Technical Advancements in Removable Dental Prostheses for the Elderly Edentates

SRINIVASAN, Murali

Abstract

La réhabilitation des mâchoires édentées à l'aide de prothèses dentaires amovibles implanto-portées (IOD) est une approche bien fondée qui peut être considérée comme minimalement invasive et économique. Le concept IOD réduit la charge de traitement en évitant les chirurgies complexes et en diminuant les risques de morbidité chirurgicale associés. Le concept permet également de réduire le nombre d'implants nécessaires et les coûts de laboratoire. En utilisant des nouveaux systèmes d'attache qui s'accommodent plus facilement aux grandes divergences angulaires inter-implantaires, la charge de traitement peut être davantage réduite. En outre, l'adoption de nouvelles technologies de conception et de fabrication assistées par ordinateur (CFAO) ainsi que leurs protocoles cliniques respectifs peuvent potentiellement réduire le nombre de visites pour les patients et le temps de traitement. Par conséquent, notre objectif de recherche était de mettre à l'essai les nouveaux systèmes d'attache et certains aspects liés aux prothèses dentaires amovibles usinées par CFAO.

Reference


DOI : 10.13097/archive-ouverte/unige:120320

Available at:
http://archive-ouverte.unige.ch/unige:120320

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“Technical Advancements in Removable Dental Prostheses for the Elderly Edentates”

Thesis submitted to the Faculty of Medicine of the University of Geneva

for the degree of Privat-Docent

by

Murali SRINIVASAN
Geneva

2019
Acknowledgements

My sincere and heartfelt thanks to Professor Dr. Frauke Müller for welcoming me in her division, for being a pillar of support, and for being a constant source of inspiration throughout. Everything was possible only because of her generosity and kindness.

My sincere thanks to Professor Dr. Martin Schimmel, who was instrumental in recruiting me in this division and the cause. I would like to thank Professor Emeritus Dr. Urs Belser and the ITI foundation, for providing me an opportunity to come to Geneva. I would like also thank my fellow ITI scholar, Dr. Mariko Kobayashi, and my former student, Dr. Yoann Cantin, with whom I started these first sets of bench experiments in Geneva. These initial experiments began new lines of research in our division and still continue today.

I wish to express my gratitude to Dr. Jean Perriard for his help with the experimental models, Isabelle Badoud for the Instron testing, and the late Dr. Maria Cattani-Lorente for her expertise with the mechanical testing of the resins. I would like to thank Professor Dr. François R. Herrmann for his brilliance in the statistical analyses, and Professor Dr. Albert Mehl for his enormous patience and help with the color mapping.

I would like to thank the entire team (former and current) in the division of Gerodontology and Removable Prosthodontics, the clinic chiefs - Drs. Serge Borgis, Manfred Imsand, Manual Naharro, and Julien Luraschi; the respective teams at our satellite clinics at Hôpital Belle-idée, at Hôpital Loëx, and at the former satellite clinic at Maison de retrait (Trembley), for welcoming me in their midst and allowing me to grow. They have been, and are, an exceptional team to work with. Some special thanks are due to Ms. Marie-Christine Righetti for taking such good care and looking after me at the beginning of my tenure here, who still continues to do so today.

Thanks to my dear friends, Drs. Philippe Rieder, Harald Gjengedal, Linda Grütter, and Nicole Kalberer, for just being there when I needed them; and my wonderful students (past and present) for putting up with my bad French, especially Simon Gruber for helping me with the Swiss boards. Thanks are due to Drs. PD Norbert Cionca, and PD Stephane Durual for their guidance in preparing this thesis. I wish to also thank every single person whomsoever I have encountered in my life, they all have played some significant part in making me who I am today.
Lastly and most importantly, I wish to thank my parents and my children, Malvika and Tejaswi, for their undeterred patience, unconditional love, and their total understanding. Thank you all for playing the pivotal role in my life.
This thesis is dedicated to, my mentor and role model in gerodontology,

Professor Frauke Müller.
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<th>Abbreviation</th>
<th>Full Form</th>
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<tr>
<td>AD</td>
<td>Alzheimer’s Disease</td>
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<td>C</td>
<td>Canine</td>
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<td>IOD</td>
<td>Implant Overdenture</td>
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<td>IODs</td>
<td>Implant Overdentures</td>
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<tr>
<td>CAD/CAM</td>
<td>Computer Aided Designing / Computer Aided Manufacturing</td>
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<td>CAD/CAE</td>
<td>Computer Aided Designing / Computer Aided Engineering</td>
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<tr>
<td>CBCT</td>
<td>Cone Beam Computerized Tomography</td>
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<tr>
<td>CCD</td>
<td>Charge Coupled-Device</td>
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<tr>
<td>CNC</td>
<td>Computerized Numerical Control milling</td>
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<td>CRDP</td>
<td>Complete Removable Dental Prosthesis</td>
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<tr>
<td>CRDPs</td>
<td>Complete Removable Dental Prostheses</td>
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<tr>
<td>DLP</td>
<td>Digital Light Projection</td>
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<tr>
<td>DMLS</td>
<td>Direct Metal Laser Sintering</td>
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<tr>
<td>FSO</td>
<td>Swiss Federal Statistical Office</td>
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<tr>
<td>GPT-9</td>
<td>Glossary of Prosthodontic Terms, Ninth Edition</td>
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<tr>
<td>LI</td>
<td>Lateral Incisor</td>
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<tr>
<td>OHRQoL</td>
<td>Oral Health Related Quality of Life</td>
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<tr>
<td>PAEK</td>
<td>Polyaryletherketone</td>
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<tr>
<td>PC</td>
<td>Personal Computer</td>
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<tr>
<td>PEEK</td>
<td>Polyetheretherketone</td>
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<tr>
<td>PEKK</td>
<td>Polyetherketoneketone</td>
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<td>PM1</td>
<td>First Premolar</td>
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<tr>
<td>PM2</td>
<td>Second Premolar</td>
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<tr>
<td>PMMA</td>
<td>Polymethylmethacrylate</td>
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<td>PRDP</td>
<td>Partial Removable Dental Prosthesis</td>
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<td>PRDPs</td>
<td>Partial Removable Dental Prostheses</td>
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<tr>
<td>PROMs</td>
<td>Patient Reported Outcome Measures</td>
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<td>QoL</td>
<td>Quality of Life</td>
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<td>RDP</td>
<td>Removable Dental Prosthesis</td>
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<td>Removable Dental Prostheses</td>
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<td>RL</td>
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<td>RLs</td>
<td>Research Lines</td>
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<td>RL1</td>
<td>Research Line 1 (First Line of Research)</td>
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<td>RL2</td>
<td>Research Line 2 (Second Line of Research)</td>
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<tr>
<td>RP</td>
<td>Rapid Prototyping</td>
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<tr>
<td>RRR</td>
<td>Residual Ridge Resorption</td>
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<tr>
<td>SFE</td>
<td>Sinus Floor Elevation</td>
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<td>SFI</td>
<td>Stress Free Implant</td>
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<td>SLA</td>
<td>Stereolithography Apparatus</td>
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<td>SLS</td>
<td>Selective Laser Sintering</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>STL</td>
<td>Stereolithography / Standard Tessellation Language / Standard Triangle Language</td>
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<tr>
<td>SSO</td>
<td>Swiss Dental Society - Schweizerische Zahnärzte Gesselschaft</td>
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<tr>
<td>UN</td>
<td>United Nations</td>
</tr>
<tr>
<td>UN DESA</td>
<td>United Nations Department of Economic and Social Affairs</td>
</tr>
<tr>
<td>UNO</td>
<td>United Nations Organization.</td>
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<tr>
<td>3D</td>
<td>Three-Dimensional</td>
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<td>©</td>
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<td>Registered Trademark Symbol (All Rights Reserved)</td>
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Summary

Treatment challenges while rehabilitating the elderly edentulous patients pertain to providing a successful functional rehabilitation and to challenges in managing barriers associated with aging. The comprehensive treatment plan must take into account the systemic factors, functional and anatomic limitations and, to a certain extent, also the psychosocial as well as the economic aspects. The therapeutic goal must primarily focus on adopting minimally invasive procedures thereby limiting the treatment burden of the procedures (i.e., surgical and restorative) and the involved costs.

Rehabilitation of the edentulous jaws with implant-retained/supported removable dental prostheses/overdentures (IODs), is a sound treatment protocol that is minimally invasive and cost-effective. Elderly edentulous patients rehabilitated with IODs, experience a significant improvement in their oral health-related quality of life (OHRQoL) and their masticatory performance, as well as elicit a high treatment satisfaction. With reference to fixed implant-supported restorations, the IOD concept reduces the treatment burden by avoiding complex surgeries, decreasing the risks of surgical morbidity, reducing the number of implants needed and lowering the clinical and laboratory costs. By incorporating novel attachment systems that are clinically more accommodative with regards to large inter-implant angular discrepancies, the treatment burden can be further decreased. Moreover, the adoption of newer computer aided design and manufacturing (CAD/CAM) technologies along with their respective clinical protocols, can potentially reduce the number of patient visits and treatment time. The improved materials used in these novel technologies also could potentially widen the range of the prosthetic designs per se, and possibly broaden the spectrum of clinical indications. Therefore, our research goal was to bench test the novel attachment systems and, certain aspects related to CAD/CAM milled complete removable dental prostheses (CRDPs).

Our first line of research (RL1) evaluated age-related potential barriers as well as novel attachment systems for IODs and focused on the following research questions:

1. Is the retentive behavior of a chairside prefabricated bar attachment system better during cyclic dislodging, compared with that of traditional freestanding attachment systems?
2. Do novel purpose-designed freestanding attachments function and compensate well under cyclic dislodging and under large inter-implant angular discrepancies?
3. Does a liquid medium have any role on the retentive force behaviors of the freestanding IOD attachments?

We were able to demonstrate that the prefabricated bar attachment systems functioned well in retentive behavior and they were unaffected by minor inter-implant angular discrepancies. We also demonstrated that the retentive force of a novel freestanding attachment, which is indicated for severe inter-implant angular discrepancies, was unaffected. Furthermore, we concluded that retentive force was not influenced by the liquid medium used in in vitro bench experiments.

For our second line of research (RL2), we investigated CAD/CAM milled CRDPs, and evaluated their accuracy and material properties. This line of research was initiated in our division as a series of experiments to justify the use of these newer systems and techniques in clinics. The RL2 addressed the following research questions:

1. Is the trueness of the CAD/CAM milled CRDPs better than that of conventional CRDPs?
2. Are the biocompatibility, material properties, and surface roughness of pre-polymerized polymethylmethacrylate (PMMA) resin on par with, if not better than, the traditional heat-polymerized PMMA resin used in conventional CRDPs?

Our RL2 findings were that the trueness of the intaglio surfaces of the milled CRDPs, although not superior to that of conventionally manufactured CRDPs, was within the clinically acceptable range. However, we were able to validate that the pre-polymerized PMMA resins used in the fabrication of the milled CRDPs were equally biocompatible and superior in material properties when compared with traditional heat polymerized PMMA resins.

The interesting findings from our two research lines help broaden the possibilities of using minimally invasive treatment concepts in the elderly edentulous patients with the aid of removable dental prostheses, by exploiting the newer systems and technological advancements.
List of Original Publications

This cumulative thesis is based on the following original publications

   
   Effects of in vitro cyclic dislodging on retentive force and removal torque of three overdenture attachments.
   

   
   Influence of implant angulation and cyclic dislodging on the retentive force of two different overdenture attachments – an in vitro study.
   
   Clinical Oral Implants Research 2016 (27), 604-611. Impact factor: 3.624

   
   
   Clinical Oral Implants Research 2016 (27), 771-775. Impact factor: 3.624

   
   CAD/CAM milled removable complete dentures: an in vitro evaluation of trueness.
   

   
   CAD/CAM milled complete removable dental prostheses: An in vitro evaluation of biocompatibility, mechanical properties, and surface roughness.
   
Résumé (Summary in French)

Des défis lors de la réhabilitation de l'édentement totale chez la personne âgée se montrent non seulement lors de la réalisation d'une réhabilitation fonctionnelle réussie mais également quand il s'agit de franchir les barrières associées au vieillissement. Une approche intégrale lors de la planification de traitement doit englober les facteurs systémiques, fonctionnels, ainsi que les limites anatomiques. D'une manière holistique, les aspects psychosociaux et économiques doivent également être évalués. L'objectif de la prise en charge doit principalement viser à adopter des procédures peu invasives, limitant ainsi la charge du traitement en termes de procédures (chirurgicales et réparatrices) et de coûts impliqués.

