UNIVERSIDADE DE SÃO PAULO
FACULDADE DE ODONTOLOGIA DE BAURU

ILANA SANTOS RAMALHO

Influence of abutment fabrication method and fixation mode on the three-dimensional fit and reliability of implant-supported prostheses

Influência do método de fabricação de pilares e modo de fixação na adaptação tridimensional e confiabilidade de próteses sobre implantes

BAURU
2019

ILANA SANTOS RAMALHO

Influence of abutment fabrication method and fixation mode on the three-dimensional fit and reliability of implant-supported prostheses

Influência do método de fabricação de pilares e modo de fixação na adaptação tridimensional e confiabilidade de próteses sobre implantes

Tese constituída por artigos apresentada a Faculdade de Odontologia de Bauru da Universidade de São Paulo para obtenção do título de Doutor em Ciências no Programa de Ciências Odontológicas Aplicadas, na área de concentração Reabilitação Oral.

Orientador: Prof. Dr. Estevam Augusto Bonfante

BAURU

2019

Santos Ramalho, Ilana
Influence of abutment fabrication method and fixation mode on the three-dimensional fit and reliability of implant-supported prostheses / Ilana Santos Ramalho. – Bauru, 2019
106p. : il. ; 31cm.

Tese (Doutorado) – Faculdade de Odontologia de Bauru. Universidade de São Paulo

Orientador: Prof. Dr. Estevam A. Bonfante

Autorizo, exclusivamente para fins acadêmicos e científicos, a reprodução total ou parcial desta dissertação, por processos fotocopiadores e outros meios eletrônicos.

Assinatura:

Data:

Comitê de Ética da FOB-USP
Protocolo nº:
Data:

(Cole a cópia de sua folha de aprovação aqui)

DEDICATÓRIA

A **Deus** por ter me dado a permissão de chegar até aqui, e por toda a força concedida na concretização desse sonho. Agradeço a Ele por todas as pessoas especiais que cruzaram meu caminho e que estão aqui citadas.

Aos meus pais, **Nida e Déo**, pelo amor, dedicação e incentivo a tudo que realizo. A vocês, que se doaram inteiros e renunciaram aos seus sonhos, para que, muitas vezes, pudesse realizar os meus. O momento que vivo agora é fascinante e só existe porque vocês se doaram em silêncio e aceitaram viver comigo o meu sonho. Presentearam-me com a riqueza do estudo e isso ninguém pode tirar de mim. A vocês devo tudo o que tenho e sou, pois vocês são minha fonte de inspiração, meus exemplos, minha base de sustentação. Mãe, a sua força me inspira a ser uma mulher melhor, o zelo e a educação que deu aos seus filhos me inspiram a ser uma mãe exemplar, seu cuidado com sua mãe e seus irmãos me inspiram a ser uma filha e irmã amorosa e sua dedicação e amor ao meu pai me inspiram a ser esposa companheira e cuidadosa! Pai, sua responsabilidade, dedicação à família, serenidade, honestidade, inteligência, determinação, vontade de trabalhar, fazem de você o homem que mais admiro nesse mundo. Se eu conseguir ser a metade da pessoa que você é, sentirei que cumpri meu papel nessa vida! Obrigada pela nossa família! Amo muito vocês!

Aos meus orientadores, Prof. Dr. Luiz Fernando Pegoraro e Prof. Dr. Estevam Augusto Bonfante. Quando paro pra pensar sobre a minha jornada na pós graduação vejo o quão privilegiada sou por ter sido orientada por dois grandes mestres. Dizem que os orientados acabam seus cursos parecidos com os orientadores. Confesso que se isso for verdade, me sinto imensamente orgulhosa por herdar alguma característica dos dois. **Professor Pegoraro** será sempre meu exemplo de humildade, amor à profissão, competência e generosidade. Quem me conhece sabe o quanto sou fã e grata por ter convivido e aprendido tanto com ele, a quem devo todo meu conhecimento de prótese e tenho o maior orgulho em dizer que fui escolhida pra ser sua dentista. Palavras nunca serão suficientes para expressar minha gratidão, admiração, carinho e respeito. Meus sinceros agradecimentos por toda confiança em mim depositada, por me fazer acreditar no meu potencial e saber que qualquer dificuldade que eu encontrasse durante o caminho, poderia contar com seu apoio.

Professor Estevam será pra mim eternamente um exemplo de dedicação, inteligência, competência, disciplina, e ajuda ao próximo. Ele pode não dimensionar a importância dele em minha vida, mas com certeza sua orientação foi um divisor de águas. Ele me incentivou e abriu oportunidades que me mostraram o quão forte posso ser e foi o grande responsável por uma das mais incríveis experiências da minha vida, o Doutorado Sanduíche. Serei eternamente grata por seu acolhimento, incentivo e apoio.

E ambos são meus exemplos de equilíbrio entre a vida pessoal e profissional, e de valorização da família. Muito obrigada por tornarem essa jornada muito mais leve e alegre.

AGRADECIMENTOS

A minha irMÃE, **Lauana,** sempre tão presente e dedicada, esteve ao meu lado em cada conquista da minha vida, sempre me incentivando e apoiando. Obrigada por ter ajudado a formar a pessoa que sou, por seus conselhos sempre bem vindos e por todo seu amor! Sinto diariamente a sua presença constante ao meu lado, pois a nossa ligação é muito forte, e por isso, fico tranquila, pois, tenho em você um porto seguro, e sei que você sempre fará o possível e o impossível para me ver feliz. Saiba que a recíproca é verdadeira e eu que eu te amo demais! Agradeço pelo melhor presente que você me deu, meu sobrinho **Leonardo**, que me proporcionou tantas felicidades e que traduz a ligação que temos uma pela outra, meu amor por ele não pode ser medido e nem explicado por palavras. Leco, serei sua eterna “Tia Nana” e não importa o quanto você cresça, terei sempre a imagem daquele menininininho carinhoso e amável que cresceu comigo. Eu tenho muito orgulho do homem íntegro, responsável e trabalhador que você se tornou. Ao meu cunhado, **Lelo,** por quem tenho um amor de irmão, agradeço por todo amor e cuidado comigo.

Ao meu querido e amado irmão, **Vandré,** que muitas vezes, sem perceber, me alegrou e me arrancou um sorriso quando eu mais precisava. Tenho em você um exemplo de generosidade e amor ao próximo, o seu coração gigante me inspira a fazer sempre o bem! Eu te amo demais! Obrigada a você por me fazerem reviver uma das maiores alegrias da vida de alguém, ser tia! Nossa princesa **Lorenna** veio trazer mais felicidade pra minha vida e deixar a saudade de casa ainda maior. Ló, quando você crescer e já conseguir entender essa mensagem, queria que você soubesse que o amor que eu tenho por você é imenso e que tudo que eu puder fazer pra te ver feliz, eu farei! Amo vocês!

Durante o meu doutorado tive muitas surpresas, a mais linda delas foi ter conhecido uma pessoa com um dos corações mais lindos que já vi. Meu amor, **Adolfo**, alguém que virou meu companheiro em literalmente todas as horas do dia, alguém que me traz paz, segurança e muita felicidade. Um amor recíproco, cúmplice, companheiro e cheio de respeito e admiração mútua. Agradeço por todo carinho, dedicação ao nosso amor, e incentivo a tudo o que faço. Te amo!

Ao meu avô **Hilton Ramalho**, que nos deixou no meio do meu Doutorado, mas deixou as mais importantes lições: união da família e valorização do estudo. Exemplo de dignidade, honestidade, determinação e de uma inteligência sem igual! A minha avó **Ritinha**, meu amor, com sua doçura, me faz sentir a pessoa mais especial do mundo! Uma mulher pequena no tamanho, mas gigante de coração, me inspiro na sua força! Amo muito vocês!

A toda minha família que, sempre que possível, se fazem presentes nas minhas idas e vindas e que me fazem sentir muito amada, sempre vibrando com cada vitória minha. Vocês não sabem o quanto isso torna a minha luta diária contra a saudade mais fácil. Em especial às minhas primas-irmãs e aos meus tios e tias queridos.

Ao **S. Coelho e D. Selma**, por terem me recebido e acolhido tão bem. Por todo cuidado e preocupação, por muitas vezes fazendo diminuir a saudade de casa.

Às minhas amigas da vida inteira, **Mari, Lá e Bi**, por me mostrarem que independente do tempo e da distância, nossos corações estarão sempre ligados por nossa amizade verdadeira!s

Aos meus amigos de faculdade, em especial ao **Ana Paula, Johnny, Larissa, Lara e Simone**, por continuarem cruzando meu caminho com sorrisos, abraços e acima de tudo amizade, pelo incentivo e carinho de sempre. Sinto muita falta do nosso convívio diário.

A minha turma de mestrado **Andréa, Fernanda, Guilherme, Gustavo, Oscar, Patrick, Thereza, Verena e Vinícius** agradeço pelo convívio harmonioso, pelas experiências vividas, pelo apoio e incentivo que sempre me deram. E apesar das obrigações da vida nos afastarem um pouco no Doutorado, levarei pra sempre comigo cada um de vocês no meu coração.

