SUMMARY AND GENERAL DISCUSSION

This thesis is a culmination of interrelated in-vitro studies pertinent to the application of additive manufacturing (AM) /3D-printing techniques in Prosthodontics. Several studies were performed to investigate the influence of various technical factors involved in the manufacturing process on the accuracy, fit and mechanical properties of the printed parts. The potential for printing zirconia was also investigated.

AM techniques are emerging rapidly and bring about a new era in digital dentistry in general and in Prosthodontics specifically. Chapter 1 presents a critical review of the literature on the application of 3D-printing technology in the field of Prosthodontics. Various materials used in the field of Prosthetic Dentistry necessitate the application of different AM techniques. SLA, DLP and DLP-jetting techniques allow the fabrication of direct and indirect tooth colored restorations and wax patterns. Metallic dental restorations and frameworks can be fabricated using SLS/SLM and DMLS. The 3D-printing of tooth-colored zirconia restorations has been attempted but is still limited to the research phase.

Photopolymerization techniques used in SLA permits high dimensional accuracy of the printed part whereas the availability of a single material reservoir represents a drawback of this technique. DLP based jetting may offer multiple material printing with the advantages of the photopolymerization techniques. The application of 3D-printing in complete and partial removable prostodontics is still limited due to the lack of design software and a reference library for the components frequently used to design the prosthesis. Furthermore, due to the uncontrolled mobility of the soft tissues in the edentulous patients, digital data acquisition is difficult.

The challenges involved with AM techniques start with the process of acquiring an STL file and end with the actual manufacturing process. Build orientation, slice thickness and support structure generation are all interrelated parameters and each of them influence the mechanical and physical properties of manufactured objects. Chapters 2 and 3 investigated the influence of build orientation on the compressive and flexure strength of a novel 3D-printed dental restorative material. Vertically printed specimens with the layers oriented perpendicular to load direction showed a statistically significant higher compressive strength (297 MPa) compared to horizontally printed specimens (257 MPa) in which the layers were printed parallel to load direction. The recorded compressive strength for the vertically printed material was high (297 MPa) and comparable with the average values reported for a well-established hybrid composite resin restorative material (289 MPa) with a long-term clinical record. In chapter 3 the flexure strength was evaluated and no statistical difference was found between vertically and horizontally printed specimens. However, fractographic analysis revealed a different fracture
pattern. Layers printed parallel to the load showed the laser pattern on the fractured surfaces. Although no difference was observed in the values of flexure strength, the presence of laser pattern on the fractured surfaces may indicate layer separation (chapter 3).10

In the same context, support angle and the support configuration have been reported to influence the surface quality, dimensional accuracy and total build time. Dimensional accuracy is of utmost importance when fabricating a full coverage restorations. However, in the literature when 3D-printing is the fabrication method of choice no guidelines are yet available. Thus, **chapter 4 and 5** evaluated the influence of different build angulation on the dimensional accuracy of SLA and DLP printed interim full coverage dental restorations. Nine build angles were selected based on the recommendation of an experienced technician; 90, 120, 135, 150, 180, 225, 250, 270 degrees and compared. The results revealed that SLA 3D-printed restorations offer higher dimensional accuracy compared to DLP counterpart and the difference between build angles was minimal.11,12 This can be attributed to the inherent differences between the two techniques, which was explained in **chapter 1**. Further, the accuracy of the DLP technique is influenced by the optical specifications integrated in the DMD, lens quality, pixel size and platform resolution.1,13 The selected build angle should offer the highest dimensional accuracy thus creating a self-supported geometry of the printed part. Consequently, this will result in the least amount of support structure and minimal time needed for finishing and polishing. Although the difference between different build angles in both SLA and DLP techniques was insignificant, in prosthodontics minor differences on micron level may influence the fit of dental restorations especially in three-unit fixed partial dentures. Thus, it can be recommended that in both techniques a 90° build angle should be avoided, as in that case most of the fitting surface is unsupported. Furthermore, the support structure is located in close vicinity to the critical margin area, which may be damaged following the removal of the support structure. Also when printing in 90° build angles, the forces may be directed parallel to the layers and this may jeopardize the mechanical properties of the restoration (chapters 2, 3).

The influence of the support structure configuration (thick versus thin) on the dimensional accuracy of SLA printed restorations was also evaluated in **chapter 4**. It was found that the distribution rather than the size of support structure results in higher dimensional accuracy as it allows for the self-supporting geometry of the printed parts. Inadequate support of a full coverage restoration with thick support type resulted in higher deviation values.11