La réhabilitation des mâchoires édentées à l'aide de prothèses dentaires amovibles implanto-portées (IOD) est une approche bien fondée qui peut être considérée comme minimalement invasive et économique. Après réhabilitation avec des IODs, les patients âgés édentés se montrent très satisfaits, avec une amélioration significative de leur qualité de vie liée à la santé bucco-dentaire (OHRQoL) et une amélioration de leur performance masticatoire. Comparé aux restaurations fixes implanto-portées, le concept IOD réduit la charge de traitement en évitant les chirurgies complexes et en diminuant les risques de morbidité chirurgicale associés. Le concept permet également de réduire le nombre d'implants nécessaires et les coûts de laboratoire. En utilisant des nouveaux systèmes d'attachement qui s'accommodent plus facilement aux grandes divergences angulaires inter-implantaires, la charge de traitement peut être davantage réduite. En outre, l'adoption de nouvelles technologies de conception et de fabrication assistées par ordinateur (CFAO) ainsi que leurs protocoles cliniques respectifs peuvent potentiellement réduire le nombre de visites pour les patients et le temps de traitement. Les matériaux améliorés utilisés dans ces nouvelles technologies pourraient quant à eux d'avantage élargir la portée de la conception prothétique, ce qui pourrait agrandir le spectre des indications cliniques. Par conséquent, notre objectif de recherche était de mettre à l'essai les nouveaux systèmes d'attachements et certains aspects liés aux prothèses dentaires amovibles complètes (CRDP) usinées par CFAO.

Notre première ligne de recherche (RL1) a évalué des nouveaux systèmes d'attachements pour IOD et s'est concentrée sur les questions de recherche suivantes:
1. Si un système de fixation par barre préfabriquée directement au fauteuil montre un meilleur comportement de rétention quand soumis aux cycles de délogement, par opposition aux systèmes traditionnels d'attachements non-solidarisées?

2. Si des nouveaux systèmes d'attachements non-solidarisées conçus spécialement à cet effet ont bien fonctionné et ont bien compensé le délogement cyclique et les grandes divergences angulaires inter-implantaires?

3. Si le milieu liquide a joué un rôle sur la force de rétention des attachements IOD ?

Nous avons pu démontrer que les systèmes de fixation des barres préfabriquées fonctionnaient bien en terme de comportement rétentif et n'étaient pas affectés par une légère divergence angulaire inter-implantaire. Nous avons également trouvé que la force de rétention d'un nouvel attachement non-solidarisé, indiqué pour de grandes divergences angulaires inter-implantaires, n'a pas été affectée. De plus, nous avons conclu que la force de rétention n'était pas influencée par le milieu liquide utilisé dans les expériences de laboratoire in vitro.

Notre deuxième ligne de recherche (RL2) s'est concentrée sur les CRDP fraisés par CFAO, et a évalué leur précision et les propriétés de leurs matériaux. Cette ligne de recherche a été initiée dans notre division comme série d'expériences pour justifier l'utilisation clinique de ces nouvelles techniques. Dans notre RL2 nous avons abordé les questions de recherche suivantes:

1. La justesse des CRDP usinés par CFAO était-elle meilleure que celle des CRDP conventionnelles?

2. La biocompatibilité, les propriétés des matériaux et la rugosité de surface de la résine polymétacrylate de méthyle (PMMA) pré-polymérisée sont-elles équivalentes, voire meilleures, à celles de la résine PMMA polymérisée à chaud, traditionnellement utilisée lors de la confection des CRDP conventionnels?

Les résultats de notre RL2 ont démontré que la justesse de la surface intrados des CRDP confectionnées par fraisage, bien que comparable à celle des CRDP fabriquées de manière conventionnelle, se situait à un niveau cliniquement acceptable. Nous avons pu valider les résines PMMA pré-polymérisées utilisées dans la fabrication des CRDP fraisées en ce qui concerne leur biocompatibilité et leur supériorité en terme de propriétés mécaniques des matériaux par rapport aux résines PMMA traditionnelles, polymérisées à chaud.
Les résultats de nos deux lignes de recherche aident à mettre au point les concepts de traitement minimalement invasifs à l'aide de prothèses dentaires amovibles chez les patients âgés édentés, ceci en utilisant de nouveaux systèmes et en exploitant les progrès technologiques.
Liste des publications originales

Cette thèse cumulative est basée sur les publications originales suivantes :


   Effects of in vitro cyclic dislodging on retentive force and removal torque of three overdenture attachments.


   & Müller F.

   Influence of implant angulation and cyclic dislodging on the retentive force of two different overdenture attachments – an in vitro study.

   Clinical Oral Implants Research 2016 (27), 604-611. Impact factor: 3.624

   & Müller F.


   Clinical Oral Implants Research 2016 (27), 771-775. Impact factor: 3.624


   CAD/CAM milled removable complete dentures: an in vitro evaluation of trueness.


   CAD/CAM milled complete removable dental prostheses: An in vitro evaluation of biocompatibility, mechanical properties, and surface roughness.

Introduction

Dental treatment concepts for the elderly primarily focus on rehabilitating masticatory function in order to restore nutrition, and the Oral-health Related Quality of Life (OHRQoL) (Ervin et al. 2012, Gil-Montoya et al. 2008, Gil-Montoya et al. 2013, Müller et al. 2016, Stenman et al. 2012). This primary goal should be achieved with concepts and protocols that are minimally invasive (MacEntee et al. 2010) and present a low treatment burden, i.e. decreased load of the surgical and restorative procedures on the patient as well as diminished associated costs (Schimmel et al. 2017). Minimally or rather, optimally invasive concepts can be accomplished by adopting protocols that promote preventive measures, simplify restorative procedures, and avoid complex surgeries (da Mata et al. 2015, Friberg et al. 2000, McKenna et al. 2014, McKenna et al. 2015, Srinivasan et al. 2014a, Srinivasan et al. 2014b, ten Bruggenkate et al. 1998). The development of minimally invasive techniques can be effectuated by the use of novel technologies that offer a plethora of options in terms of novel and improved materials, components, devices, techniques, concepts, and protocols.

Removable dental prostheses (RDPs) supported/retained by dental implants [i.e., implant supported/retained overdenture (IOD)] significantly improve masticatory performance and provide better patient satisfaction along with an improved OHRQoL in the elderly and special-care edentulous patients. Over the years, the overdenture attachments have evolved a great deal, and their historical limitations are no longer the criteria that dictate the indications for their use. Manufacturing of bar attachments have gradually transitioned from traditional soldering in a dental laboratory to computer aided design/computer aided manufacturing (CAD/CAM), by mostly using milling techniques. Compared with conventional bars, milled bar frameworks are more precise, less prone to fracture, easier and less expensive to manufacture (Katsoulis et al. 2013, Katsoulis et al. 2015, Srinivasan 2016). The advancements are not restricted to bars, but include the freestanding attachments as well. The freestanding attachments are now available with a variety of options in design, shape, material, and retentive potential. The modern freestanding attachments are equipped with compensatory mechanisms, which can accommodate nonparallel inter-implant angular discrepancies (Müller et al. 2014, Schimmel et al. 2017). The attachment housings/female parts and the retentive inserts are also available in metal-free options, fabricated from polymers belonging to the polyaryletherketone (PAEK) family, such as polyetheretherketone (PEEK) or polyetherketonelketone (PEKK) (de Souza et al. 2018, Passia et al. 2016, Schimmel et al. 2017, Webersberger 2016).
Furthermore, the recent inception of the CAD/CAM technology into the removable prostheses’ arena has been quite rapid and has altered conventional protocols (Bilgin et al. 2016). In the last five years, CAD/CAM fabricated “digital” complete dentures have evolved dramatically (Baba et al. 2016), and have largely simplified the traditional treatment protocols (Schimmel et al. 2016). This has substantially reduced the treatment load on the patients as well as the incurred costs (Kattadiyil et al. 2017a, Srinivasan et al. 2017a, Srinivasan et al. 2018b). However, these concepts are fairly new and scientific evidence is lacking with regard to bench experiments, short- and long-term clinical data, and patient reported outcome measures (PROMs) (Bidra et al. 2013).

Population demographics and the effects of aging

The 2017 report on the world’s aging population by the United Nations Department of Economic and Social Affairs (UN DESA) concluded that there are approximately 962 million people aged 60 years and over (UN DESA 2017a). This number is expected to double by the year 2050; by this time, the number of elders aged 60 years and over are expected to surpass the number of younger individuals (10–24 years). Currently, there is an estimated global number of 137 million elders aged 80 years and over, and this number is likely to increase to about 425 million by 2050 (UN DESA 2017a, UN DESA 2017b). In the past, most of this population was concentrated in the developed nations; now, the majority exist in the developing nations and is increasing at an alarming rate. By 2050, around 35% of Europe’s population will be aged elders of 60 years and over (UN DESA 2017a, UN DESA 2017b). In Switzerland alone, 18.4% of its current population are 65 years and over with 5.1% being above 80 years old; these percentages are expected to increase to 28.7% and 11.7%, respectively (FSO 2016, UN DESA 2017a).

The increase in the aging population impacts on the society not only at a socio-economic level, but more on a biological front. Age-related changes effect a functional and structural change on the body, affecting all organ systems (Boss et al. 1981). The functionality of the organ systems declines (Janssens et al. 1999, Weinstein et al. 2010) and a diminution of the structures in the oral and perioral regions occurs (Newton et al. 1993, Newton et al. 1987, Newton et al. 2004, Tallgren 1972, Tallgren 2003, Tzakis et al. 1994). Degenerative changes are evident in the integumentary (Cerimele et al. 1990), and the musculoskeletal systems
(Campbell et al. 1973, Newton et al. 1986, Roberts et al. 2016). This degenerative change in the musculoskeletal system is an important aspect to consider when treating the elderly adults, as this change limits the general mobility of the patient. Metabolism, and responses to common drug therapies are altered (Mangoni et al. 2004), therefore the drug dosages are not standard. These age-associated physiological changes have a direct clinical relevance and influence the treatment rationale. The treatment rationale therefore, shifts towards a preventive and/or a less invasive approach with the focus aimed at an attempt to delay or reverse some of the age-related changes (Boss et al. 1981).

The elderly adult is prone to compromised health, and often presents with a multi-morbid health status. Multimorbidity is the presence of two or more chronic diseases requiring medication (Fortin et al. 2005, Wallace et al. 2015). Polypharmacy will most likely be an associated feature; consequently, drug-induced xerostomia cannot be ruled out because a large spectrum of drugs cause hyposalivation (Cockburn et al. 2017). Loss of autonomy with or without functional and cognitive declines may also be present in these individuals. Dementia is a common finding in age-advanced elders (Ferri et al. 2005), especially in the institutionalized elders who are dependent on care. An estimated 35.6 million people live with dementia worldwide (2010) and this number is expected to double every 20 years (Prince et al. 2013). Cognitive decline is considered one of the biggest health hazards in the elderly, with an incidence of 50% for Alzheimer’s disease (AD) in the elders aged 85 years and over (Bishop et al. 2010). Currently, an estimated 144,000 people live with dementia in Switzerland (FSO 2016). It has been further established that the functional and nutritional statuses are poor in elders with dementia (Zekry et al. 2008). Dementia along with loss of autonomy leads to a further decline in the nutritional status of institutionalized elders. These factors are important to consider because poor oral hygiene is a very common finding in these institutionalized dependent elders (Andersson et al. 2017), especially in those superadded with cognitive impairment and dementia (Pritchard et al. 2017). Interestingly, it has been established that elders with poor oral health and/or untreated oral infections are prone to developing cognitive impairment and the clinical manifestations of AD (Daly et al. 2018, Pritchard et al. 2017).