Em especial às amigas **Fernanda e Verena**. Obrigada por se fazerem presentes em tantos momentos importantes desta caminhada, pelos momentos felizes que passamos juntas, por todas as risadas e até pelos momentos difíceis compartilhados. São essas pessoas que nos fazem seguir em busca dos nossos

sonhos, pois ajudam a diminuir a saudade de casa e vibram junto com cada conquista! Saibam que estarei aqui pra tudo que precisarem e tenho certeza que nossa amizade se estenderá muito além da nossa pós-graduação. Só desejo coisas boas a vocês, tenho certeza que terão muito sucesso nessa caminhada.

A minha amiga, **Andréa**, pela sintonia, cumplicidade, companheirismo, carinho e amizade. Com certeza você é um presente de Deus na minha vida! Obrigada por todo incentivo em tudo que faço, obrigada pelos momentos de descontração, pelas risadas compartilhadas, por sua amizade tão leve e que me faz sentir tão bem! Desejo a você todo sucesso e felicidade que desejaria a mim mesma, que você siga o melhor caminho sempre e que Deus te ilumine. Muito sucesso na sua vida! Muito obrigada por tudo! Rezo pra que nossa parceria seja pra vida inteira e que nós possamos realizar muitos projetos juntas! E não poderia deixar de agradecer a uma pessoa muito especial, amigo querido, Ricardo. Obrigada por tantas conversas, por seu bom coração, por sua alegria, carinho e incentivo. Nosso quarteto só me traz lembranças boas e o desejo de compartilhar momentos assim pra toda vida.

À família mais linda que se formou nesse doutorado, minha querida amiga **Thereza**, nosso pacotinho de amor **Maitê** e o querido amigo **Patrick**. Agradeço pela amizade valiosa, parceria, incentivo, projetos e por todos os momentos de descontração e felicidade.

Aos maiores presentes que a NYU me deu : **Edmara, Paula, Nathalia e João.** Cada um com seu jeito único fez crescer e fortalecer uma amizade que tempo ou distância alguma irão destruir. Só nós sabemos tudo o que vivemos lá e o quanto a força da amizade tornou aquela experiência inesquecível para todos. Não poderia deixar de agradecer especialmente à Ed, minha amiga, cúmplice e companheira que possui um dos corações mais generosos que eu conheço. À **Marina, Márcia e Anna**, as quais tive o privilégio de conhecer e conviver.

Serei eternamente grata ao **Dr. Paulo Coelho**, pela oportunidade de trabalhar em seu laboratório e por todo conhecimento compartilhado. Ao **Lukasz**, por ter sido chefe, amigo, parceiro, por todo incentivo mesmo com as nossas dificuldades, por

cada trabalho que nos foi confiado. Ao Nick **Tovar**, pela amizade, risadas e momentos compartilhados.

A minha amiga, **Laís**, um dos melhores presentes que Bauru me deu! Obrigada por toda alegria que você traz pra minha vida, obrigada por toda preocupação, por toda ajuda e incentivo! Amizades assim, são muito valiosas, pois nos levam sempre à frente e nos impulsionam! Tenho certeza que nossa amizade vai permanecer além do tempo e da distância.

À pessoa mais doce que conheço, **Juliana Hotta.** Obrigada pelos abraços, sorrisos sinceros e aventuras compartilhadas.

A minha "eterna turma de doutorado", **Max, Vitor, Hugo Vidotti, Luiz, Lívia Aguiar, Luana, Carol e Livia Maria**, que me receberam de braços abertos quando iniciei minha caminhada em Bauru, não medindo esforços em transmitir ensinamentos e tornando minha vida aqui mais leve e mais divertida! Com vocês aprendi o que é trabalho em equipe, respeito pelos professores, determinação em alcançar os objetivos, esforço para realizar o melhor trabalho possível! Levarei a amizade de vocês pro resto da vida!

Em especial, às minhas grandes amigas **Lívia Aguiar, Luaninha e Carol,** cada uma com sua particularidade, conseguiram conquistar meu coração de um modo singular. Lívia, obrigada por você existir em minha vida, obrigada por todos os conselhos sábios e por toda ajuda, sua luz irradia a todas as pessoas que estão a sua volta! Luaninha, acho que independente do que eu fale aqui, você não vai acreditar no quanto eu gosto de você! Você é minha ciumentinha predileta, estar com você é sinônimo de diversão e boas risadas, sua amizade e companhia são muito valiosas pra mim! Admiro sua inteligência, competência e responsabilidade, saiba que aprendi muitas coisas com você! Carol, muito obrigada por todos os seus abraços carinhosos, por todas as conversas prazerosas e por todos os momentos bons que passamos! Você é uma pessoa única e maravilhosa! E principalmente obrigada por todo incentivo e oportunidades nesse fim da jornada de pós-graduação. Vou te levar pra sempre em meu coração.

Aos meus colegas pós-graduandos por todo conhecimento compartilhado e disponibilidade em ajudar sempre.

À amiga **Camila Libardi**, por toda ajuda nos momentos em que mais precisei! Obrigada por ser tão generosa e prestativa! Você tem um lugar especial no meu coração!

À amiga **Polly** que foi contagiada pelo clima de Bauru e decidiu se aventurar conosco nessa caminhada. Com quem compartilhei todas as mudanças da vida. Obrigada por sua amizade, serenidade e palavras sensatas.

Ao **Meneguel,** que com seu jeito único e espontâneo e seu coração gigante traz tanta alegria as nossas vidas.

À minha eterna **Turma LII**, por terem me proporcionado um dos momentos mais importantes e felizes da minha pós-graduação. Ouvir vocês batucando e gritando meu nome me proporcionou uma alegria imensurável. Jamais esquecerei vocês!

Ao **Prof. José Maurício e Profa. Lígia** da FOAR-UNESP, por terem me acolhido tão bem nessa instituição e por tornarem minha primeira experiência docente muito mais leve e que com certeza será marcante em minha vida.

A todos os professores do departamento de prótese: Prof. Dr. José Henrique Rubo, Prof. Dr. Paulo César Rodrigues Conti; Prof. Dr. Carlos dos Reis Pereira de Araújo, Profa. Dra. Karin Hermana Neppelenbroek, Prof. Dr. Renato de Freitas, Prof. Dr. Vinícius Carvalho Porto, Prof. Dr. Wellington Cardoso Bonachela, Profa. Dra. Lucimar Falavinha Vieira, Profa. Dra. Simone Soares por todo conhecimento transmitido.

De maneira especial, agradeço àqueles com os quais eu tive uma convivência maior, Profa. Dra. Ana Lúcia Pompéia Fraga de Almeida, Prof. Dr. Accácio Lins do Valle, Prof. Dr. Pedro César Garcia de Oliveira por todos os ensinamentos. Por serem exemplos de simplicidade e humildade. Por me tratarem sempre com tanto carinho e amizade.

Ao querido professor, Prof. Dr. Gerson Bonfante por todo carinho e por me ser exemplo de que a busca pelo conhecimento deve ser uma constante em nossa vida profissional.

Às funcionárias da clínica de pós-graduação, Cleusa e Hebe, pela convivência leve e pelo apoio de sempre. Muito obrigada pelo carinho com que sempre me trataram e por terem me recebido tão bem desde o primeiro dia em que cheguei na clínica, ainda como estagiária. Vou levar a lembrança de vocês pro resto da minha vida!

À equipe de funcionários da comissão de pós-graduação pelo trabalho árduo e silencioso que realizam todos os dias em prol de nossa universidade.

Aos queridos funcionários do departamento de prótese, Cleide, Cláudia, Déborah, Valquíria, Marcelo e Reivanildo, pelo esforço em me ajudar sempre e pelo carinho com que sempre me trataram.

A todos os pacientes que atendi ou acompanhei durante essa jornada. A essas pessoas que não fazem ideia do quanto nos ensinam a cada dia com suas histórias e suas vidas.

À Universidade Federal de Alagoas, instituição onde me graduei, a qual sempre levarei em memória e meu coração. Não poderia deixar de agradecer ao meu orientador de TCC, Prof. Dr. Natanael Barbosa dos Santos, por tantos ensinamentos e por me mostrado o gosto pela carreira acadêmica.

À Faculdade de Odontologia de Bauru – Universidade de São Paulo, na pessoa do excelentíssimo diretor Prof. Dr. Carlos Ferreira do Santos, pelo apoio institucional.

Ao Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq pela bolsa de doutorado e Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) por minha bolsa de doutorado sanduíche, auxílios indispensáveis para realização deste trabalho.

Aos professores integrantes da banca examinadora, por terem analisado, arguido e contribuído para a otimização deste trabalho.

A todos que direta ou indiretamente, ajudaram na realização desta pesquisa.

“Se você pode sonhar, você pode fazer.””

Walt Disney

ABSTRACT

Influence of abutment fabrication method and fixation mode on the three-dimensional fit and reliability of implant-supported prostheses

Objectives. To evaluate the effect of abutment fabrication method on the three-dimensional fit at the implant-abutment interface and its correlation with stress at fatigue failure of prostheses. Probability of survival (reliability) and fractography to characterize failure modes were also performed for cemented and screw-retained prostheses.

