark points to 3rd party software, like CAD, or FEA packages [34].

Examples

Term "immediate loading", indicate that implants and temporary teeth are placed within two days of implant surgery and are left in position for the healing period. Then the temporary teeth are replaced with permanent crowns. Singh et al., [35] aimed to place eight implants in fresh extraction socket in two successive sessions, for early loading. CT was made for the patient mandible after teeth extraction. The CT was used as a 3D geometric model and scale the mandibular teeth to fit on it (in place). Finally placed suitable implants with correct sizes and directions to replace teeth roots. Then CT image(s) was used to illustrate the gingiva and build thin surgical template containing thicker zones with angulated holes to help the dentist to place the implants correctly. The geometric model of the template was directly sent to the milling machine to start the surgery within 48 hours. Another immediate loading technique for a single tooth [36] that place implant(s) immediately without template while zirconia crown was milled simultaneously during the implant placement in the same session.

Dental CAD/CAM system(s)

The need for a fast 3D geometric model(s) for teeth forced producers of dental CAM machine to include scanners with their systems. Recently digital impressions taken directly from the alveolar ridges and natural teeth using the intra-oral camera are used. Upper/lower scanned impressions are used for accurate estimation of missing teeth dimensions. The integrated software builds up the prosthesis by using the embedded set of thirty-two teeth (as standard shapes) as wireframe models. The CAD/CAM specialist can make scaling and points movements on the wireframe models to fit the available space before sending the model to the milling machine. Recently CAD/CAM systems are involved in the production of artificial bone, denture base, crown, bridge, veneer shades, ... etc.

Several types of research [35][36][37][38] discussed the immediate loading or immediate replacing tooth. Implant immediate loading needs fast imaging, viewing, bone thickness estimation, to determine the suitable implant(s) direction(s). Two examples will be shortly presented here:

1. Delcam (Birmingham, UK), produced special dental CAD/CAM solutions system including five-axis milling machine. While the geometric modelling to be acquired from external scanner or CT image(s), the system is capable to interface with wide range of scanners. The geometry of the scanned part was transferred as STereoLithography (STL) file [39], which is a type of Wireframe technique of geometric modelling, before extract 3D model with dimensions from Dicom files.

2. EnvisionTec (Gladbeck, Germany) offered a family of rapid prototyping printers "Perfactory PixCera". That is used to produce casts and prostheses from polymeric resins and metallic base one(s) [40]. The metallic one(s) will be covered by porcelain and veneer to match the other teeth shape and colour.

The rapid prototyping can't improve its quality at finish line thus the special care could be done manually. Contrarily the CAD/CAM system is capable of defining the finish line and matching a tool pass with a finishing tool. Finally, CAD/CAM can produce complete zirconia tooth to replace extracted one for immediate loading, which is not possible with rapid prototyping printers.

New dental instrument design(s)

Engineering CAD/CAM software(s) are used to model new dental tools before implementing stress analysis and producing prototypes for testing. New versions of CAD/CAM software(s) include stress analysis module(s), while modelling modules in stress analysis packages have limited capabilities. Designers prefer to use CAD/CAM software for geometric modelling and transfer their model(s) to finite element packages. That Initial-Graphics-Exchange-Specification (IGES) file format showed the best performance for surfaces transfer to FEA software(s). While Standard-ACIS-Text (SAT) file format is perfectly used for transferring volumes (3D solid geometric model).

Conclusions

The dental material market is flooding by several materials. Unfortunately, there are no available dental materials with ideal properties for any dental applications. With the start of nanotechnology era, improvements in existing materials' properties and development of new materials appeared in new products. In reality, nanomaterials will never completely replace the other dental materials like ceramics and composites for several reasons like economics, short-term materials usage, preparation time, ...etc. but for sure it will strongly compete with them.

Accurate geometric modelling is essential for CAM processes and stress analysis checks. Engineering CAD/CAM packages may be not suitable for many dental applications, but will never be replaced in designing new tools/instruments for dentistry. On the other hand, imaging teeth and transfer it into wireframe model before CAM is currently available. New dental solutions systems offered a lot of features for dentist and laboratory operators about implants types and size databases, locations of high dens bone, ...etc. One drawback to obtaining a suitable solid model from CT images to start stress analysis is still problematic.

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