**Prevalence of edentulism**

Aging is progressive, irreversible and general. Age-advanced individuals will eventually be the main patient pool for all fields of medicine in general, and more importantly in dentistry. In
the developed nations, teeth are being retained to an advanced age because of advancements in dentistry, the provision of efficient dental care, successful preventive programs, and improved access to care (Schneider et al. 2017, Zitzmann et al. 2008). Predictions in the past have suggested that there would be a steady decline in edentulism and the denture market (Mojon et al. 2004, Slade et al. 2014). The cascading effect or “the Domino effect”, as described by Walls and Steele in 2001, may hold true and a decline in edentulism may be evident in all adult-age segments (Walls et al. 2001). Edentulism, however, will not be eradicated. This conclusion can be translated from the present demographic trends that indicate a steady increase in the population, along with a proportional increase in the number of the older adults. A factor to consider is that although the retention of the teeth to an older stratum may be beneficial, inherent risks such as caries, periodontal infections, poor oral health and infections, often exist (Holmen et al. 2012, Imsand et al. 2002, Quagliarello et al. 2005, Stromberg et al. 2012, Zuluaga et al. 2012). Problems with dental health commence in this advanced age due to the presence of the age-associated chronic diseases and/or the disabilities present. Tooth loss eventually presents itself in a much older individuals and, more frequently, in the frail dependent institutionalized population segment. Edentulism, therefore, simply shifts to a much older age strata and CRDPs will continue to remain a viable treatment in this cohort (Mojon 2003, Müller et al. 2007).

A predicted number of almost 61 million CRDPs are expected to be manufactured in the United States for the year 2020 (Douglass et al. 2002), this number would be exponentially higher in a more global perspective. With the rising numbers of elderly individuals and, edentulism continuing to prevail in to the advanced age group, CRDP therapy is expected to be still necessary.

Whether administered for maintaining healthy natural teeth or for rehabilitating lost dentition, dental treatments are and will become a more expensive and complicated affair in dependent elders. Therefore, a definite need arises for treatment procedures that are preventive, minimally invasive, and cost-effective. Furthermore, access to oral health care must be assured to all individuals of the society. The need for clinically apt CRDP therapy protocols and inexpensive manufacturing techniques are therefore the call for the day with great expectations from emerging innovations in technologies to provide simplified and novel solutions.
Dental implant therapy in elders

Treatment of edentulism (partial or complete) with dental implants has been an extremely successful treatment protocol spanning over almost five decades (Adell et al. 1981, Branemark 1977, Branemark 1983, Branemark et al. 2003, Schmitt et al. 1993). This treatment protocol originally began in the early 1980s, with rehabilitating the edentulous jaws using implant-supported fixed dental prostheses (Adell et al. 1990, Branemark et al. 1995, van Steenberghe et al. 1997). Since then the clinical indications, surgical techniques, implant materials and surfaces, connections, abutments, and the available prosthetic options, have broadened and advanced immensely. Today dental implant therapy is considered one of the best treatment options for restoring the partial/completely edentulous jaws. Therefore, implant-based rehabilitations are routinely sought after in this patient cohort, as warranted by the clinical situation.

In 2002, it was estimated that 97.4% of the Swiss population belonging to the age group of ≥85 years were rehabilitated with some form of a dental prosthesis; and most (86%) individuals in this group were restored with a RDP (Zitzmann et al. 2007). Over the following 10 years, a dramatic shift occurred in that the percentage of RDP wearers in this age group reduced to 60% (Schneider et al. 2017). Furthermore, a reduction in the number of missing teeth from 19 to 12, and an increase in the percentage of fixed prostheses users from 12.3% to 36.2% was observed. More interestingly, during this period, the number of implant-supported restorations had also increased by six-folds in the same elderly age group (Schneider et al. 2017).

With the prime focus of rehabilitation in elders, being towards reducing the treatment burden and restoring function, many clinicians would argue that dental implant-based protocols are invasive and expensive in this patient cohort. However, if the treating clinician integrates geriatric considerations in the proposed treatment plan, implant therapy can be successfully and satisfactorily accomplished, even in this patient cohort. Based on the global demographic trends on aging, this elderly patient segment in the near future will invariably become the prime patient cohort for advanced dental procedures that includes implant therapy. In fact, the trend has already shifted towards this direction, as evidenced by the current trends in implant therapy in Switzerland (Bornstein et al. 2008, Brügger et al. 2015, Schimmel et al. 2017).
Despite this effect, dental implant therapy is still not commonly prevalent in the age-advanced individuals and/or in the institutionalized elders (Visser et al. 2011). Only a relatively small percentage of the elderly population has benefitted from this therapy (Osterberg et al. 2000, Schneider et al. 2017, Zitzmann et al. 2007, Zitzmann et al. 2008,). The reasons for this finding could involve many factors such as, but not entirely restricted to, poor awareness, lack of understanding, general health status, and objections to implant therapy because of apprehensions towards surgery, involved costs, and/or other psychological factors (Müller et al. 2012, Pommer et al. 2011a, Pommer et al. 2011b, Tepper et al. 2003b, Tepper et al. 2003a, Walton et al. 2005, Zimmer et al. 1992). Furthermore, the caregivers’ limited awareness and understanding of dental implants along with lack of knowledge on providing care and maintenance to implant-borne reconstructions, have further signaled concerns for clinicians before advocating this therapy in dependent elders (Holtzman et al. 1985, Visser et al. 2011).

It is a frequent misconception that implant therapy should be avoided in the elderly population because of advanced age. Age by itself is not a contraindication to dental implant therapy. A meta-analysis of prospective studies reporting on the use of dental implants in the elderly population (≥65 years) demonstrated that short-term implant survival was high (97.6% at 1-year, and 96.2% at 5-years post implant loading), and at 10 years it was found to be 91.2% (Srinivasan et al. 2017b). Even at an advanced age (≥75 years) and talking into account the effect of the common chronic medical conditions prevalent in the elders, dental implants are considered predictable and successful with a high rate of implant survival (Schimmel et al. 2018). Long-term implant survival is clinically more relevant in younger cohorts; whereas, in the age-advanced cohorts medium- or even short-term survival may be considered clinically relevant when accounting for the patient’s life expectancy, and morbidity. This clinical relevance can be better explained by reflecting on the rehabilitation of cancer-affected patients or those elderly subjects with hyposalivation. In these patients, implant-assisted prostheses may be the only option that provides a functional rehabilitation (Müller et al. 2004). Having mentioned this aspect, it must also be emphasized that in elders, implant survival rates alone must not be an element for the final clinical decision-making. The decision for adopting implant therapy must instead be based on the patients’ ultimate benefits such as an improvement in the quality of life (QoL) and, even then must only be considered if the benefits truly outweigh the involved risks. Furthermore, this assessment should not be based on conventional implant success/survival criteria that are normally employed, but should be based
on some modified criteria that are more relevant to a geriatric population that relatively takes into account the geriatric aspects for treatment success (Müller et al. 2016).

Apart from the obvious clinical situation, which predominantly decides the indication for implant therapy in elders, other cardinal aspects are the patient’s cognitive status and the existing physical handicaps. These two factors are very important because they contribute towards post-insertion oral hygiene, denture handling, and overall maintenance (Müller et al. 2013). Therefore, Schimmel and coworkers (2017) described certain treatment predictors to aid in effective clinical decision-making for implant therapy in the elderly population. The following four important aspects were suggested:

1. Provide sufficient information to the elderly patient in order to help the patient understand the benefits of the treatment so that any reluctance (if present) can be avoided (Müller et al. 2012, Walton et al. 2005).

2. Evaluate the patients’ adroitness in using their hands (i.e., manual dexterity) and their physical state should be evaluated as a part of the initial patient examination and treatment planning process (Zhang et al. 2002). This would help ascertain the level of successful post-insertion prosthesis handling, maintenance, and overall care.

3. Educate the family members and the caregivers with regard to the proposed implant treatment and involve them at the early stage of the treatment planning. This effort would help avoid numerous maintenance problems associated with poor post-insertion aftercare frequently observed in the dependent elders because of improper training and/or a lack of knowledge among the caregivers (de Lugt-Lustig et al. 2014, De Visschere et al. 2011).

4. Finally, advocate a post-treatment diet counselling and this must be provided to both the elder and the caregivers, in an attempt to provide information as well as educate them that more fruits and vegetables, along with harder aliments can be consumed. This information would potentially help achieve a more healthy and nutritional dietary habit (Komagamine et al. 2016, Palmer 2003).

Implant therapy in elderly individuals is indicated for predominantly the same reasons as in younger cohorts. However, it is important to consider the aforesaid geriatric aspects and treatment predictors before effectuating this therapy. Further concerns to consider when
planning is the prospect of a patient’s future dependency and the state of a patient’s functional decline. These concerns would determine certain aspects of prosthodontic planning and avoid the utilization of unnecessary and complex superstructures, which may become very complicated to handle. As an alternative, the IOD design could be modifiable to allow its complexity to be adapted in accordance with the patient’s functional decline (Müller et al. 2016).

By and large, the main indications for implants in age-advanced patients are to avoid the use of RDPs, mainly in short-span partially edentulous situations, to preserve existing or manufacture esthetic partial removable dental prostheses (PRDPs), support distal extension PRDPs, and stabilize mandibular CRDPs. Less frequently, other reasons for implant therapy in geriatric patients may include single tooth replacements or palate-free maxillary IODs. In the clinical scenario in which the patient has an existing PRDP and the principal abutment tooth that provides support for direct retention has to be removed due to a pathological condition and/or other factors (Tada et al. 2013), the replacement of the principal abutment tooth with an implant may provide a practical solution. The entire process of remaking a new PRDP can be avoided, thereby avoiding new design process, patient visits, and associated costs. Furthermore, since the existing PRDP will be modified to be compatible with the new implant attachment-retention assembly, the patients’ adaptation to the prosthesis is rapid and uneventful. Therefore, this aspect may be extremely beneficial in an older patient, who may have difficulty in adapting to a new PRDP (Müller et al. 1993, Müller et al. 1995). Distal extension PRDPs are usually not very well supported by patients because of various biomechanical factors (Bortolini et al. 2011, Goncalves et al. 2014, Kono et al. 2014, Mitrani et al. 2003). Posterior residual ridge resorption (RRR) and the need for frequent relining (de Freitas et al. 2012, Griffin et al. 2004, Verri et al. 2007) as well as damage to the distal abutment teeth during long-term function, are stated reasons for the avoidance and failure of these PRDPs (Chou et al. 1991). A key design principle adopted for ameliorating the clinical situation to favor long-term success is by adding a posterior implant support (as distant as clinically viable) and by adhering to the principles of minimal invasiveness (Abd El-Khalik et al. 2016, Bural et al. 2016, Mitrani et al. 2003, Wismeijer et al. 2013). Thus, converting a Kennedy Class I to Class II or Class III and converting a Kennedy Class II to Class III, is extremely beneficial (Elsyad et al. 2011, Keltjens et al. 1993, Mijiritsky et al. 2004, Mitrani et al. 2003, Zancope et al. 2015). The benefits of such a design include, but are not restricted to, better retention and

It is noteworthy to reiterate that, when considering implant therapy in elders, a broader perspective needs to be considered with regard to functional, restorative, economic, clinician- and patient-centered outcome measures. However, age alone should not be a concern for not effectuating this beneficial therapy; as far as possible, it should be a routinely recommended option in the rehabilitation of elderly edentates to help ameliorate oral function and OHRQoL.

**Implant overdentures (IODs) in the elderly**

Severely resorbed residual ridges in edentulous patients frequently preclude the construction of retentive and stable CRDPs. Ill-fitting and poorly retained CRDPs can affect oral function, and may cause psychosocial problems. The RRR patterns in the mandible are twice as much than in the maxilla in the first year after extraction, and four times more in the following years, although the RRR gradually slows in the ensuing years (Karaagaclioglu et al. 1994).

Problems with poor denture construction are predominantly associated with the severely resorbed mandibles (Carlsson et al. 2010, Polzer et al. 2010). Restoration of an edentulous maxilla usually is not as problematic as that of an edentulous mandible. A conventionally constructed CRDP that abides with the standard clinical principles of denture construction would be clinically acceptable and avail satisfactory results for the edentulous maxilla (da Conceicao Araujo et al. 2018). IODs are comprise of RDPs that rest on, and are partially or completely supported by dental implants (GPT-9 2005). IODs help preserve the residual ridges in the peri-implant area (de Jong et al. 2010, Khalifa et al. 2016). They are either entirely implant-supported or implant-tissue supported, based on the number and distribution of the implants as well as the chosen type of attachment (Clepper 1999).
The mandibular IOD on two interforaminal implants, opposing a conventional maxillary CRDP, has been proposed as a “minimum standard” of care for the completely edentulous subjects, by certain schools of researchers (Feine et al. 2002, Thomason et al. 2009, Thomason et al. 2012). This concept has provided a predictable long-term success and is well documented in the literature (Awad et al. 2003, Raghoebbar et al. 2000). Evidently, the advantages of using IODs in elderly edentates are numerous. Elderly edentates rehabilitated with IODs have demonstrated better masticatory function and have reported an improved satisfaction (van der Bilt et al. 2010, van Kampen et al. 2004). The OHRQoL has also been shown to be significantly improved in patients restored with IODs than those restored with conventional CRDPs (Awad et al. 2014, Emami et al. 2009, Rashid et al. 2011), especially in dependent elders (Müller et al. 2013).