Methods. Central incisor crowns were milled to restore implants and divided in 3 cemented and 3 screwed-retained groups, as follows (n=21/group): [Digital-Sc]: milled one-piece monolithic abutment/crown; [TiB-Sc]: milled crowns cemented onto Ti-base abutments; [UCLA]: screw-retained crown using UCLA abutments; [Digital-Ce]: milled two-piece assembly comprised by screwed monolithic abutment and a cemented crown; [TiB-Ce]: milled coping cemented onto Ti-base abutments to receive a cemented crown; [UCLA-Ce]: UCLA abutments that received an overcast coping and a cemented crown. Volume measurements were performed to assess the internal misfit using silicone replica of the implant/abutment interface area three-dimensionally reconstructed after microcomputed tomography (µCT). Implant/crown systems were subjected to step-stress accelerated life testing (SSALT) in water. The use-level probability Weibull curves and reliability for a mission of 50,000 cycles at calculated stress at failure of 2,300, 3,300 and 4,300 MPa were plotted. Fractographic analysis was performed with scanning electron microscopy. Internal misfit was analyzed through one-way ANOVA following post-hoc comparisons by Tukey test ($P<0.05$). Correlation between misfit volume and the stress at fatigue failure was assessed by Pearson test.

Results. Similar misfit volumes were observed for TiB-Sc (0.458 mm^3), TiB-Ce (0.461 mm^3), UCLA (0.471 mm^3) and UCLA-Ce (0.480 mm^3), which were significantly lower than Digital-Sc (0.676 mm^3) and Digital-Ce (0.633 mm^3). The mean β values were: 1.68, 1.39, 1.48, 2.41, 2.27 and 0.71 for Digital-Sc, TiB-Sc, UCLA, Digital-Ce, TiB-Ce and UCLA-Ce, respectively, indicating that fatigue was an accelerating factor for failure of all groups, except for UCLA-Ce. Higher stress at failure decreased the

reliability of all groups, more significantly for screw compared to cement-retained groups, especially for Digital-Sc that demonstrated the lowest reliability. The failure mode was restricted to abutment screw fracture. A negative correlation was observed between misfit values and stress at failure ($r = -0.302$, $P=0.01$).

Conclusions. Ti-Base and UCLA abutments exhibited better internal fit at the implant/abutment interfaces compared to full commercial lab fabrication process (CAD-CAM custom abutments). An impairment of the mechanical resistance according to different levels of internal misfit was observed, since the higher the volume of misfit, the lower the stress at failure during fatigue. Probability of survival decreased at higher stress, especially for screw compared to cement-retained groups, and failures were confined to abutment screws.

Keywords: Dental Implant-Abutment Designs. Dental Implant-Abutment Interface. Dental Implants. MicroCT. Reliability. Computer-Aided Design.

RESUMO

Influência do método de fabricação de pilares e modo de fixação na adaptação tridimensional e confiabilidade de próteses sobre implantes

Objetivos. Avaliar o efeito do método de fabricação de pilares sobre a adaptação tridimensional na interface implante-pilar e sua correlação com o estresse à fratura por fadiga das próteses. Probabilidade de sobrevida (confiabilidade) e fractografia para caracterizar modos de falha também foram realizadas para próteses cimentadas e parafusadas.

Métodos. Coroas de incisivos centrais foram confeccionadas para restaurar implantes e divididas em seis grupos, sendo 3 grupos parafusados e 3 cimentados (n=21/grupo): [Dig-Par] – coroa fresada monolítica parafusada; [TiB-Par] – coroa fresada cimentada sobre pilar Ti-Base e parafusados ao implante; [UCLA] – coroa fundida sobre UCLA parafusada; [Dig-Cim] – pilar fresado parafusado para receber coroa fresada cimentada; [TiB-Cim] – pilar fresado e cimentado sobre Ti-Base para receber coroa cimentada; [UCLA-Cim] – pilar fundido sobre UCLA parafusado para receber coroa cimentada. Mensurações de volume foram realizadas para avaliar o desajuste interno usando réplica de silicone na área da interface implante/pilar reconstruída tridimensionalmente após a microtomografia computadorizada (µCT). Os espécimes foram submetidos ao teste de fadiga acelerada progressiva na presença de água. As curvas de probabilidade de Weibull e a confiabilidade para missões de 50.000 ciclos a 2.300, 3.300 e 4.300 Mpa foram plotadas e calculadas em função do estresse. A análise fractográfica foi realizada com microscopia eletrônica de varredura. O desajuste interno foi analisado através de ANOVA seguida de comparações múltiplas pelo teste de Tukey ($P<0,05$). A correlação entre o volume de desajuste e o estresse à fratura por fadiga foi avaliada pelo teste de correlação de Pearson.

Resultados. Volumes de desajuste semelhantes foram observados para TiB-Par (0,458 mm^3), TiB-Cim (0,461 mm^3), UCLA (0,471 mm^3) e UCLA-Cim (0,480 mm^3), que foram significativamente menores que Dig-Par (0,676 mm^3) e Dig-Cim (0,633 mm^3). Os valores médios de β foram: 1,68, 1,39, 1,48, 2,41, 2,27 e 0,71 para Dig-Par, TiB-Par, UCLA, Dig-Cim, TiB-Cim e UCLA-Cim, respectivamente, indicando que

o acúmulo de danos em função da fadiga foi um fator de aceleração para as falhas em todos os grupos, exceto para UCLA-Cim. Maior estresse à fratura diminuiu a confiabilidade de todos os grupos, mais significativamente para os grupos parafusados comparado aos cimentados, especialmente para o Dig-Par, que demonstrou a menor confiabilidade. O modo de falha predominante foi a fratura do parafuso do pilar. Uma correlação negativa foi observada entre os valores de desajuste e estresse à fratura (r = -0,302, P = 0,01).

Conclusões. Os pilares do tipo Ti-Base e UCLA exibiram melhor ajuste interno na interface implante/pilar comparado com os pilares fresados em laboratório comercial (customizados CAD-CAM). Observou-se um comprometimento da resistência mecânica de acordo com os diferentes níveis de desajuste interno, visto que quanto maior o volume de desajuste, menor o estresse à fratura durante a fadiga. Probabilidade de sobrevivência diminuiu em nível maior de estresse, especialmente para os grupos parafusados em comparação com os cimentados, e as falhas foram confinadas aos parafusos do pilar.

Palavras-chave: Implantes dentários. MicroCT. Confiabilidade. Projeto Auxiliado por Computador.

TABLE OF CONTENTS

1 INTRODUCTION

1 INTRODUCTION

Implant-based therapy is a predictable and reliable treatment modality in the rehabilitation of missing or lost teeth [1, 2]. The literature on dental implants has advanced remarkably over the last decade, and recent reports have been shown success rates upwards of 95% [3]. Although high success rates are commonly reported for such treatment [1, 4], the less common report of cumulative survival rates suggests that the actual failure rates of dental implants are likely to be higher than the rates published in the clinical literature and therefore success may be inflated [3].

According to a recent systematic review [4], the total number of technical complications was statistically similar for internal and external connections, with a 5-year complication rate of 10.1% and 12.4%, respectively. Also, it has been reported that the most common complication is abutment screw fracture, with a cumulative rate of 10.4% in 5 years and a twofold increase to 20.4% in 10 years [5]. Such findings emphasize that treatment with implants, despite its advantages, should predict complications, time, and additional cost for maintenance [1].

Considering that complication rates increase over time [6], indicating that the fatigue damage accumulation degrades prostheses strength, it is essential to acknowledge that technical complications in implant dentistry are prevalent, and the importance of their characterization in preclinical studies has been increasingly valued [7, 8]. In this context, the use of *in vitro* mechanical testing methods to characterize the implant-prostheses complex becomes paramount, since clinical studies demand proper design, long-term follow-up, and robust data from many volunteers would need to be statistically addressed to provide meaningful results [8]. The use of *Step-stress Accelerated Life Testing* (SSALT) for reliability and failure mode analysis of several implant restorative scenarios has been widely reported [9-13].

Given the vast possibility of a combination between variables in an implant-supported rehabilitation, the selection of restorative components and crown fixation mode must be considered as a factor for long-term clinical success [14,2]. For improved performance, abutments should present the best fit at the implant connection [15], since higher values of misfit between components may increase microleakage and mechanical stress on connection structures and surrounding tissues [16-18]. Depending on the level of misfit, it may lead to mechanical problems, such as damage to the internal threads, screw preload loss or screw fracture [16, 19]. Additionally, biologic complications due to the microorganism colonization of the implant well may eventually participate in the multifactorial role of peri-implant tissue inflammation, which can cause pain, bone strain, marginal bone loss, and in the worst scenario the loss of osseointegration [17, 18, 20, 21].

There has been little information presented on the three-dimensional internal gap misfit between abutments fabricated through different techniques connected to implants with internal connection. The methods commonly used to measure marginal and internal discrepancies of restorations involve direct visualization or sectioning of the specimens, followed by measurement of the interface using scanning electron microscopy (SEM) [22, 23], optical microscopy [24], travelling microscope [25, 26] among others. These measurements commonly involve human error that, along with the non-standardized evaluation sites make interpretation and comparison between studies a challenge [27, 28]. In recent years, micro-computed (μCT) tomography has gained popularity in implantology [29-31] because it allows the non-destructive and three-dimensional (3D) evaluation of the materials, promoting a feasible quantitative and qualitative analysis of marginal or internal misfit [32]. Additionally, 3D reconstruction software may be used for the volumetric quantification of the misfit and internal/marginal gaps at the implant–abutment interface.