Recently with the burgeoning increase in the application of printing technology in the field of Prosthodontics, several questions arise and need to be addressed. Is there a difference in the marginal and internal fit between fabricated and milled restorations? Do different finish line designs; knife-edge (KE), chamfer (C), rounded-shoulder (RS), rounded-shoulder with bevel (RSB) influence the fit of printed restorations? And furthermore, which factor would be more
influential on the marginal and internal fit of full coverage interim restorations; fabrication method or finish line design? Chapter 6 attempted to answer these questions. Milled and SLA-printed full coverage interim dental restorations were fabricated on four-typodont models of a maxillary central incisor with different finish line designs; (KE), (C), (RS), and (RSB), the marginal and internal fit was evaluated. The results revealed that the fabrication methods have more influence on the fit of the restorations than the finish line design \( P = .000 \). SLA-printed restorations exhibit lower marginal and internal gaps compared to milled restorations. The inferior marginal and internal fit of milled restorations may be attributed to errors resulting from the tolerance of milling burs. The mean internal gaps for 3D-printed restorations were 66, 149, 130, 95 μm for KE, C, RS, and RSB respectively and for the mean absolute marginal discrepancy (AMD) the values were 30, 41, 30, 28 μm respectively. Owing to the additive nature of the technique, a “stair-stepping effect” is more evident when printing curved, tapered or steep parts. A chamfer finish line has more curved axio-gingival line angles which may, during printing, exhibit more stair-stepping error and thus the greater internal and AMD gap values recorded.

The availability of different materials is another factor that should be considered when 3D-printing technology is discussed. Printing of ceramic materials has proved difficult and is still at an early research stage. The characteristics of most of ceramic 3D-printed materials cannot yet be considered adequate for dental applications. Manufacturing of high performance monolithic ceramics achieved by using photocure resins with a high loading of ceramic material, requires a thermal de-bonding process which results in a very high firing shrinkage that can affect the dimensional stability of the printed object during the firing/sintering process. Low density and strength of printed parts due to the burn out of the organic binder, and the restriction on particle size that is required to let the process function correctly are other encountered issues when 3D-printing ceramic materials.

In chapter 7, a one-piece zirconia dental implant was 3D-printed using digital light processing (DLP) technique. The geometrical accuracy of the printed implant was evaluated along with the mechanical properties and surface topography of printed zirconia discs. The dental implant was successfully printed with 0.1 mm dimensional accuracy and surface roughness of 1.59 μm Ra, which falls well within the range of what in implant manufacturing is called a moderately rough surface (1.0-2.0 μm). Such a surface is required for optimal osseointegration as reported by Albrektsson & Wennnerberg. The Weibull analysis of biaxial flexure test of the zirconia 3D-printed specimens revealed a statistically significant higher characteristic strength (1006.6 MPa) of vertically printed specimens compared to specimens printed both at 45° and horizontally (892.2 and 866.7 MPa respectively). The SEM micrograph of the printed implants and representative fractured specimens revealed porosities ranging in size from 196 nm to 3.3 μm, some of which were deeply connected within the structure of the material. Future trials
should focus on the 3D-printing of ceramic parts that are free of cracks and porosities similar to the microstructure of conventionally milled ceramics. Manufacturing of such parts can be achieved by optimizing the parameters of the AM process or performing extra densification steps following the completion of printing process.\textsuperscript{15}

**Challenges faced throughout the project**

At the outset of the project, no guidelines were yet available for the fabrication of dental restorations and appliances using 3D-printers. Rather, the process was guided by personal opinions, and recommendations from the manufacturer with no scientific evidence. This thesis is the first to provide guidelines to clinicians and researchers to understand the technical factors involved in the fabrication process for optimal results. The availability of 3D-printers calibrated with suitable restorative materials formed a huge challenge as well as the cost of the available machines. Initially, pink colored PMMA was the only available printable restorative material. Recently in 2017, a multi-shade tooth colored material can be printed in one build.

Comparing our findings with different studies revealed perplexity and lack of consistency among the multiple definitions applied in this field particularly when the build angle is defined. A consensus is recommended that the object be described as vertically printed when the layers are stacked along the height of the printed part during the build process regardless of its geometry. Tilting the specimen 90° from the vertical position, so that the layers are stacked along the length of the specimen can be defined as a horizontally printed specimen. Further, test methods followed for testing AM parts are not yet verified and still follow the well-established ISO standards used to evaluate conventionally milled parts.
Future directions

Interestingly, there is growing interest in implementation of AM techniques in the field of Prosthetic Dentistry. The majority of the studies in this field were in-vitro studies and one may question whether these results can be translated clinically. Therefore, additional in-vivo as well as in-vitro studies are necessary for verification of the findings of the current study. Furthermore, future research is needed to cover other parameters involved with the additive manufacturing approach.

Factors to be explored include the effect of build direction/orientation, slice thickness, support structure distribution, different AM techniques, printing speed and position of the object within the build platform. Last but not least, research should focus on 3D-printing of ceramic parts that are free of cracks and porosities via optimization of the printing and sintering parameters which can be applied for the fabrication of customized implants. My trips to conferences and trade exhibitions during the last five years taught me that development in the field of Biomaterials and close collaboration with industry are inevitable to broaden the application of different AM techniques in the dental field. I am sure that in the near future, the face of dentistry will be changed combining 3D-printing and Artificial Intelligence offering new tools in diagnosis and treatment for our patients.
REFERENCES