The IOD concept for the edentulous mandible is a successful therapy, regardless of whether it is supported/retained by two or even more implants (Meijer et al. 2009, Timmerman et al. 2004, Visser et al. 2005, Wismeijer et al. 1997). In fact, successful outcomes have also been reported with an IOD supported/retained by a single midline implant in the mandible. The single-implant IOD, which seems to be a reliable protocol, adheres to the concepts of minimal invasiveness and demonstrates good patient satisfaction with an improvement in masticatory performance as well as in the OHRQoL (Alsabeeha et al. 2011, Cordioli et al. 1997, Grover et al. 2014, Harder et al. 2011, Krennmark et al. 2001, Liddelow et al. 2010, Passia et al. 2017, Passia et al. 2015). The protocol, however, may still not be recommended as a definitive protocol owing to concerns related to long-term effects on the residual posterior supporting structures, as well as aspects relating to prosthodontic maintenance and, a lack of sufficient scientific evidence (Bryant et al. 2015, Srinivasan et al. 2016).

In most instances implant support may be deemed unnecessary for the edentulous maxilla. Nevertheless, implant assistance is sought in the maxilla when it is a patient’s preference, or in order to avoid the palatal plate of the CRDP, or to improve phonetics and patient comfort (Sadowsky et al. 2016). An unfavorable shape of the denture bearing tissues, whether because of low tuberosities without undercuts or flabby ridges in which the bony tissues have been replaced by connective tissue after long-term overload, may equally be an indication for implant placement.
The lack of saliva may also be a factor that limits the success of a conventional CRDP and implants may replace the missing cohesive forces from the saliva film. When indicated, an appropriate number of implants may be positioned in the edentulous maxilla to construct an IOD (Batenburg et al. 1998, Slot et al. 2016).

The ideal number and position of implants for an IOD are primarily determined by the jaw to be rehabilitated, secondarily by the anatomic structures present in the respective jaw, and finally by the choice of the attachments. In the mandible, the ideal minimum number for an IOD is two implants (Batenburg et al. 1998), although four implants can also be used (Visser et al. 2005). The location of the implants are usually positioned in the interforaminal region in the anterior mandible (Batenburg et al. 1998, Heydenrijk et al. 1998, Meijer et al. 1994). In this region, placing two implants is possible most of the time. The placement of four interforaminal implants is dictated largely by the residual condition of the mandible, the proximity of the mental foramen, and further presence of anatomic constraints. The recommended implant position in the mandible for two implants is ideally in the canine regions (C–C), and for four implants the recommended configuration is in the canine – second premolar regions (PM2–C–C–PM2) (Müller et al. 2016). If this configuration is not possible, then the lateral incisor–first premolar configuration could be adopted (PM1–LI–LI–PM1) (Müller et al. 2016). Whether two or four implants are placed also depends also on the patient’s maximum bite force, as a larger support area is needed to protect the posterior ridges in patients without significant atrophy of the chewing muscles. In instances where the decision to place implants in the posterior mandible has to made, then the proximity of the inferior alveolar nerve dictates the implant positioning, the need for complex bone augmentation procedures or, the adoption of minimally invasive options such as short dental implants may be justified. In any event, geriatric treatment predictors have to be considered thoroughly along with the patient’s health status and preference, before delving into any complicated and expensive procedures.

In the maxilla, the minimum number of four implants is recommended for the IOD support. Maxillary IODs supported by fewer than four implants seem to experience far greater implant failures than those supported by ≥ 4 implants (Kern et al. 2016). The recommended maxillary implant configuration is the positioning of the anterior implants in the canine regions, whereas the posterior implants are located close to or on the chewing center. However, the position of the posterior implants is largely governed by their proximity to vital anatomic
structures, in this case, the maxillary sinus (Müller et al. 2016). Hence, in order to remain minimally invasive and avoid complex sinus floor elevation (SFE) procedures, the posterior implant may be positioned in a more anterior position, i.e. immediately anterior to the sinus, but as close as possible to the chewing center of the CRDP (Müller et al. 2016). However, recent studies have reported promising outcomes with only two implants for a maxillary IOD when compared with the conventional CRDPs (Zembic et al. 2014). Successful outcomes have also been reported for maxillary IODs supported by three implants (Ma et al. 2016) which have demonstrated that there were no differences between the type of attachments employed, splinted or freestanding. However, to date, the recommendation on the minimum number of implants for maxillary IOD support remains at four implants (Batenburg et al. 1998, Müller et al. 2016) as a predictable criterion for the long-term success and the prevention of implant failure (Kern et al. 2016).

**Attachments for implant overdentures (IODs)**

The success of IODs depends on various factors among which are the performance of the IOD attachments, which is substantially important (Rutkunas et al. 2011). IODs, for their retention and stability, are primarily dependent on the retentive potentials of the attachment system being employed. It is thus logical to assume that the functional efficiency of an IOD is dependent on the performance of the attachment system utilized. Hence, the attachment behavior must be predictable and durable long-term. The attachment must further be universal in its clinical indication, provide multiple options in its retentive capacity, should be easy to repair/remake, not difficult to maintain, easy to clean, and offer the possibility for an uncomplicated retrieval without damage to the prosthodontic construction.

Attachment systems for IODs are classified in several ways, based on different criteria. The widely professed universal classification is based on the attachment's ability to splint implants (Priescel 1996). Hence, based on this criterion, IOD attachments that:

i. splint implants are known as “splinted attachments” (e.g., bar attachments),

ii. do not splint implants, and are called “freestanding attachments” or “single anchorage systems” (e.g., stud attachments).
I. Splinted attachments (bar attachments)

Splinted attachments comprise of a bar framework fabricated in either gold alloy or titanium. The shape of the bar may be round, ovoid (e.g., Dolder bar) or, U-shaped, and may even be a variation of these principal shapes. The round and ovoid bars permit a denture rotation about the bar superstructure and may affect the survival of the implants (Bergendal et al. 1998). Whereas, the U-shaped bar provides a more rigid fixation, and thereby promotes a healthy peri-implant structure and improved function (Zou et al. 2013), and thus precipitates high patient satisfaction (Mericske-Stern et al. 2009). The bars may be individually cast, soldered from prefabricated components or, more recently, milled from a block of chosen material (Katsoulis et al. 2015). The CAD/CAM milled bars can be manufactured either in titanium or zirconia (Katsoulis et al. 2013).

The retentive element (i.e., female part), the clip, is prefabricated and is ideally manufactured from gold alloy. The clips are available in shapes and in dimensions that correspond to the form of the fabricated bars. The clips either provide an intimate contact with the parallel surfaces of the rectangular bar (i.e., friction) or engage in the undercuts of the round or ovoid bars (i.e., retention). These retainers are cut to the desired lengths as dictated by the clinical situation. The prefabricated clips can also be resilient plastics clips, which are held in place by a small metal housing processed in the IOD. These plastic clips can be easily changed during a chairside procedure. However, they cannot be activated but, are available in different retentive strengths and are color-coded for ease of use. The plastic clips are inexpensive but they may require more frequent replacement, compared with rigid metal clips (Krennmair et al. 2008). In daily clinical practice, the classic gold alloy clip still remains the preferred choice for the bar attachments. They can be activated to increase their retentive strength. Conversely, the retentive force can be reduced by gently and adequately opening the wings/fins of the gold clip until achieving the desired retentive force. Fixation of the gold clip, however, is a slightly complicated procedure and is frequently performed in a dental laboratory. Minor corrections may be accomplished in the dental office, but for major repairs, a dental laboratory support is essential.

Bar attachments have numerous advantages. They are ideal for uniform distribution and the spread of forces during function (Hussein 2013). They definitely offer higher retentive strength and require lower prosthodontic maintenance than do conventional freestanding
anchorage systems (Walton et al. 2002). The main advantage of the bar attachments is that they can be used in clinical situations in which multiple implants are involved and the implants are not parallel, a situation very commonly encountered in the maxilla (Calvert et al. 2013, Slot et al. 2013). Bars can compensate for unfavorable axial inclinations to provide a single path of insertion for the IOD prostheses.

The bar attachment is also the attachment of choice when intentional splinting of implants is indicated. Splinting multiple short implants with a bar attachment ensures a uniform force distribution (Hussein 2013), and thereby makes the IOD more stable. Moreover, the survival of short implants is reported to be better when they are splinted (Mendonca et al. 2014). The bar attachment can also be fabricated with distal extensions, the benefits of which include enlarged posterior support and the prevention of posterior bone loss (Behneke 1996). The use of posterior cantilever extensions has been documented to favorably provide posterior support, and thus make the IOD entirely implant-borne (McCartney 1992, Mericske-Stern 1997). However, caution is advised with such distal cantilever extensions because the soldered bar attachments may fracture during functional loading. A single-piece CAD/CAM milled bar may be a feasible solution to reduce such fractures. The length of this distal cantilever extension must be carefully selected as in vitro studies suggest that it may cause non-axial overloading of the distal implants and may cause crestal bone-level changes (Ebadian et al. 2016, White et al. 1994). However, clinical studies do not confirm these effects (Sadowsky et al. 2004, Semper et al. 2010). Distal extensions may be applied in bar designs to support IODs, as opposed to conventional CRDPs, or used in frail elders in whom the likelihood of excessive bite force is low and the benefits of a larger support area are high (Srinivasan 2016).

Bar attachments, however, do have a few disadvantages. An adequate amount of inter-arch space (12–14 mm) is usually required for the IODs employing bar attachments (Ahuja et al. 2010, Bansal et al. 2014, Lee et al. 2006, Pasciuta et al. 2005). An optimum inter-implant distance is also recommended to provide sufficient space for the retentive clips. Issues with hygiene maintenance have been reported with bar attachments because patients find it difficult to remove plaque under the bar and on its lingual side (Zou et al. 2013). Gingival hyperplasia under the bar is a commonly reported problem (Elsyad 2012). Although this is a benign condition, it is nevertheless considered troublesome because the hygiene maintenance becomes more complicated. Bar attachments are considered cumbersome to manufacture, and have high
initial costs (Steffen et al. 2004). Although the prosthodontic maintenance events are considerably less for the bar attachments than for freestanding overdenture attachments (MacEntee 2008, Stoker et al. 2007, van Kampen et al. 2003, Visser et al. 2007), repairs and remakes when warranted are expensive and are usually not managed chairside (Gotfredsen et al. 2000). The newer CAD/CAM milled bars and prefabricated bar systems have reduced the need for repairs and remakes; however, long-term clinical evidence remains scarce.

**The SFI-Bar® attachment**

The SFI-Bar® (Cendres+Métaux SA, Biel, Switzerland) is a prefabricated bar attachment system that is designed to be fabricated chairside; hence, it is suitable for immediate loading protocols (Kim et al. 2011). It is indicated for use for IODs in the edentulous lower jaw supported by a minimum of two interforaminal implants and can be used for up to six implants in the upper and lower edentulous jaws. It is limited to clinical situations where the inter-implant distance does not exceed 26 mm and a minimum distance of 8 mm is available. An angular compensation between implants up to 30 degrees is possible.

The system is available in two versions: the SFI-Bar® 2-implant system and the SFI-Bar® 4-implant system. The difference between the two versions is the design of the abutment (height, 3.10 mm) that connects to the bar. The SFI-Bar® 2-implant system uses a *large ball joint* S abutment that connects to the bar unidirectionally and is a terminal abutment; no further additions/extensions are possible. The SFI-Bar® 4-implant system employs a *half shell ball* S abutment in combination with a *small ball joint* S abutment that allows connectivity to the bar on its two sides. This design permits the extension of the bar and facilitates easy connectivity to the additional adjacent implants. A maximum of six implants is recommended by the manufacturer.

The SFI-Bar® has a round cross-section with a diameter of 2 mm and is constructed from titanium of grade 5 quality. The bar is hollow with a telescope-like connection to the implant abutment. This design permits the bar to be shortened and fitted as clinically required. The bars can be extended in a similar mechanism and connected to additional implants if needed. Neither soldering, casting, nor welding procedures are required to unify the bar pieces. The bar is cut to the desired length using a tube bar gauge and a conventional cutting disk.
After achieving the desired length, the terminal parts of the bar are smoothened and polished before fitting it onto the abutment.