The selection of the implant abutment for each patient case is an essential part of the implant-prosthetic treatment phase. Firstly, a fundamental distinction needs to be made between ‘prefabricated’ or ‘stock’ and ‘custom-made’ abutments. The former comprises a standard geometry commercial abutment. Several prefabricated abutments are available in the market, which vary in indication and design, generally being indicated when the implant is placed in an almost ideal prosthetic position. Although the claimed better fit of stock abutments provided by the industry, which demand approval by regulatory agencies, their customization may be limited, considering each patient’s difference in peri-implant soft tissue emergence profile. Therefore, the need for custom abutments is gradually increasing over the years.

Opportunities for individualization include the use of custom-made abutments fabricated through either a conventional casting procedure using universal casting long abutments (UCLA) or through a digital workflow using the computer-aided design/computer-aided manufacturing (CAD/CAM) technology. In the latter, two customization options are available: 1) full digital lab fabrication process: a one-piece monolithic abutment/crown may be designed and milled in a commercial laboratory by CAD/CAM system (currently feasible for external or internal non-conical connections); or 2) hybrid fabrication process: an industrially manufactured abutment system receives custom CAD/CAM restoration fabricated by a commercial laboratory (final crown or custom core).

The UCLA-type abutment is one of the most versatile abutments produced by conventional casting procedures. Although the indications may vary, the UCLA-type abutment is practically universal and at a lower cost when compared to other prefabricated abutments. However, the castable base of the abutment that will adapt to the implant undergoes distortions during the casting procedures, impairing the fit and passivity at the implant/abutment connection, thus causing mechanical and biological problems, as previously reported [19, 33, 34]. In order to minimize such effect, castable UCLA abutments with metallic base should be used because the metal (Co-Cr) suffers minor changes during casting as its melting point is higher than the temperature used for investment heating and compatible with the temperature for alloy injection [25, 35], which in theory preserves the fit provided by the industry.

CAD/CAM technology has introduced several advantages for fabricating abutments and has been suggested as an improvement over the conventional methods [36, 37]. The benefits of employing a fully digital laboratory fabrication process for abutments and prostheses include customization and rapid chair-side or commercial laboratory fabrication regardless of industry abutment availability. Such a technology is well known to allow the high-precision machining of prefabricated blocks of various materials including ceramics, composite resin, acrylic resin and metal alloys [36]. Despite the evident advantages of abutments produced by a full digital workflow, the internal fit of such abutments is roughly dependent on several variables involved in the accuracy of milling of the CAD/CAM systems unit and the selected milling strategy [5]. Also of concern is the fact that milling of abutments by commercial labs is not yet controlled by international standards or norms, as it is for industry-provided prefabricated abutments, which undergo standard quality assurance and quality control evaluation.

A potential workaround has been recently introduced where industry-fabricated Titanium-base (or Ti-base) abutments and their inclusion in CAD/CAM libraries allowing the rapid fabrication of either a customized milled core (e.g: zirconia) or the crown by commercial laboratories. This concept is based on a titanium connector featuring a female component that connects to the implant well and a external configuration with geometry available for insertion in most CAD/CAM systems where monolithic or bilayered restorations of any given material can be cemented chairside [38-40]. The main advantage and rationale for use of Ti-base abutments comprise the maintenance of industry provided fit of the female part, in contrast to UCLA abutments where overcasting and post processing (e.g. aluminum oxide blasting) change the titanium surface topography and fit [25]. Also, retrievability is maintained when cementing the final prostheses directly to Ti-base since CAD/CAM blocks are provided with screw access holes that allow extra-oral bonding and excess cement removal, eventually reducing cementation induced peri-implantitis [41-43].

Along with the plethora of implant restorative components available, the fixation modes of the implant-supported restoration can be either screwed, cemented, or a combination of both. There is a rich literature on the advantages and disadvantages of the prosthesis retention systems [42, 44-50]. A current consensus has been published [50] and, in general, the clinical recommendations for screw retention include: implants placed in a prosthetically ideal position, with the presence of minimal interarch space (4 mm); FDPs (fixed dental prostheses) with a cantilever design; long-span FDPs; in esthetic areas, where provisionalization of implants is required to enable soft tissue conditioning and emergence profile improvement or when retrievability is desired. Also, the cement retention is recommended in the following situations: for short-span prostheses with margins at or above the mucosa level, to compensate for improperly inclined implants, for cases where an easier control of occlusion without an access hole is desired (e.g. narrow-diameter crowns)[50]. Although less technical complications of cement-retained relative to screw-retained crowns has been reported [51], the performance of hybrid systems that combine extra-orally cemented and screw-retained crowns warrants investigation.

Considering the increased use of customizable abutments in restorative dentistry and given that, once under function in the mouth, any restorative system's strength will degrade over time due to fatigue damage accumulation, the characterization of the internal fit at the implant/abutment connection of abutments fabricated by a commercial laboratory (milled or cast) compared to abutments provided by the industry, as well as the impact of misfit levels on the mechanical performance of prostheses still requires investigation. Therefore, the overall objective of this work was to evaluate the effect of abutment fabrication method on the three-dimensional fit at the implant-abutment interface and its correlation with stress at fatigue failure of prostheses. Probability of survival (reliability) and fractography to characterize failure modes were also performed for cemented and screw-retained prostheses.

2 ARTICLES

2 ARTICLES

The articles below were written according to the Journal of Prosthetic Dentistry instructions and guideline for article submission.

- ARTICLE 1 – **Abutment fabrication method affects the three-dimensional fit of the implant-abutment connection**

- ARTICLE 2 – **Implant-abutment fit influences the mechanical performance of single-crown prostheses**

2.1 ARTICLE 1

Abutment fabrication method affects the three-dimensional fit of the implant-abutment connection

ABSTRACT

Purpose. To three-dimensionally (3D) evaluate the internal fit at the implant-abutment interface of abutments fabricated through different workflows using a combination of the silicone replica technique and micro-computed tomography (µCT).

Materials and Methods. Thirty abutments were fabricated to restore internal connection implants that were divided in 3 groups according to abutment fabrication method, as follows: 1) Full-Digital (abutment machined by CAD/CAM system); 2) Ti-Base (prefabricated standard Ti-Base abutments); and 3) UCLA (UCLA-type abutments) (n=10/group). Linear and volume measurements were performed to assess the internal misfit using silicone replica of the implant/abutment interface misfit area three-dimensionally reconstructed after µCT. The internal discrepancy in 3 different regions of interest ($Gap_{superior}$, $Gap_{marginal}$ and Gap_{center}) was assessed. Data were statistically evaluated through analysis of variance and Tukey test (P<.05).

Results. Ti-Base and UCLA abutments presented significantly lower volume of misfit (0.49mm^3, CI:±0.045mm^3 and 0.48mm^3, CI:±0.045mm^3, respectively) and mean internal gap (25.20µm, CI:±3.14µm and 27.97µm, CI:±3.14µm, respectively) relative to Full-Digital group (0.70mm^3, CI:±0.045mm^3 and 34.90µm, CI:±3.14µm)(P<.001), without significant difference between each other (P=.825). While Gap_{center} was significantly higher for the Full-Digital group (P<.001), $Gap_{superior}$ and $Gap_{marginal}$ did not demonstrate significant differences among groups. All regions were statistically similar within groups, except for the $\text{Gap}_{\text{center}}$ in the Full-digital group that exhibited higher mean values compared to the other regions (P=.000). The three-dimensional measurement for quantification of internal discrepancy was strongly associated to the two-dimensional measurements.

Conclusion. Ti-Base and UCLA-type abutments exhibited better internal fit at the implant/abutment interfaces compared to fully digitalized workflow (CAD-CAM custom abutments). Three-dimensional reconstruction software may be used for the volumetric quantification of the misfit and internal/marginal gaps at the implant–abutment interface.

Keywords: Dental Implant-Abutment Interface. CAD/CAM. UCLA. Internal Fit. MicroCT.

INRODUCTION

On the basis of the osseointegration phenomenon,[1] implant-based therapy is an established treatment modality in dental practice, providing high success ratios.[2, 3] Given the wide possibility of combination between variables in an implant-supported rehabilitation, the abutment fabrication method should be carefully evaluated, since the implant/abutment connection is one of the most important factors for prostheses stability and long-term success.[3] Misfit between such components is recognized as a major concern because it may lead not only to mechanical problems,[4, 5] such as damage to the internal threads and screw loosening, but also to biologic complications due to the microorganism colonization in the inner part of the implant that may eventually cause the inflammation of peri-implant tissues, and consequently, pain, bone strain, marginal bone loss, and in the worst scenario the loss of osseointegration.[6-9]

Firstly, a fundamental distinction needs to be made between ‘prefabricated’ or ‘stock’ and ‘custom-made’ abutments. The former comprises a standard commercial abutment, not customizable. The custom-made abutments may be produced by casting (such as the UCLA-type abutments) or may be entirely designed and milled by using the computer-aided design/computer-aided manufacturing (CAD/CAM) process. Since the prefabricated abutments may not provide ideal peri-implant soft tissue emergence profiles, the need of custom abutments is gradually increasing over the years.