The system has two different options for the female part. The first option is called the female part asymmetrical E, which is a conventional metal clip made from a yellow precious metal alloy, called Elitor® (Cendres+Métaux SA). The exact composition of this alloy is discussed in our publication (Kobayashi et al. 2014). The component’s design permits a favorable retention to the PMMA within the IOD. As in conventional bar-clip systems, the female part can also be activated and deactivated by using the activator set and a desactivator macro, respectively. The second female part option is called the female part T. This is fabricated from pure titanium and is equipped with grooves that aid during cutting when customizing to the required length. The female part T houses a replaceable resilient retention insert G. These inserts are available in three strengths. The levels of retention can be chosen as indicated by the patient’s needs.

One shortcoming of the SFI-Bar® 4-implant system is the plaque retention on its half shell ball abutment. Since the component is not completely encased, there is always the possibility that the crevices in the assembly may act as nidi for the accumulation of debris. However, the clinical advantages of this system, outweigh its shortcomings. The entire fabrication procedure is chairside, allowing it to be processed conveniently and directly in the mouth, even in situations with inter-implant angular discrepancies. The bar fabrication and design have flexible features, it can be extended to additional adjacent implants by simply changing the abutment connection. The construction can be extended to a maximum of six implants, which is a helpful feature when additional implants are required at a later time, thereby saving clinical steps, time, elaborate laboratory procedures, and costs. This feature may also be an advantage for frail dependent elderly patients in whom this system can provide a quick and simple solution with great flexibility for future modifications at a low cost (Ha et al. 2012).

II. Freestanding attachments (unsplinted systems)

The classic examples of freestanding attachments are telescopic crowns, stud attachments, and magnets. High implant survival, stable peri-implant conditions, and good patient satisfaction have been reported with IODs on freestanding implants (Davis et al. 1999, Krennmair et al.
Although, no observed differences exist in patient satisfaction and in clinical performance between the different types of freestanding attachments, it has been consistently reported that magnets are rated slightly inferior in terms of retention (Davis et al. 1999).

Telescopic attachments rely on friction from parallel surfaces and thus provide a particularly rigid fit, which is often referred to as “secondary splinting”. The latter effect is provided via the removable component of the attachment system rather than by direct splinting, which is achieved by linking the implants directly. If the IOD is supported entirely by implants with telescopic attachments, then this IOD is often referred to as a “removable bridge”; this reconstruction has the advantages of a fixed prosthesis, but the flexibility of a removable prosthesis. Telescopic attachments are costly to manufacture, but reportedly need very little maintenance (Heckmann et al. 2001).

The stud-type attachments, which rely on the principle of retention, comprise of spherical ball anchors, and attachments such as the LOCATOR® (Zest Anchors LLC, Escondido, CA, USA), the NOVALOC® (Institut Straumann AG, Basel, Switzerland), or the CMLoc® (Cendres+Métaux SA, Biel, Switzerland). They are the most frequently used freestanding/unsplinted attachments for IODs. The spherical ball anchor in combination with the Dalbo®-Plus (Cendres+Métaux SA) female part is considered, till date, the “Gold-Standard” among all unsplinted IOD attachments (Naert et al. 2004). The spherical ball anchors are easy to manipulate, process, repair, and maintain, and elicit good patient satisfaction. Moreover, the ball anchor is a versatile attachment that has a plethora of options for the female part [O-ring, Dalbo®-Plus, Dalbo®-Classic, Dalbo®-B, Profix, Pro-Snap, Dalbo®-Z; (all by Cendres+Métaux)] to suit different space requirements, and have different retentive potentials. However, the ball attachment does have a few limitations. It is not always available with different height options for the gingival tissues and moreover, it can compensate for angular discrepancies between the implants only up to 15 degrees (Quirynen et al. 2005). Ball anchor attachments require more prosthetic space than some of the newer stud attachments like the LOCATOR® attachment. It is recommended to use the spherical ball anchor in conjunction with a female part that consists of a metallic retentive insert where the retentive force can be adjusted, for e.g., the Dalbo®-Plus or the Dalbo® Classic, because this construction helps in maintaining the functionality of the attachment, even when the attachment head is compromised by wear (Bayer et al. 2007). The utilization of a metal insert limits damage to the attachment head and provides a stable retentive
potential in the long-term, and thereby lowers the maintenance needs (Bayer et al. 2011, Ludwig et al. 2006b).

LOCATOR® attachments are the modern cap-type stud attachments used for IODs and are extremely popular among clinicians. In fact, based on an international survey conducted among 116 prosthodontists from 33 countries, the investigators concluded that the LOCATOR® attachment was the system most commonly employed for mandibular IODs (Kronstrom et al. 2017). The LOCATOR® attachment was designed to eliminate most limitations exhibited by the classic ball anchor. The height of the LOCATOR® is considerably smaller than that of the ball attachment; therefore, it can be used in patients with a limited vertical prosthetic space. Next, the LOCATOR® attachment’s design allows a compensation for angular discrepancies of up to 40 degrees. This compensation is possible by utilizing a second type of retention insert. Moreover, the attachment is available for different gingival tissue heights ranging from 1–6 mm. The LOCATOR® attachment has a dedicated denture cap (i.e., housing) which lodges the retentive insert. The retentive inserts are made of nylon and are available in different color-coded strengths.

Though this attachment is a popular option for IODs; it also has several disadvantages. The attachment demonstrates a highly unpredictable and variant retentive behavior. It is affected by repeated insertions and removals (Evtimovska et al. 2009), and by implant angulations (Al-Ghafli et al. 2009). The attachment exhibits severe attachment and insert wear (Alsabeeha et al. 2010, Kleis et al. 2010); hence, it requires increased maintenance (Abi Nader et al. 2011). Another aspect, which is disturbing in a clinical context, is the reported “nuisance factor” (Mackie et al. 2011). The accumulation of food debris and retention of plaque along with other deposits have been reported for the central lacuna of the LOCATOR® attachment. This accumulation can be problematic in elderly individuals with restricted manual dexterity or poor vision, or for those elders who are dependent for care in settings where the effective cleaning of the attachment head to clear away the accumulations and deposits from the LOCATOR® attachment may be a difficult task. A blocked central lacuna precludes the IOD from engaging the attachment, and thereby causes poor seating of the denture with an increased risk of fracture, as well as causes inconvenience and stress to the elderly patient. In clinical practice, however, this problem can be prevented by sealing the lacuna space with a provisional light curing temporary resin cement, which can be easily removed when required.
Nevertheless, the LOCATOR® attachments are preferred by most practitioners because of the ease of manipulation.

*SFI-Anchor® attachment*

The SFI-Anchor® (Cendres+Métaux SA) is a freestanding stud-type IOD attachment, which was the first of its kind that ‘genuinely’ compensated angular discrepancies. This novel attachment has three principal components: an abutment component (i.e., male part), an attachment housing (i.e., female part), and a retentive insert. The abutment component of the SFI-Anchor® is a stud-type design with a “star-shape.” The SFI-Anchor® abutment is available as three purpose-built abutments, SFI-Anchor® D20, SFI-Anchor® D60, and SFI-Anchor® CD20. The former two abutments (i.e., D20 and D60) are used directly on the implants as freestanding attachments, whereas the latter abutment is used as an auxiliary attachment on a rigid bar framework. The basic star-shape design of the abutment head is similar in all the three abutments with the difference being the mechanisms by which they provide angular compensation. The SFI-Anchor® D20 and SFI-Anchor® CD20 both provide what the manufacturers label as “extended compensation.” Extended compensation implies that the attachment is designed to handle an inter-implant angular discrepancy of up to 20 degrees. The SFI-Anchor® D60 is equipped with a “true-alignment” technology, which compensates for up to 60 degrees of angular discrepancy. This abutment is first screwed directly on the implant and torqued to 35 Ncm. The D60 angular compensation mechanism physically corrects the angular discrepancy by allowing its head to have a free swiveling movement for axis alignment. The star-shaped head can be freely rotated on a hollow dome, and the aligned position can be fixed by injecting a dual-curing resin cement via a central hole. After achieving this alignment, the SFI-Anchor® housings are processed adhering to conventional principles similar to other well-established attachments systems. However, the vertical space requirements for each of the three abutments varies, as follows: 2.5 mm, 3.33 mm, and 2.0 mm for D20, D60, and CD20, respectively. The retentive inserts are manufactured from a polymer called Pekkton® (Cendres+Métaux SA) and are available in four different retentive capacities. An Elitor® insert is available when extra-strong retention is needed. The SFI-Anchor offers extended benefits to clinical cases that are complicated because of inter-implant angular deviations. This fact may be of a particular advantage in patients with multiple implants positioned in the edentulous maxilla and/or in edentates, in which the anatomic situation may restrict an ideal parallel position.
The CAD/CAM milled CRDPs

Digital technology has been successfully introduced in clinical medicine and dentistry for diagnostic procedures, treatment planning, as well as the treatment itself. By using digital technologies, complicated surgeries can now be performed with increased ease and accuracy. Computer-aided design and manufacturing (CAD/CAM) methods exploit digital technologies to design, and construct tools that aid in treatment planning, the treatment procedure, or, for CRDPs, to manufacture the end products that are the treatment per se. This technology was introduced to dentistry in the 1980s (Duret 1986, Duret et al. 1988) and since then has witnessed a tremendous evolution. The workflow first involves a data acquisition step, followed by the computer-aided designing (CAD) of the product. The final step involves the computer-aided manufacturing (CAM). Personal computer (PC) software-packages are available for data import and denture design, whereas the final step of manufacturing is usually performed in an industry setting.

Data acquisition is the process of recording analog information and converting it to digital data. This data acquisition can be accomplished by different scanning techniques and devices. Scanning devices established in dentistry involve either three-dimensional (3D) laser scanning, charge coupled-device (CCD) cameras, or an extraoral CBCT (cone beam computerized tomography) scan technique (Busch et al. 2006, Goodacre et al. 2012, Inokoshi et al. 2012, Kanazawa et al. 2011, Kawahata et al. 1997, Maeda et al. 1994). The first attempts to use ultrasound for soft tissue-preserving 3D impressions have been promising, but are not yet ready for clinical practice (Vollborn et al. 2014).

Modern dental 3D laboratory scanners employ a heterodyne phase shift-based structured white light in conjunction with photogrammetry to produce high-resolution scans. These scans can be accurate to about 5 microns. The scan data generated is then exported as a binary *.stl file (also called “stereolithography file” or “standard tessellation language file”, or “standard triangle language file”), which is the standard format used in the CAD/CAM technologies. The CAM processes may be classified as an additive or a subtractive procedure.

The CAD/CAM additive methods are commonly referred to as “rapid prototyping” (RP), or “3D printing.” As the name implies, this is a manufacturing process that creates an
object by the sequential layering of the chosen print material. For dental applications, RP usually involves one of the five following methods:

1. Stereolithography apparatus (SLA) 3D printing,
2. Digital light projection (DLP),
3. Jet (Polyjet/Projet) printing,
4. Selective laser sintering (SLS), and
5. Direct metal laser sintering (DMLS).

The RP technique is selected, based on the choice of the material to be printed and its clinical application. SLA printing uses liquid resins that are sensitive to ultra-violet (UV) light, whereas, DLP prototyping involves the use of UV and visible light for the polymerization procedure. Jet printing employs a series of ink-jet heads which jet out layers of the print material on a print platform, followed by curing/hardening the jetted layers either by a light source or an UV source or a heat source. SLS uses a high-powered laser to fuse plastic, ceramic, or glass particles. When used for fusing metal particles it is referred to as DMLS. In SLS or DMLS, a layer of plastic or metal particles is spread on the working platform. The laser then melts the plastic particles or directly fuses the metal particles to the preceding layer below. This process is repeated until the designed object is shaped. In dentistry, RP is commonly used for printing dental models, wax patterns, provisional restorations, resin removable partial denture frameworks to be conventionally cast in chrome, copings, occlusal splints, and surgical drill guides. More recently, RP has also been employed for manufacturing try-in, and even definitive CRDPs.

The CAD/CAM subtractive techniques include computerized numeric control (CNC) milling and spark erosion. The CNC milling is more popular than the other subtractive CAD/CAM techniques for dental applications especially in the arena of removable and fixed prosthodontics (Miyazaki et al. 2009). CNC milling usually involves the creation of an object by the process of subtractive diamond grinding or by carbide/laser milling of a prefabricated/pre-sintered/pre-polymerized block of material, based on a digital image designed with CAD software. The process is carried out in a milling station that is classified, based on its device properties, and can be either a 3-, 4-, or 5-axis milling device.
The construction of CRDPs by traditional techniques has been practiced for more than a century (Jacobs 1998). This protocol requires multiple clinical visits alternating with laboratory procedures. Although this process is still the “gold standard” technique in denture construction, it cannot be denied, that it is time consuming and cumbersome, especially for fragile and elderly patients. The use of CAD/CAM in CRDP construction has revolutionized both, the clinical protocols as well as the laboratory procedures (Goodacre et al. 2012). The latter manufacturing step has all the potential to become a disruptive technology. The first attempts of CRDP construction using CAD/CAM techniques have been published in the 1990s (Kawahata et al. 1997, Maeda et al. 1994). The real breakthroughs have occurred only recently; but since the 1990s, this discipline has evolved exponentially (Baba et al. 2016).

The CAD/CAM CRDPs are constructed in just two clinical visits (Schimmel et al. 2016); in the first visit, all clinical records are captured. These records are then transferred to the digital dental laboratory where the entire CRDP is designed virtually. This design preview is sent to the clinician for approval; the digital dental laboratory mills the CRDP and transports it the clinician. In the second clinical visit the, CRDPs are ready for insertion.

The CAD/CAM CRDP protocols involve fewer visits, lesser treatment time, reduced chairside time as well as a reduction in the associated overall costs (Srinivasan et al. 2017a, Srinivasan et al. 2018b). In the clinical context, it is up to the clinician to combine steps from the digital workflow with conventional procedures, which is particularly helpful for checking the accuracy of the recorded parameters, and to obtain the patient’s approval before the work is completed. Evidence indicates that the milled CRDPs have better fit, material properties, and surface properties (Goodacre et al. 2016, Steinmassl et al. 2018a, Steinmassl et al. 2018b). Being milled from a pre-polymerized PMMA that is manufactured under high pressure, it is expected that the residual monomer content in such CRDPs is lower than that of conventionally manufactured CRDPs. However, this assumption could not be confirmed (Steinmassl et al. 2017). The practical advantages of digitally manufactured CRDPs have been stated as superior retention, significantly reduced treatment time, and a permanent digital record (Kattadiyil et al. 2017a). The two-visit milled CRDP protocol has proven to be highly beneficial to both, the clinicians and the patients (Kattadiyil et al. 2015). However, issues related to esthetics and retention have been reported (Kattadiyil et al. 2017b). It has been suggested that the
incorporation of a trial denture option in the digital CRDP workflow could help minimize these problems.

Based on the demographic trends of the population, increasing life expectancy, and the improvements in tooth retention, the highest prevalence of completely edentulous patients is in the advanced age strata. Treating edentulism, especially in an individual with an advanced age may be a difficult task and is even more challenging if the individual’s health, physical state, and cognition are compromised. The digital CRDP protocol may actually be a feasible solution for geriatric individuals because of its relatively low treatment time and low costs incurred. This treatment protocol perfectly fits in the geriatric criteria of reducing the treatment burden for the elders by avoiding multiple sessions. However, the first session may still be longer than a conventional clinical appointment; depending on the patient’s resilience, this session may have to be split into several smaller ones. However, the simplicity of these protocols may be more widely accepted, which would make the patient more compliant. Clinical decision-making depends on many factors, and the economic aspect is certainly a major criterion for both the clinician and the patient. In a more global perspective, these cost-effective protocols would ensure that the treatment is accessible to larger populations, particularly to those patients with financial limitations. However, these assumptions can only be validated by large-scale clinical studies designed with health economics outcome measures. The CAD/CAM CRDPs remain in their stages of infancy and need to be assessed over a long-term, with regard to a variety of aspects such as material properties, clinical performance, clinician- as well as patient-centered outcomes and economic perspectives; only then a well-founded recommendation can be proposed.
First Line of Research (RL1): Novel Attachment Systems for Implant Overdentures

The success of IOD therapy, amongst other factors, depends on the use of an ideal attachment system, which is usually dictated by the clinical situation. Bar attachments splint the implants, whereas stud-type attachments are freestanding. The bar attachments can be used in clinical situations where the inter-implant angulation is not ideal, i.e., not parallel. This capability is a considerable advantage; however, the process of fabricating conventional bar attachments for IODs and repairing or replacing them are nevertheless considered cumbersome and quite expensive. Freestanding attachments are easy to manipulate, easy to repair or replace, and do not demand a high initial cost. They require a nearly ideal clinical situation wherein the implants need to be parallel. In situations where the implants are not parallel, these systems demonstrate a decline in their clinical performance such as a rapid decrease in their retentive potentials or attachment wear, and require frequent replacements of the retentive elements and/or perhaps the attachment itself. These factors increase the maintenance needs and the associated costs. Furthermore, freestanding attachments with metallic inserts are said to be influenced by their clinical environments such as the presence of the saliva.

This RL1 was aimed at investigating the possibility of utilizing novel attachment systems that could eliminate the disadvantages of both the aforementioned principal attachment systems. It was an attempt to promote minimally invasive rehabilitation protocols for the elderly individuals.

The RL1 primarily focused on three aspects. First, the aim was to investigate whether the retentive behavior of prefabricated bar attachments was better than that of traditional freestanding attachments when under the influence of cyclic dislodging (i.e., repeated insertion–removal cycles). This was under the assumption that, if this prefabricated bar performed similarly or better, it could be an easier, quicker, and inexpensive alternative to conventional bar attachments. This research question was tested using a novel prefabricated bar attachment system (SFI-Bar) that could be easily processed by the clinician as a chairside procedure. This attachment was compared against the conventional stud-type attachments that are frequently used in IOD protheses. An in vitro experimental setup was conceived that simulated the situation of a mandibular two-implant retained overdenture protheses. Custom-
manufactured polyvinylchloride (PVC) models were fabricated for the purpose of these experiments.

The first experiment had three major experimental groups: Ball with Dalbo-Plus®, SFI-Bar®, and the LOCATOR®. Each major group further had two subgroups that simulated the situation of parallel implants, and nonparallel (13° inter-implant angular discrepancy). A total of 30 samples were constructed for the purpose of this first experiment. The tests were run in an Instron® device (Instron, Norwood, MA, USA) in a wet environment. Each sample underwent 14,600 insertion–removal cycles (i.e., cyclic dislodging).

The second aspect investigated in this RL1 was to evaluate whether a novel purpose-designed freestanding IOD attachment could successfully compensate for severe inter-implant angular discrepancies. The retentive potentials under the influence of cyclic dislodging and with different the angular discrepancies were also studied. The experimental setup used two attachments (LOCATOR® and SFI-Anchor®), which were designed to be used in clinical situations where the inter-implant angular discrepancies were far from ideal. As in the first experiment, similar custom-fabricated models were manufactured. In this experiment, five major groups were classified, based on the inter-implant angular discrepancies designed in the experimental models: 0°, 20°, 30°, 40°, and 60°. Each of these groups had two subgroups (except the 60° group), based on the overdenture attachments used (i.e., LOCATOR® or SFI-Anchor®). Ninety samples were constructed in total for this experiment, and a special custom-fabricated artificial saliva was manufactured solely for this experiment. As in the previous experiment, the testing was carried out using the Instron® device. All the samples underwent 10,000 insertion–removal cycles.

Based on our first experiment findings, we were able to conclude that, over time, the SFI-Bar exhibited higher retentive capacities than did the LOCATOR® attachment whereas, it was similar to the spherical attachment with a Dalbo-Plus®. In this experiment, we were further able to demonstrate that an inter-implant angulation not exceeding 12° did not seem to have a significant effect on the retentive behaviors of the tested attachments. Therefore, this experiment clearly demonstrated that the prefabricated bar attachment system did performed similarly to the popular stud attachment and even better than the LOCATOR®. This novel
prefabricated bar could therefore be a quick and inexpensive option in an elderly patient for whom time and finances are a constraint.

In our second experiment, we demonstrated that the novel SFI-Anchor® attachment was able to successfully compensate for severe angular deviations of up to 60°. The retentive potentials remained unaffected by the angular discrepancies. This experiment provided evidence to justify that, in clinical situations where the implant placements cannot be in an ideal configuration, it is possible to provide a satisfactory rehabilitation by using these attachments. This possibility prevents the need for invasive procedures to achieve a perfect clinical situation.

A third aspect investigated in the RL1 was to assess whether a liquid medium influenced the retentive force of freestanding attachments that utilized nonmetallic retentive inserts. This aspect was investigated using the LOCATOR® attachments and an ideal parallel inter-implant angulation. An isotonic 0.9% sodium chloride (NaCl) solution was compared with a custom-manufactured artificial saliva solution. The tests were run on 10 samples for each liquid medium. Based on the findings of this final experiment in our RL1, we concluded that with overdenture attachments with nonmetallic retentive inserts such as LOCATOR®, the retentive potentials were unaffected by a liquid medium. This finding hypothetically can be translated to a clinical situation wherein it can be assumed that, irrespective of the consistency of the saliva, the attachment performance may be unaltered.
Article 1 (RL1): Effects Of In Vitro Cyclic Dislodging on Retentive Force and Removal Torque of Three Overdenture Attachment Systems.

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Impact factor: 3.889

Summary
The objective of this in vitro study was to evaluate the retentive behaviour of three overdenture attachments when they were subjected to repeated insertion-removal cycles. The study further aimed to measure the removal torque of these attachments following this cyclic dislodging. For the purpose of this in vitro experiment, polyvinylchloride models with an upper and lower member were fabricated. The models corresponded to an overdenture situation with two implants. The upper member housed the female components while the lower member housed the implants and the corresponding attachments. A total of 30 models were manufactured and were distributed into three attachment groups (Locator*: n=10; spherical attachments with Dalbo®-PLUS: n=10; SFI®-Bar: n=10). Each attachment group was further divided into two subgroups (parallel implants: n=5; angulated implants n=5). The attachments were tightened as per the manufacturers’ recommendations and the models were tested under wet conditions in a universal testing machine. They were subjected to 14,600 cycles and the retentive forces were measured during the entire course of the experiment. The removal torque was measured before and after the dislodging cycles. Multiple linear regression and 3-way ANOVA models were applied for analyses.

The results of this study revealed that the Locator attachments demonstrated lower mean retentive forces than the other two attachment groups while the other two attachment groups showed a steady increase in their retentive forces during the experiment. The inter-implant angulation of 12 degrees did not seem to have an effect on the retentive forces. There was no evidence of wear in any of the attachment groups and also no catastrophic failures were
observed. The removal torques measured at the end of the experiment was significantly lower than the baseline measurement. The abutment level fixation screw of the SFI-Bar might be a cause for concern in terms of screw loosening but could be avoided if regular and timely recall visits were respected.
Article 2 (RL1): Influence of Implant Angulation and Cyclic Dislodging on The Retentive Force of Two Different Overdenture Attachments – An In Vitro Study.

Srinivasan M., Schimmel M., Badoud I., Amman P., Herrmann F. R. & Müller F.
Clinical Oral Implants Research 2016 (27), 604-611.
© 2015 John Wiley & Sons A/S. Published by John Wiley & Sons Ltd.
Impact factor: 3.624

Summary
The objective of this bench experiment was to study the effect of different inter-implant angulations on the retentive capacities of the two overdenture anchorage systems when subjected to repeated insertion-removal cycles.

A total of 90 experimental models that represented an implant overdenture situation on 2 implants were manufactured. These models were distributed in to 5 angle groups (0, 20, 30, 40, and 60 degrees). Each of these angle groups, except the 60 degree group, were further divided into two attachment subgroups (Locator group and SFI-Anchor group). The models were subjected to 10,000 repeated insertion-removal cycles in a universal testing machine, in wet conditions using a custom-prepared artificial saliva solution. Retentive forces were measured during the course of the experiment. Mean retentive forces were calculated and statistically analyzed using ANOVA and linear regression models.

The cyclic dislodging did have an effect on the retentive force of both the attachment groups. However, the inter-implant angulation had a significant effect on the retentive force of the LOCATOR® groups only. Moreover with increasing inter-implant angulations, the retentive forces of the Locator groups were significantly higher than the SFI-Anchor groups. There was no significant difference between attachment groups when the implants were parallel (0 degrees).