The UCLA-type abutment is one of the most versatile custom abutments produced by conventional casting procedures. Although the indications may vary, the UCLA-type abutment is practically universal and at a lower cost when compared to prefabricated abutments. However, the castable base of the abutment that will adapt to the implant undergoes distortions during the casting procedures, impairing the fit and passivity at the implant/abutment connection, thus causing mechanical and biological problems, as previously reported.[5, 10, 11] In order to minimize such effect, castable UCLA abutments with metallic base should be used because the metal (Co-Cr) suffers minor changes during casting as its melting point is higher than the temperature used for investment heating and compatible with the temperature for alloy injection,[12, 13] which in theory preserves the fit provided by the industry.

CAD/CAM technology has introduced several advantages for fabricating abutments and has been suggested as an improvement over the conventional methods. The benefits of employing a fully digital workflow are undeniable, including clinical time reduction, freedom in the selection of machining material, high level of customization, reduced laboratory technique sensitivity and, last but not least, independence of the professional in relation to the industry of prefabricated components. Such a technology is well known to allow the high-precision machining of prefabricated blocks of various materials including ceramics, composite resin, acrylic resin and metal alloys. Despite the evident advantages of abutments produced by a full digital workflow, the control of internal misfit is not yet controlled by international standards or norms (as it is for prefabricated abutments) and is dependent on several variables involved in the milling of the CAD/CAM systems.

In an attempt to overcome this issue, a recently introduced concept based on industrially manufactured abutment systems that receives custom milled restorations resulting in hybrid abutments has received interest.[14] Also known as Ti-base abutments, this concept is based on a titanium connector featuring a female element that connects to the implant and a external configuration with geometry stored in a CAD/CAM system in which monolithic or bilayered restorations of any given material can be cemented chairside.[15, 16] In addition to the aforementioned advantages to the full digital workflow, the main advantages of such concept comprise the maintenance of industry provided fit of the female part and the opportunity of performing the extra-oral bonding procedure and excess cement removal, achieving a final bond area polishing that decrease soft tissue reaction due to remnants of cement.[17, 18]

The methods commonly used to measure marginal and internal discrepancies of restorations involve direct visualization or sectioning of the specimens, followed by measurement of the interface using scanning electron microscopy (SEM),[19, 20] optical microscopy,[21] travelling microscope,[13, 22] among others. These measurements commonly involve human error that, along with the non-standardized evaluation sites make interpretation and comparison between studies a challenge.[23, 24] In recent years, micro-computed (μCT) tomography has gained popularity in implantology[25-27] because it allows the non-destructive and three-dimensional (3D) evaluation of the materials, promoting a feasible quantitative and qualitative analysis of marginal or internal misfit.[28]

Moreover, there has been little information presented on the three-dimensional internal gap misfit between abutments fabricated through different techniques connected to implants with internal connection. Three-dimensional reconstruction software may be used for the volumetric quantification of the misfit and internal/marginal gaps at the implant–abutment interface. Therefore, the purpose of this study was to evaluate the effect of different workflow for abutment fabrication on the internal fit at the implant/abutment interface and to correlate the two- and three-dimensional misfit measurements. The null postulated hypotheses were: (i) the abutment fabrication methods have no influence on the internal fit at the implant/abutment connection and (ii) there is no statistically significant relationship between the two- and three-dimensional misfit measurements.

MATERIAL AND METHODS

Specimen preparation

Thirty abutments were fabricated to restore internal nonconical connection implants (4 x 10 mm, IH, Novo Colosso; Emfils) that were divided in 3 groups, according to fabrication method, as follows (n = 10/group) (Fig. 1):

- *Fully digitalized workflow* [Full-Digital]: abutment machined by CAD/CAM system and directly screwed to the implant. The implant geometry previously stored in the CAD software (Ceramill® mind; Amann Girrbach) was used to design the abutments, which were then milled using CoCr discs (Ceramill sintron®; Amann Girrbach).

- *Pre-fabricated Ti-base* [Ti-base]: prefabricated standard Ti-Base abutments (non-rotational Ti-Base, Colosso; Emfils).
- *Conventional workflow* [UCLA]: screw-retained abutment using custom-cast long abutments (UCLA). For standardized abutment anatomy, they were designed in the same CAD software (Ceramill® mind; Amann Girrbach) as for Full-Digital group and milled in wax (Ceramill® wax; Amann Girrbach) pattern followed by conventional casting procedures using UCLA-Type abutments (Castable non-rotational in CoCr base with plastic sleeve abutment, Colosso; Emfils).

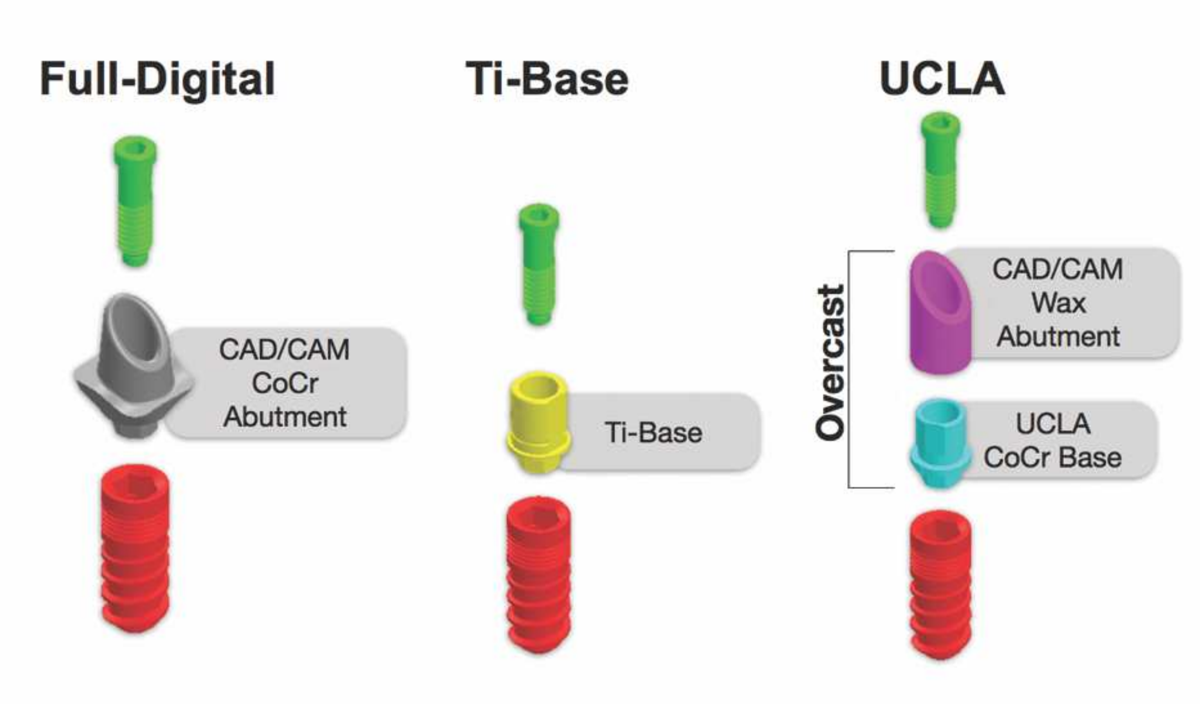


Figure 1. Workflow of the specimen preparation according to the fabrication methods.

Fit evaluation

Linear and volume measurements were performed to assess the internal misfit at the implant-abutment connection using silicone replica three-dimensionally reconstructed after micro-computed tomography (µCT) (µCT 40; Scanco Medical). All implants were vertically embedded in an acrylic resin (Orthoresin; Degudent) and plastic tube (Ø25 mm x 35 mm) with the implant's platform positioned at the same level of acrylic resin. The implants were filled with a medium-bodied consistency silicone impression material (Express^{TM} XT Regular Body; 3M Oral Care) and the abutments were then tightened with torque recommended by the manufacturer (32 N.cm) using a digital torque gauge (Tohnichi BTG150CN-S; Tohnichi America). After the impression material had set, the abutment was untightened and carefully removed from the implant while the thin polyvinyl siloxane film remained on the inner surface of the implant. Then, the polyvinyl siloxane film was gently removed from the implant. At this point, to ensure greater stability of the replica specimen, the excess of impression material drawn into the screw hole was not eliminated (Fig. 2A-B).