Therefore, this study evidenced that the novel SFI-Anchor attachment demonstrated that it was not affected by inter-implant angular discrepancies of up to 60 degrees. Hence this
attachment may be particularly suitable in clinical situations where there are multiple implants and the inter-implant angulations are not ideal.
**Article 3 (RL1): Influence of Different Lubrication on the Retentive Force of LOCATOR® Attachments – An In Vitro Pilot Study.**

**Srinivasan M., Schimmel M., Kobayashi M., Badoud I., Amman P., Herrmann F. R. & Müller F.**

Clinical Oral Implants Research 2016 (27), 771-775.

© 2015 John Wiley & Sons A/S. Published by John Wiley & Sons Ltd.

Impact factor: 3.624

**Summary**

The objective of this *in vitro* study was to assess if a liquid medium played any significant role on the retentive behaviour of a commonly used overdenture attachment (Locator attachment).

Custom fabricated polyvinylchloride models (n=20) simulating a 2-implant retained overdenture situation utilizing Locator attachments were manufactured. The two implants in the experimental models were positioned parallel to one another. The 20 models were equally distributed into two experimental groups (NaCl solution group and Artificial saliva group). The models were tested in a universal testing machine and underwent cyclic dislodging for 10,000 cycles, in one of the two media mentioned. Mean retentive forces were calculated for each experimental group and statistically analyzed. Mixed regression models were applied for statistical analysis.

This *in vitro* pilot experiment, did not demonstrate any differences in the mean retentive forces of the evaluated overdenture attachment when tested in either the NaCl solution or in artificial saliva.
Second Line of Research (RL2): CAD/CAM Milled CRDPs

The use of CAD/CAM technology has been quite recent in the field of removable prosthodontics. It offers many promising features that can be exploited in clinical practices especially in geriatric dentistry. The clinical protocols are less conventional, require fewer visits, reduce the treatment time, reduce laboratory costs and possibly reduce clinical costs. Owing to the digitization of the clinical records, the fabrication process is simplified because the clinical steps do not need to be repeated when a remake or duplication of the prostheses is necessary. These factors are substantial advantages, especially for an elderly dependent patient who is immobile or has limited access and/or finances. The entire manufacturing process is digitally executed and uses precision milling; therefore, the fit of the resultant CRDPs are supposed to be superior to conventionally fabricated CRDPs. The prostheses are milled from pre-polymerized PMMA resin pucks, which are manufactured under high pressure. These pucks are claimed to be better than the conventional heat-polymerized PMMA resins in material properties.

Our RL2 was undertaken to test these industry claims and to validate them before recommending them for routine clinical use and before undertaking a large-scale clinical study. Therefore, our RL2 addressed two research aspects.

First, we addressed the accuracy of the CAD/CAM milled CRDPs. In our first experiment, the trueness of the intaglio surfaces of the milled CRDPs were compared with that of the intaglio surfaces of conventionally fabricated CRDPs. The experimental design used a master cobalt-chrome maxillary edentulous model. By using this master reference model, a CAD design for the CRDPs was constructed, and the design was sent for approval. On approval, the CRDPs were milled. The milled CRDPs were then duplicated using conventional denture fabricating procedures. Two popular conventional fabrication methods were used: the flask-pack-press and technique and the injection-molding technique. Therefore, three sets of CRDPs were eventually fabricated. The 33 fabricated CRDPs were identical in every aspect, except in their manufacturing technique. All the CRDPs were incubated in an artificial saliva solution for three weeks. The intaglio surfaces of the three groups of CRDPs were scanned on receipt (i.e., before incubation) and after incubation in the artificial saliva solution. These intaglio surface scans were compared with the reference scan of the cobalt-chrome master model by using a 3D comparison software. The differences in the superimpositions were analyzed for each
CRDP group. The analyses were performed for the entire intaglio surfaces and for certain specific regions of interests. The differences were compared and statistically analyzed.

For the second aim of our RL2, we evaluated the biocompatibility, mechanical properties, and the surface roughness of the CAD/CAM PMMA resin by comparing it with those of the conventional heat-polymerized PMMA resin. Biocompatibility was evaluated by culturing human primary osteoblasts (hOBs) and embryonic mouse fibroblasts (3T3 cells) on the two test resin substrates. Mechanical properties were assessed by conducting nanoindentation and three-point bending tests using a nanoindenter and an Instron® testing devices, respectively. Surface roughness of the two resins were analyzed using laser profilometry.

With the first experiment, we demonstrated that the CAD/CAM fabricated CRDPs, although not superior in trueness to the conventionally fabricated CRDPs, were clinically acceptable in terms of their trueness. Based on the findings of our second experiment, we found that the CAD/CAM PMMA resin was equally biocompatible to the conventional PMMA resin. For mechanical properties, the experiments demonstrated that the CAD/CAM PMMA resin was superior to the conventional heat-polymerized PMMA. For surface roughness, we found that the CAD/CAM PMMA resins exhibited a rougher surface.

In RL2 we demonstrated that CAD/CAM technology is a viable method for manufacturing CRDPs. This opens many possibilities for clinical indications in geriatric dentistry for both CRDPs and for IODs.

Srinivasan M., Cantin Y., Mehl A., Gjengedal H., Müller F. & Schimmel M. 
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Impact factor: 2.308 

Summary
The objective of this study was to compare the trueness of the intaglio surfaces of CAD-CAM milled complete dentures with the intaglio surfaces of complete dentures fabricated by conventional techniques (injection-molding technique and conventional flask-pack-press method).

A total of 33 maxillary complete dentures were fabricated employing three different manufacturing techniques (CAD-CAM milled: n=11; Injection-molding technique: n=11; Conventional method: n=11). All groups of dentures were fabricated from the same reference cobalt-chrome edentulous maxillary master model. Following manufacturing, the intaglio surfaces of the dentures were scanned. They were then incubated in artificial saliva solution for a period of three weeks (21 days) at ambient room temperature. Following incubation the intaglio surfaces of the dentures were again scanned. The trueness of the intaglio surfaces of the denture groups were compared against the original master reference model using a 3D surface comparison software and statistically analyzed. The comparison was done for the entire intaglio surface along with five specific regions of interests.

This study did not demonstrate any significant difference between the three denture groups for the entire intaglio surface. CAD-CAM milled dentures showed the maximum variability amongst the three groups. Incubation in artificial saliva demonstrated an overall improvement in the trueness for all the three denture groups for most regions of interest but a significant improvement was seen only for the entire intaglio surface in the conventional flask-pack-press group. The majority of the deviations of the intaglio surface for all the three groups remained in a clinically acceptable range below 0.1 mm.
The high variability of the CAD-CAM milled complete dentures was perhaps because of the milling instrument.

Srinivasan M., Gjengedal H., Cattani-Lorente M., Moussa M., Durual S., Schimmel M. & Müller F.
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Impact factor: 1.073

Summary
The objective of this in vitro study was to compare the biocompatibility, mechanical properties, and the surface roughness of the resin used for manufacturing CAD-CAM milled complete dentures and the conventional PMMA resin used for fabricating conventional complete dentures.

The two groups of resin samples were manufactured using the different resins (CAD-CAM resin and conventional resin) that were to be evaluated. Biocompatibility assays were run by culturing hOBs and 3T3 cells on the resin substrates. Three-point bending test, nanoindentation test, and laser profilometry were performed to evaluate the mechanical properties and surface roughness of the two resins.

The CAD-CAM resin was noninferior to the conventional resin with regard to biocompatibility but exhibited better mechanical properties. However, the CAD-CAM resin had a rougher surface profile than the conventional PMMA resin.
General Conclusions and Perspectives

RL1: Novel attachments for IODs

Elderly edentates frequently present with a multitude of problems including, but not restricted to, extremely resorbed jaws, systemic health issues, functional decline, diminished adaptive capacities, and other age-associated complications (Carlsson et al. 2010, Mericske-Stern et al. 2000, Müller et al. 2001, Müller et al. 2007, Polzer et al. 2010). Providing a successful oral rehabilitation with removable prostheses for a patient with a compromised health status, impaired function and poor compliance is difficult. Despite exploiting the full range of technical possibilities by the treating clinician, a prosthesis may still be compromised in its retention and stability, which may ultimately decrease function, lead to nutritional and psychosocial problems, and impair QoL (Allen et al. 2001, Awad et al. 2003, Heckmann et al. 2009). The primary goal in restorative geriatric dentistry is to restore oral function and in a larger scheme to restore nutrition and improve the OHRQoL (Stenman et al. 2012). RDPs can successfully accomplish this restoration by incorporating an optimum number of dental implants to satisfactorily stabilize and retain it during function, and thereby increase patient comfort, compliance, satisfaction, and the resultant oral function, when compared with the conventional tissue-born complete denture (Allen et al. 2001, Attard et al. 2004, Cune et al. 2005, Cune et al. 2010, Doundoulakis et al. 2003, Thomason et al. 2003). The placement of two dental implants in the interforaminal region to stabilize a mandibular denture has been frequently suggested as the minimal standard of care for the completely edentulous mandible, by various research groups from developed nations (Feine et al. 2002, Thomason et al. 2009, Thomason et al. 2012).

IODs utilize retentive elements to sustain the retention and stability of the prostheses. The implants have to be positioned in the jaws in a parallel or near parallel alignment. This criterion is essential for most freestanding IOD attachments in order for them to function satisfactorily or to the best of their intended potentials (Walton et al. 2001). It has been frequently reported that when the inter-implant parallelism is compromised, it is possible that the retentive potentials of the overdenture attachments may fail prematurely or lead to other deleterious effects such as an accentuated wear or damage to the retentive element and/or to the attachment itself (Rutkunas et al. 2005, Yang et al. 2011, Zarb et al. 1990).
The *in vitro* experiments we developed for our first line of research permitted us to provide evidence that the novel prefabricated bar and freestanding attachment systems available for IODs can function satisfactorily in non-ideal situations in quasi-clinical experiments (Kobayashi et al. 2014, Srinivasan et al. 2016a). Based on this evidence, it can be concluded that these attachments can help provide minimally invasive and cost-effective solutions for the rehabilitation of elderly edentulous patients. Even when the implants are not in the ideal position or alignment, the use of appropriate overdenture attachments that allow correction of the inter-implant angular discrepancies can provide a successful rehabilitation with RDPs. In effect, advanced surgeries such as bone augmentations and sinus grafting procedures can eventually be avoided and deliberate placement of implants in anticipated non-ideal positions may well be acceptable in selected clinical cases. Hence this can effectively reduce the treatment burden such as surgical morbidity and associated costs, which are important factors when planning a successful long-term treatment outcome for the geriatric patient.

Bar attachments are usually preferred in cases of severe axial divergences (Carlson et al. 1994, Eckert et al. 2004, Katsoulis et al. 2011, Quirynen et al. 2005, Zitzmann et al. 1999), but they are relatively expensive to manufacture, difficult to repair, and maintain (Naert et al. 1999). However, they provide superior retention and have lower incidences of complications, compared with stud attachments. Therefore, an ideal bar attachment that would be preferred by the clinician would be one that is easy to manufacture, repair, and maintain. The chosen prefabricated round bar attachment system (SFI-bar) used in our first experiment allows chairside fabrication and, when indicated, permits an immediate loading protocol (Kim et al. 2011). We also attempted to also evaluate the attachment wear and the frequently reported complication of attachment screw loosening in IODs, along with the principal focus remaining on evaluating the retentive behavior of the attachment under cyclic dislodging (14,600 cycles) and the effect of mild inter-implant angular discrepancy (not exceeding 12°). This first experiment demonstrated that the prefabricated bar did not seem to be affected by the induced inter-implant angular discrepancy and maintained its retentive capacity similar to the spherical ball attachment with a Dalbo-PLUS female part under cyclic dislodging. The bar also relatively outperformed the other attachment, the LOCATOR®, which was evaluated in this study.
An interesting feature observed in our experiment was that the retentive capacities of the bar and the spherical anchor steadily increased with the evolution of the experiment. This complex behavior is attributed to the fact that both of these attachment systems use metallic components. As a consequence of this type of component, repeated dislodging would perpetuate a potential surface roughening of the elements. This roughening would in effect increase the friction between the opposing surfaces, and consequently increase the resistance to removal. Therefore, this resistance is translated as an increase in retention forces. This behavior has been previously observed in studies of a similar nature (Fromentin et al. 2010, Fromentin et al. 2011, Ludwig et al. 2006a, Ludwig et al. 2006b, Ludwig et al. 2003). This phenomenon was not observed with the LOCATOR® attachment.

In our second experiment, we successfully demonstrated that novel freestanding attachments with alignment mechanisms can correct inter-implant angular discrepancies and satisfactorily function without deleterious effects to their retentive potentials. The two attachments used in the experiment each had the correctional capability for inter-implant angular discrepancies. The LOCATOR® had a compensation mechanism wherein different types of retentive inserts were used, depending on the severity of the inter-implant angular deviations. However, the SFI-Anchor® was a true alignment system in which the attachment could be swiveled to the correct alignment, and fixed with a resin cement, to produce parallelism between the implants (Müller et al. 2016, Webersberger 2016). The LOCATOR® only affords a correction of up to 40°, whereas the SFI-Anchor® can correct inter-implant angular discrepancies of up to 60°. Both systems used nonmetallic retentive inserts; therefore, their retentive behaviors were very similar under cyclic dislodging (10,000 cycles).

However, a key difference was observed when the attachments were subjected to different implant angulations. The retentive force of the LOCATOR® groups significantly increased with higher inter-implant angulation, which signified that angulation had an effect on retentive behavior. By contrast, the SFI-Anchor®, did not demonstrate this behavior with increasing angulations. The retentive force remained relatively constant for the different angle groups for this attachment. This diverse behavior of the LOCATOR® attachment may possibly accelerate the rapid loss of its retentive capacity, which has been a common finding associated with this attachment (Al-Ghaflie et al. 2009, Evtimovska et al. 2009). The increasing angular discrepancy probably increased the resistance between the insert and attachment contacting.
surface, thereby increasing the retention force. For the SFI-Anchor®, the uniform retentive behavior could be validated by the fact that the attachment actually physically corrects the angular discrepancy and therefore does not increase the resistance between the attachment and the retentive element. This sort of an angular compensatory mechanism and the retentive behavior are a great advantage in clinical situations with multiple implants where the implants are not relatively parallel. This situation may frequently arise in an edentulous maxilla or in geriatric patients in whom implant placements may be dictated more by the complicated anatomic situation and/or the need to avoid complex surgeries. These attachments would work very nicely to compensate for the discrepancy and provide a very successful rehabilitation.

It has been proposed that clinical environmental factors such as saliva has been nominated as a factor that could influence the retentive behaviors of freestanding attachments that comprise opposing metallic elements (Bayer et al. 2007, Bayer et al. 2011, Besimo et al. 2003). Modern-day freestanding attachments predominantly utilize nonmetallic retentive inserts. The current retentive inserts have evolved from metallic to nonmetallic inserts that are either nylon, Pekkton®, PEEK, or similar material.

Our third experiment demonstrated that the retentive force of the LOCATOR® attachment with its nylon insert was not influenced by the lubricant medium. Although the forces were lower in the artificial saliva solution than in the 0.9% isotonic NaCl solution, the statistical model did not reveal a significant effect (Srinivasan et al. 2016b). However, this finding should be considered with caution because our post hoc power calculations revealed that the study was underpowered. A larger number of samples in the experiment may have probably elicited a significance. It can be argued that this may not have been a factor because most previous studies that have revealed a relative effect of the lubricant medium had tested attachments with metallic components; the attachment wear observed in these studies predominantly occurred in a low viscosity NaCl solution (Ludwig et al. 2003, Ludwig et al. 2006b). The wear of the metallic components could perpetuate an increase in frictional resistance and therefore increase the retentive capacity (Ludwig et al. 2003, Ludwig et al. 2006b). By contrast, the LOCATOR® attachment used in our experiment had a nylon retentive insert, which could have caused behavior that was dissimilar with that of the attachments with metallic inserts. This behavior may be applicable to newer attachments that do not use metallic components in their retentive assemblies.
**RL2: CAD/CAM Milled CRDPs**

The second line of research developed in our division provided evidence that CAD/CAM milled CRDPs, though not superior in terms of accuracy of fabrication when compared to conventionally manufactured CRDPs, are within clinically acceptable limits (Srinivasan et al. 2017c). In RL2, we have further demonstrated that the PMMA resin used in the fabrication of the CAD/CAM milled CRDPs is similar in biocompatibility; but its mechanical properties are better than those of traditional heat-polymerized PMMA resin (Srinivasan et al. 2018a). The milled CRDPs with their novel clinical protocols and improved material properties could be exploited to simplify the treatment time and effort, which could be highly beneficial to the frail dependent elderly individuals with limited mobility.

Fabricating CRDPs for an edentulous patient necessitates various clinical steps that stretch over multiple clinical visits, which can be cumbersome for frail elderly individuals, especially those who are hospitalized/immobile/bedridden, and/or dependent on care. The influx of CAD/CAM technology for the fabrication of CRDPs has resulted in the implementation of newer clinical protocols that reduce the number of clinical visits, time, and costs (Kattadiyil et al. 2017a, Srinivasan et al. 2018b). Most popular CAD/CAM systems that fabricate CRDPs advocate protocols that deliver the final prostheses in two visits (Schimmel et al. 2016). The possibility of remakes and duplications have also been simplified because of these new protocols. These are substantial benefits for the elderly patients. If these protocols can be implemented in routine clinical practices, it could very well revolutionize the conventional CRDP treatments. For the fabrication of CRDPs, these concepts are fairly recent and therefore need scientific validation in clinical trials before being recommended as a definitive protocol.

Before our own experiment, the accuracy of the CAD/CAM milling method for CRDPs was investigated in only one study (Goodacre et al. 2016). The investigators of that study had evidence that the CAD/CAM technique was superior to the other conventional techniques used in CRDP manufacturing (Goodacre et al. 2016). However, McLaughlin and coworkers (2017) demonstrated that CAD/CAM and injection-molding techniques produced similar fitting CRDPs (McLaughlin et al. 2017). In our own study, we found that the CAD/CAM milled CRDPs were not superior to CRDPs manufactured by the flask-pack-press or injection-molding techniques (Srinivasan et al. 2017c). We found that the manufacturing accuracy of all
three investigated methods, remained within the range of 0.1 mm of the original master reference model scan. This range was very well within the clinically acceptable standards with regard to CRDPs because this precision in fit would not limit a prosthesis from achieving the required amount of retention.

An interesting finding in our study was the variability of the precision of the manufactured CRDPs. It was expected that the milled CRDPs would have been the most consistent in reproducibility. This expectation was assumed because of the fact that a single common design was used for the fabrication. Therefore, the corresponding CRDPs that were produced based on this design should be completely identical. Errors due to resin processing are literally nonexistent when using this method because the CRDPs are milled from pre-polymerized PMMA pucks that do not require a further final curing process. Human errors can also be excluded because the prostheses are milled in a commercial 5-axis milling station. It was surprisingly that the milled CRDP group was by far the most variable among the three groups. The reasons for this finding can only be speculated because many factors may have had a role in this variability. For example, the CRDPs could have been manufactured by different milling stations and there may have been calibration differences between the stations. The size of the milling instrument and the age of the instrument used are factors worth considering because the cutting efficiency of the milling bur is definitely influenced by the number of times it has been used and how sharp it remains. Another factor to consider is the size of the milling instrument. Larger instruments leave the inner surface with a somewhat terraced surface, which may explain the large variability in the fitting surface of the CAD/CAM dentures. Smaller instruments may result in smoother surfaces, but their use would substantially increase the milling time, which represents an economic disadvantage. By contrast, the surface fit of a conventional flask-pack and press prosthesis is only limited by the particle size of the plaster cast and the size of the molecules of the PMMA, with the two being brought into intimate contact under several atmospheres of pressure. At this stage, all of these explanations are speculations and further research is warranted. We have assumed that the quality-control measures of the manufacturer are of extremely high standards and the accuracy remained within clinically acceptable standards, these sources of errors can be judiciously overlooked.
The conventional heat-polymerized CRDP manufacturing with the traditional heat-polymerized PMMA resin has been time-tested and remains the “gold standard”, despite the various commonly encountered polymerization errors such as: denture porosities, crazing, denture warpage, and different forms of shrinkages (Woelfel et al. 1960, Wong et al. 1999). The CAD/CAM milled CRDPs are supposed to be devoid of these processing errors, as the puck used for manufacturing is pre-polymerized. The puck is manufactured under high pressure; therefore, the resin should be of better surface characteristics and mechanical properties. The manufacturers further state that the CAD/CAM resin is inherently more bio-hygienic when compared to conventional PMMA resins.

Our second experiment in RL2 focused on the biocompatibility aspects, mechanical properties and the surface characteristics of the CAD/CAM PMMA resin. The biocompatibility assays demonstrated favorable cell proliferations in both the yielded cell lines. A healthy proliferation of both hOBs and 3T3 cells was found on both resin substrate groups. In fact, a tendency for greater proliferation of the cells were seen on the CAD/CAM resin substrate group, but this finding was not statistically significant. The increase in the cell proliferation could be due to the fact that our findings revealed that the surface was significantly rougher than the heat-polymerized substrates. This finding seems to support the biocompatibility aspect; however, it cannot be ignored that, in a clinical context, this finding would support the adhesion of oral biofilm and its components. Increased surface roughness favors oral biofilm adhesion (Jackson et al. 2014, Verran et al. 2014). Evidence is lacking that clarifies whether these milled CRDPs attract more biofilm formation than conventional CRDPs and hence should be assessed by means of well-designed clinical studies. However, in terms of in vitro analysis, it has been confirmed that the CAD/CAM method of fabricating CRDPs reduced the adherence of Candida on the resin substrate surface (Al-Fouzan et al. 2017).

With regard to mechanical properties, the CAD/CAM resin was superior to the conventional PMMA in toughness, ultimate strength, and elastic modulus. These superior features of the CAD/CAM resin could allow for the resultant milled CRDP to be fabricated with a thinner base than that of conventional CRDPs, which require a certain thickness to avoid fractures. The smaller volume would definitely afford better patient comfort and have a significant role in speech; however, evidence to corroborate these effects are currently unavailable. The higher elastic modulus permits the denture to remain resistant to deformation.
This results in a more rigid and dimensionally stable CRDP that would theoretically provide a more stable occlusion.

Prosthesis deformation under function and the effects a rigid prosthesis may have on the underlying tissues have not yet been investigated and requires clinical validation. The relining capabilities of the milled CAD/CAM CRDPs have also not been studied. It can only be assumed that because these are chemically the same polymer, a problem in relining should not be a factor. However, the manner of fabrication of the CAD/CAM resin raises a few questions as to its compatibility with, and the bonding to, traditional heat-polymerized PMMA resins. Evidence in terms of long-term clinical observations and evaluations can only further shed light on these issues.

With the constant evolution of the attachment systems for IODs, newer attachments with better surface modifications and improved retentive potentials will arrive in the near future. Advancements in the CAD/CAM technologies would further simplify the clinical protocols and manufacturing processes, and would make the treatment of the elderly edentates easier, less invasive, and more cost-effective. However, all of these tooth replacements are nonbiological devices with all the associated shortcomings. They replace most of the lost tissues, but still fail to entirely restore oral function in mastication, tactile sensitivity, taste, appearance, and psychosocial well-being. Future research should also focus on bioengineered replacement teeth, although the current state of research in this field does not promise a clinical treatment concept for today’s generation of elderly edentates.
Financial Support

1. For publications #1, #2, and #3:
   - The studies were completed with divisional funds allocated to the Division of Gerodontology and Removable Prosthodontics, University Clinics of Dental Medicine, University of Geneva, Geneva, Switzerland.
   - The ITI Foundation, Basel, Switzerland awarded scholarship grants to Drs. Murali Srinivasan & Mariko Kobayashi during the year 2011.
   - All the attachment and implant components used in the studies were provided free of charge by the following companies: Institut Straumann AG, Basel, Switzerland, and Cendres+Métaux SA, Biel, Switzerland.

2. For publications #4, & #5:
   - The studies were completed entirely by divisional funds allocated to the Division of Gerodontology and Removable Prosthodontics, University Clinics of Dental Medicine, University of Geneva, Geneva, Switzerland.
   - The 3D laboratory scanner used in study #5 was purchased with the funds from a grant (SSO Grant No. 281–14) from the Swiss Dental Association (SSO-Schweizerische Zahnärzte Gesellschaft).
   - The laser scanner used in study #6 was purchased with the funds from a grant (SSO Grant No. 276–13) from the Swiss Dental Association (SSO-Schweizerische Zahnärzte Gesellschaft) awarded to Professor Susanne Scherrer of the Division of Fixed Prosthodontics and Biomaterials, University Clinics of Dental Medicine, University of Geneva, Geneva, Switzerland.
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