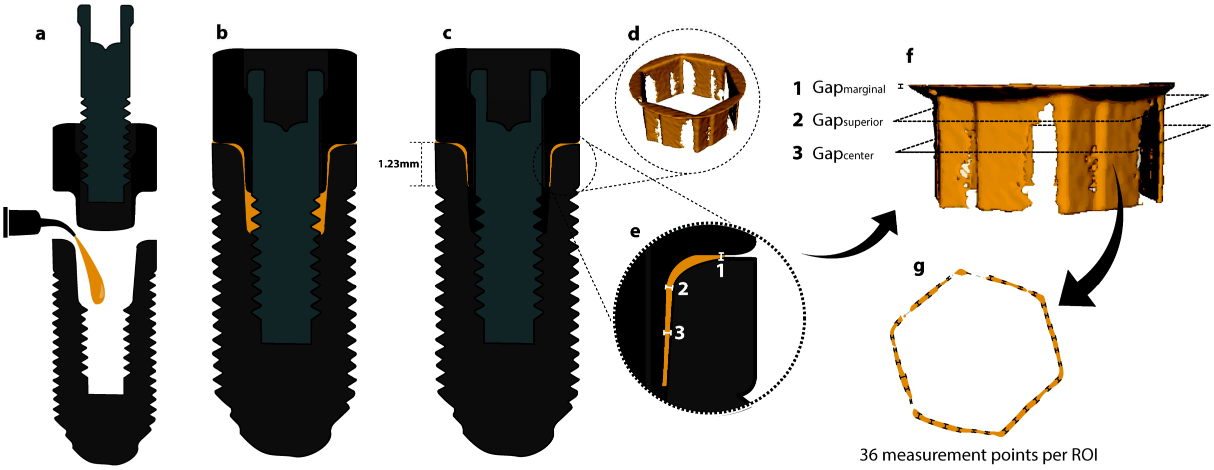


Figure 2. Schematic of the internal fit evaluation. (a) Silicone impression material inserted into the implant. (b,c) To obtain similar volumes for analysis across groups, the excess of impression material drawn into the screw hole was removed by means of Amira software and the ROI was defined by cropping the silicone replica image data at the equivalent height to the first implant thread (1.23 mm from the implant platform). (d) 3D reconstruction of the silicone replica. (e,f) ROIs for linear measurements. g) Section of replica specimen image data showing the predetermined equidistant measurement points per ROI.

Each replica specimen was scanned using a micro-computed tomography scanner (μCT 40; Scanco Medical). Five specimens at a time were placed in the sample holder. The instrument was operated at medium resolution (16 μm/slice) using 70 kVp (114 μA) resulting in approximately 380 slices per sample. All data were exported in a DICOM-format and imported into Amira software (Amira, version 5.5.2; VSG) for quantification of implant-abutment internal discrepancy, which was represented by the thickness of the medium-body polyvinyl siloxane. Three-dimensional (3D) rendering of the image set was performed using a standard "silicone mask" in Amira software. The same software was used to remove all silicone excess and define the region of interest (ROI) (Fig. 2C). To ensure that the replica specimens of different groups were all cut in an identical fashion and to obtain similar volumes for analysis, the ROI was defined by cropping the silicone replica image data at the equivalent height to the first implant thread (1.23 mm from the implant platform) (Fig. 2C). A uniform threshold for silicone was determined across all groups using the Otsu algorithm ROIs. The volume of misfit was calculated using the ‘’Material Statistics’’ software function after 3D reconstruction of the silicone replica (Fig. 2D).

The internal discrepancy was assessed by measuring the thickness of the silicone replica image data using 108 predetermined equidistant points that were divided into three different ROIs. $\text{Gap}_{\text{marginal}}$ was defined as the vertical distance between the points representing the implant platform and the abutment margin (36 measurements). $\text{Gap}_{\text{center}}$ was defined as the mean value of the 36 measurements in the middle part of the internal hexagon. $\text{Gap}_{\text{superior}}$ was defined as the mean value of the 36 measurements in the superior part of the internal hexagon (Fig. 2E-G).

The Shapiro-Wilk statistical test for normality and Levene test for homogeneity revealed normal distribution for data. Data from three-dimensional measurements (volume of misfit) were statistically evaluated through one-way analysis of variance (ANOVA) and data from two-dimensional measurements were statistically evaluated through two-way ANOVA with fixed factors of abutment fabrication method (Full-Digital, Ti-Base and UCLA) and region ($\text{Gap}_{\text{center}}$, $\text{Gap}_{\text{superior}}$ and $\text{Gap}_{\text{marginal}}$) following post-hoc comparisons by Tukey test. The level of significance was set at P=.05. Data are presented as a function of mean values with the corresponding 95% confidence interval (CI). Also, the Pearson correlation test was used to assess the association between the measurement methods used in this study for fit evaluation. All analyses were accomplished using SPSS (IBM SPSS 23; IBM Corp.).

RESULTS

Regarding to three-dimensional (3D) analysis, one-way ANOVA showed a significant difference between groups with respect to volume of misfit (F=32.086, P=.000) (Table 1). Tukey post hoc test showed that Ti-base and UCLA abutments presented significantly lower volume of misfit (0.49 mm^3, CI:±0.045 mm^3 and 0.48 mm^3, CI:±0.045 mm^3, respectively) relative to full digitalized workflow (0.70 mm^3, CI:±0.045 mm^3)(P=.000), without significant difference between each other (P=.825)(Fig. 3).

Table 1. One-way ANOVA was used to find any significant difference in the volume of misfit of studied groups. The level of significance was set at P<.05.

	Sum of Squares	*df*	Mean Square	*F*	Significance	Observed Power
Volume						
Between groups	9.296	1	9.296	32.086	0.000	1.0
Within group	0.307	2	0.154			1.0
Total	9.733	30				
R^2 = 0.704 (corrected R^2 = 0.682)						

Table 2. Two-way ANOVA was used to find any significant difference between the fixed factors fabrication method and region and their interactions. The level of significance was set at P<.05.

Source of Variation	Sum of Squares	*df*	Mean Square	*F*	Significance	Observed Power
Fabrication method	1494.613	2	747.306	10.006	0.000	1.0
Region	687.359	2	343.679	4.602	0.013	0.8
Fabrication method*Region	2760.858	4	690.215	9.241	0.000	1.0
Total	88570.054	90				
R^2 = 0.450 (corrected R^2 = 0.395)						

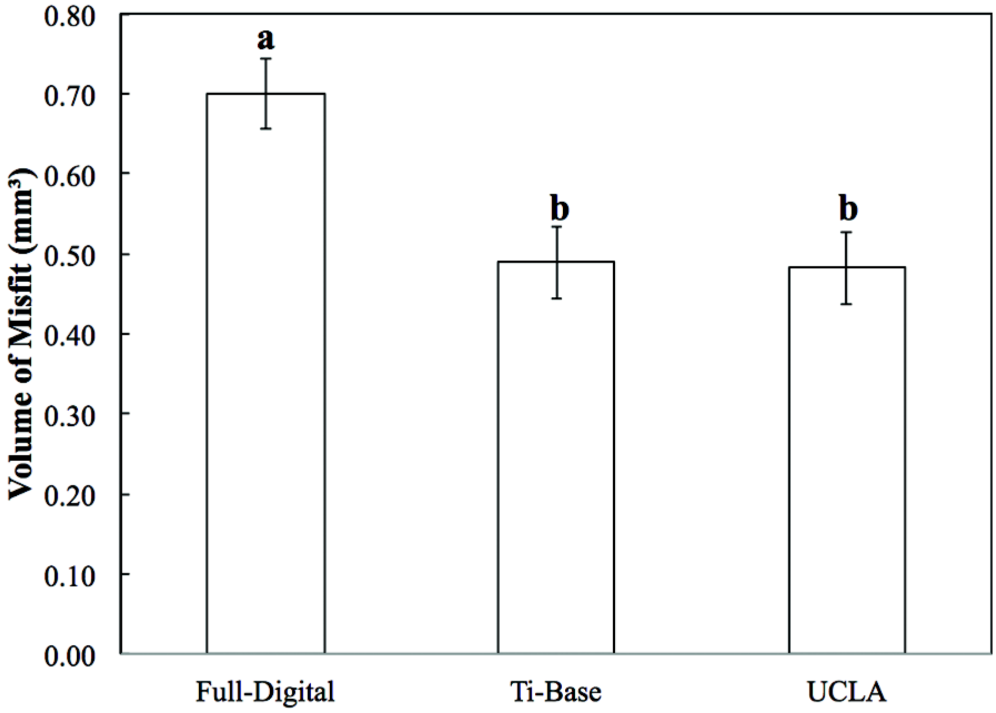


Figure 3. Misfit values from three-dimensional analysis as a function of mean and 95% confidence interval. Abutment fabrication method have influenced volume of misfit. Full-Digital presented higher volume of misfit compared to other groups. *Different letters indicate significant difference between groups (P<.05).

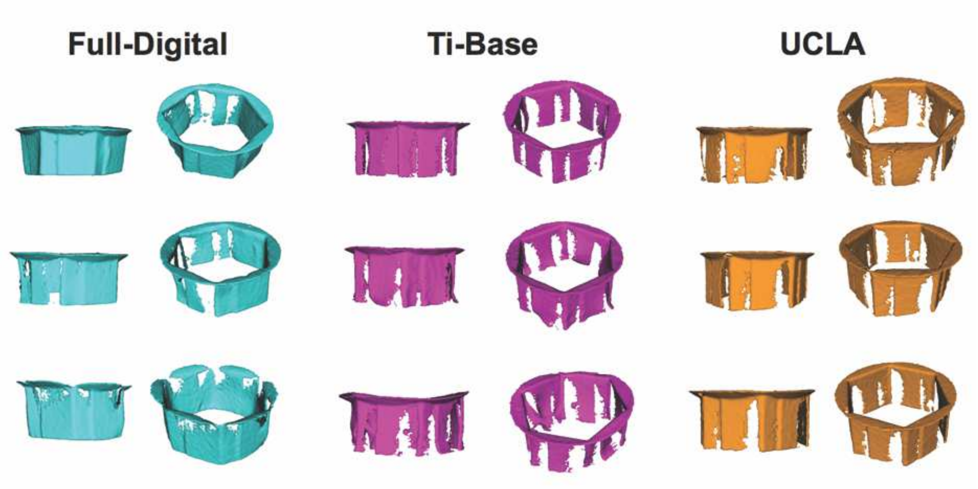


Figure 4. 3D reconstruction of three representative samples of each group showing presence of internal gaps and empty spaces (correspondent to gaps inferior to 1 μm).

Three-dimensional reconstruction of the silicone replica detected gap sized from 1 µm and above with good accuracy. Qualitative 3D image analysis of internal misfit at the implant-abutment interface depicted higher internal gaps for Full-Digital compared to Ti-Base and UCLA, which can be observed due to thicker silicone layer and fewer empty spaces (correspondent to gaps inferior to 1 µm) (Fig. 4).

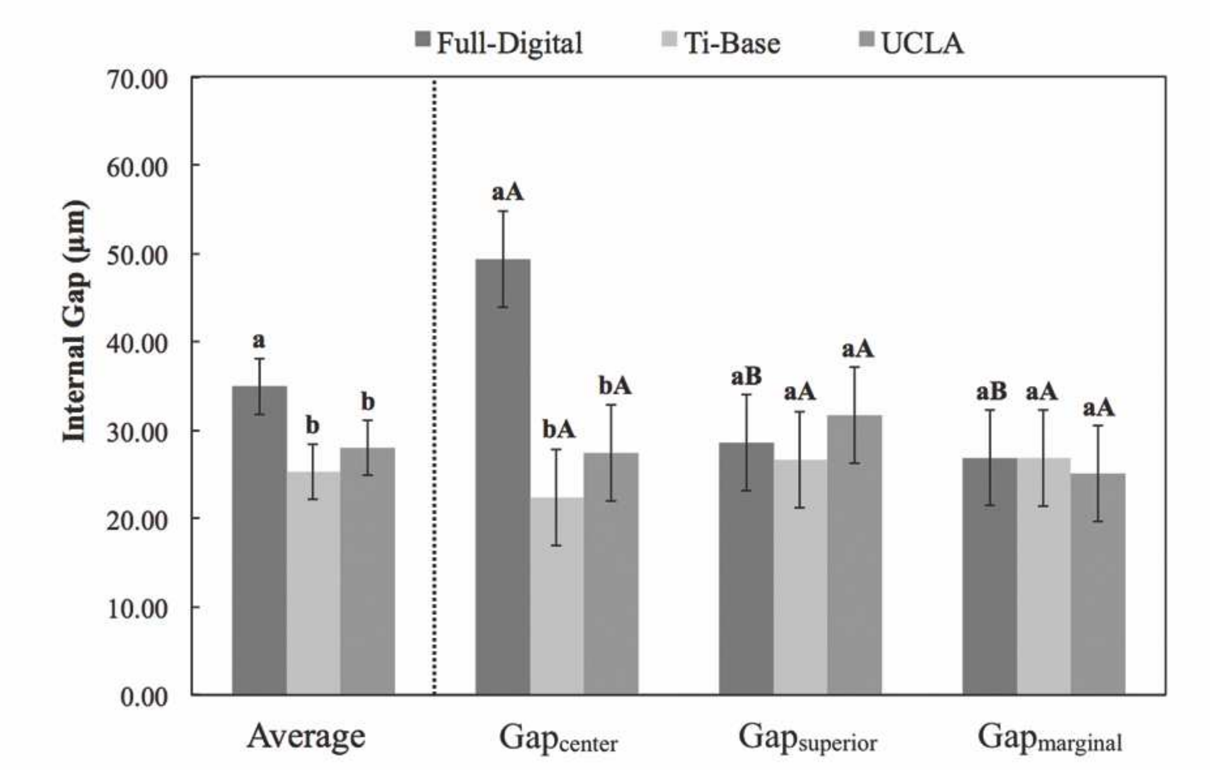


Figure 5. Misfit values from two-dimensional analysis as a function of mean and 95% confidence interval. The average internal gap values were calculated by the mean values of the three ROIs ($\text{Gap}_{\text{center}}$, $\text{Gap}_{\text{superior}}$ and $\text{Gap}_{\text{marginal}}$). Full-Digital group exhibited statistically higher average internal gap values compared to Ti-Base and UCLA groups. While $\text{Gap}_{\text{center}}$ was significantly higher for the abutments fabricated with the full-digitalized workflow, $\text{Gap}_{\text{superior}}$ and $\text{Gap}_{\text{marginal}}$ did not demonstrate significant differences among groups. All regions were statistically similar within groups, except for the $\text{Gap}_{\text{center}}$ in the Full-digital group that exhibited higher mean values compared to the other regions. *Different lowercase letters mean statistical difference between groups (P<.05). *Different uppercase letters mean statistical difference between regions within groups (P<.05).

Results from linear measurements of the internal discrepancy at the implant/abutment connection are shown in Figure 5. The factors ‘abutment fabrication method’ and ‘region’ and their interaction were statistically significant ($P<.05$) (Table 2). The pairwise comparison of different workflow was performed for each region of interest separately. The Full-Digital group exhibited the highest average internal gap (34.90 µm, CI:±3.14 µm), which was significantly different from the Ti-base and UCLA groups (25.21 µm, CI:±3.14 µm and 27.97 µm, CI:±3.14 µm, respectively)($P<.05$), which were not significantly different between each other ($P=.219$) (Fig. 5). Regarding to internal gap in the different ROIs, $\text{Gap}_{\text{center}}$ was significantly higher for the abutments fabricated with the full-digitalized workflow compared to the others ($P<.001$). $\text{Gap}_{\text{superior}}$ and $\text{Gap}_{\text{marginal}}$ did not demonstrate significant differences among groups ($P>.05$) (Fig. 5). All regions were statistically similar within groups, except for the $\text{Gap}_{\text{center}}$ in the Full-digital group that exhibited higher mean values compared to the other regions ($P<.001$).

The Pearson correlation coefficient value illustrated that there is a strong correlation between the two-dimensional and the three-dimensional gap measurements ($r=0.835$, $P<.001$).

DISCUSSION

The present study revealed that the abutment fabrication method influenced the internal fit at the implant-abutment interface. Additionally, the three-dimensional measurement for quantification of internal discrepancy was strongly correlated to two-dimensional measurements. Therefore, both null hypotheses were rejected.

Given the multifaceted and highly complex set of clinical scenarios, the ability of prefabricated abutments to meet these requirements is very limited. Hence, the rationale behind the selection of the abutments used in this study is based on the increasing need of custom abutments to attend such complex clinical sets. These allow the clinician to improve prostheses emergence profile, to customize cervical margins similar to the anatomy of a natural root, and to compensate for inadequate implant angulation. Such abutments are individually shaped according to the anatomical needs of the respective implant site.[14, 29, 30] Nowadays, besides the custom castable abutments fabricated through a conventional casting workflow, customized abutments can also be fabricated out of different materials such as metal alloys or ceramics by means of CAD/CAM manufacturing systems.[14, 30] Considering that the abutment/implant interface exerts remarkable influence on the future success and long-term stability of implant-supported rehabilitations, it becomes paramount to investigate the effect of different abutment fabrication methods on the internal fit at the implant-abutment connection.

The results of the present study revealed that abutments fabricated with fully digitalized workflow resulted in less favourable internal fit at the implant/abutment interface compared to Ti-Base and UCLA-type abutments, without significant differences between each other. This assertion is true for both the three-dimensional volume data and the two-dimensional data obtained by linear measurements. It is noteworthy that the qualitative findings of the three-dimensionally reconstructed images along with linear measurements of the internal discrepancies in the ROIs depicted that the $\text{Gap}_{\text{center}}$ was the main responsible for the statistically higher misfit values for Full-Digital group, since such region consisted of approximately a twofold increase in gap values compared to the other regions of interest ($\text{Gap}_{\text{superior}}$ and $\text{Gap}_{\text{marginal}}$ were statistically similar for all groups).

Possible explanations for the worse fit found in the Full-Digital group could be associated to several factors relative to the milling process, such as the wear of milling instruments, the change in the radius of the instruments during the milling procedure,[31] the incompatible size of the milling drill with the corresponding implant angles[32] and, more importantly, tolerances set in producing CAD/CAM screw-retained abutments/crowns, which can play a key role in the final fit.[21] Mobilio et al.[21] evaluated the marginal vertical fit along implant/abutment interface of a prefabricated abutment and three customized CAD/CAM screw-retained crowns with three different "tolerance" values. The results of such investigation demonstrated that reducing the tolerance of 10 microns lower than the manufacturer values is equal to increasing the attrition and, consequently, the vertical gap between the components.

The similarity between the misfit values of the Ti-Base and UCLA abutments can be explained by the well-controlled conditions in which such abutments were industrially produced. It is worthwhile to mention that, in the current study, UCLA abutments with metallic base were used and the customized wax patterns were milled in the CAD/CAM system followed by conventional casting procedures, which could contribute to the favorable internal fit depicted in this group. Previous investigations[11, 13] showed that prefabricated abutments, which include UCLA abutments with a CoCr base that are customized in a laboratory, are superior in adaptation to those cast from plastic burnout patterns. Conversely, Rismanchian et al.[20] found that premachined abutments exhibit smaller microgaps than those of Cast On and Castable abutments, and stated that the reasons for the increased microgap on the fitting surfaces of such abutments may be due to lack of after casting finishing and polishing procedures. Despite the controversies, finishing procedures of UCLA abutments should be standardized and refined by laboratories to avoid discrepancies in fit.[13]

In contrast to studies reporting data on marginal/internal gaps between two different surfaces, a volume of misfit (mm^3) at the implant/abutment interface was also measured in this study. Similarly, Lops et al.[33] calculated the volume of contact (mm^3) to investigate the accuracy of fit between an internal conical connection implant and prefabricated and CAD/CAM abutments, using a multisensored opto-mechanical coordinate measuring machine. In contrast to our results, lower mean values of volume of interference for the CAD/CAM abutments (0.108 mm^3) were found in comparison to the prefabricated abutments (0.134 mm^3). Although direct comparison is not feasible, given the different implant geometry and methodology used in such investigation, the authors emphasized the 3D measurement method as a more helpful approach compared to the 2D measurement for the comparison between different abutment groups.

From a technical standpoint, gaps between the implant and the abutment are inevitable in fitting the different parts. Such components cannot be accurately matched because of the precision limit during manufacturing process and therefore, some amount of microleakage will unavoidably occur regardless of the type of connection and the size of the microgaps.[7, 20, 34] Accordingly, the magnitude of these gaps and its clinical significance has been receiving significant attention[7, 9, 11, 12, 25, 35, 36] and different methodologies have been utilized for such investigation.[4, 5, 11, 21, 25, 27, 33, 35] The size of the microgap at implant/abutment connection has been reported as a wide range of 1 to 60 µm,[11, 13, 21, 37] and it is dependent, among other factors, on the implant system and the torque used to fix abutments.[7, 38] Although gaps from different magnitudes have been identified along with proportional levels of microleakage at different implant abutment configurations, it is important to bear in mind that no internal or external implant-abutment screwed connection has 100% bacterial seal.[39]

Several measuring analytical techniques for gap determination in implant-supported rehabilitations are described in the literature, which include measurement of the specimens by direct visualization under a microscope; or embedded and sectioned specimens and silicone replica analyzed under scanning electron microscopy (SEM),[19, 20] optical microscopy,[21] microtomography,[19, 27] travelling microscope,[13, 22] among others. Although such techniques are well established, most authors agree that these methodologies provide limited information,[33, 40, 41] and it is impossible to use these methods in vivo considering their destructive approach. Accordingly, with the development of digital technology, three-dimensional analysis methods has been explored, such as 3D nonlinear finite element analysis (FEA)[19] and microcomputed tomography.[19, 42] The three-dimensional measurement for quantification of internal discrepancy was strongly associated to the two-dimensional measurements. By using this technique we have demonstrated that microgaps up to 1 µm width could be measured in two and three dimensions; in the latter case, the microgaps at the implant/abutment interface could be reconstructed onto a three-dimensional rendering image, which can provide insight into the most critical areas of misfit. Oka et al.[41] proposed a methodology to evaluate the fitting accuracy of prostheses three-dimensionally (3D) using a combination of the silicone replica technique and µCT in comparison with a conventional 2D silicone replica method (stereomicroscopy) and demonstrated that 3D virtual images of the replica accurately reflected its real-life morphology.

Considering the lack of studies about the influence of different fabrication methods of abutments on the fit at the implant/abutment interface, this study showed that the fully digitalized workflow resulted in worse internal fit compared to the casting methods (UCLA) and Ti-Base abutments. It is important to mention that there is currently no international standard method for the adaptability evaluation between the implant body and abutments (ISO/NP 22683 under development). Future research to investigate the impact of gap sizes to biomechanical performance is warranted.

CONCLUSIONS

Within the limitations of this study, the following conclusions may be drawn:

- Prefabricated Ti-Base and UCLA-type abutments exhibited better internal fit at the implant/abutment connection compared to abutments fabricated through a full digitalized workflow (CAD-CAM custom abutments);
- The three-dimensional measurement (volume of misfit) for quantification of internal discrepancy was strongly associated to the two-dimensional measurements.

REFERENCES

1. Branemark PI, Adell R, Breine U, Hansson BO, Lindstrom J, Ohlsson A. Intra-osseous anchorage of dental prostheses. I. Experimental studies. Scand J Plast Reconstr Surg 1969;3:81-100.

2. Jung RE, Pjetursson BE, Glauser R, Zembic A, Zwahlen M, Lang NP. A systematic review of the 5-year survival and complication rates of implant-supported single crowns. Clin Oral Implants Res 2008;19:119-30.

3. Sailer I, Philipp A, Zembic A, Pjetursson BE, Hammerle CH, Zwahlen M. A systematic review of the performance of ceramic and metal implant abutments supporting fixed implant reconstructions. Clin Oral Implants Res 2009;20 Suppl 4:4-31.

4. al-Turki LE, Chai J, Lautenschlager EP, Hutten MC. Changes in prosthetic screw stability because of misfit of implant-supported prostheses. Int J Prosthodont 2002;15:38-42.

5. Binon PP. The effect of implant/abutment hexagonal misfit on screw joint stability. Int J Prosthodont 1996;9:149-60.

6. Alqutaibi AY, Aboalrejal AN. Microgap and Micromotion at the Implant Abutment Interface Cause Marginal Bone Loss Around Dental Implant but More Evidence is Needed. J Evid Based Dent Pract 2018;18:171-2.

7. Mishra SK, Chowdhary R, Kumari S. Microleakage at the Different Implant Abutment Interface: A Systematic Review. J Clin Diagn Res 2017;11:ZE10-ZE5.

8. Broggini N, McManus LM, Hermann JS, Medina R, Schenk RK, Buser D et al. Peri-implant inflammation defined by the implant-abutment interface. J Dent Res 2006;85:473-8.

9. Liu Y, Wang J. Influences of microgap and micromotion of implant-abutment interface on marginal bone loss around implant neck. Arch Oral Biol 2017;83:153-60.

10. Binon PP, McHugh MJ. The effect of eliminating implant/abutment rotational misfit on screw joint stability. Int J Prosthodont 1996;9:511-9.

11. Bondan JL, Oshima HM, Segundo RM, Shinkai RS, Mota EG, Meyer KR. Marginal fit analysis of premachined and castable UCLA abutments. Acta Odontol Latinoam 2009;22:139-42.

12. Kano SC, Bonfante G, Hussne R, Siqueira AF. Use of base metal casting alloys for implant framework: marginal accuracy analysis. J Appl Oral Sci 2004;12:337-43.

13. Byrne D, Houston F, Cleary R, Claffey N. The fit of cast and premachined implant abutments. J Prosthet Dent 1998;80:184-92.

14. Kurbad A, Kurbad S. CAD/CAM-based implant abutments. Int J Comput Dent 2013;16:125-41.

15. Silva CEP, Soares S, Machado CM, Bergamo ETP, Coelho PG, Witek L et al. Effect of CAD/CAM Abutment Height and Cement Type on the Retention of Zirconia Crowns. Implant Dent 2018;27:582-7.

16. Lopes ACO, Machado CM, Bonjardim LR, Bergamo ETP, Ramalho IS, Witek L et al. The Effect of CAD/CAM Crown Material and Cement Type on Retention to Implant Abutments. J Prosthodont 2018.

17. Pauletto N, Lahiffe BJ, Walton JN. Complications associated with excess cement around crowns on osseointegrated implants: a clinical report. Int J Oral Maxillofac Implants 1999;14:865-8.

18. Rodriguez LC, Saba JN, Chung KH, Wadhwani C, Rodrigues DC. In vitro effects of dental cements on hard and soft tissues associated with dental implants. J Prosthet Dent 2017;118:31-5.

19. Jorn D, Kohorst P, Besdo S, Borchers L, Stiesch M. Three-Dimensional Nonlinear Finite Element Analysis and Microcomputed Tomography Evaluation of Microgap Formation in a Dental Implant Under Oblique Loading. Int J Oral Maxillofac Implants 2016;31:e32-42.

20. Rismanchian M, Hatami M, Badrian H, Khalighinejad N, Goroohi H. Evaluation of microgap size and microbial leakage in the connection area of 4 abutments with Straumann (ITI) implant. J Oral Implantol 2012;38:677-85.

21. Mobilio N, Fasiol A, Franceschetti G, Catapano S. Marginal Vertical Fit along the Implant-Abutment Interface: A Microscope Qualitative Analysis. Dent J (Basel) 2016;4.

22. Soo S, Garriga-Majo D, Palmer RM, Curtis RV. The longitudinal accuracy of fit of titanium implant superstructures superplastically formed on investment models. Dent Mater 2004;20:269-76.

23. Contrepois M, Soenen A, Bartala M, Laviole O. Marginal adaptation of ceramic crowns: a systematic review. J Prosthet Dent 2013;110:447-54 e10.

24. Holmes JR, Bayne SC, Holland GA, Sulik WD. Considerations in measurement of marginal fit. J Prosthet Dent 1989;62:405-8.

25. Meleo D, Baggi L, Di Girolamo M, Di Carlo F, Pecci R, Bedini R. Fixture-abutment connection surface and micro-gap measurements by 3D micro-tomographic technique analysis. Ann Ist Super Sanita 2012;48:53-8.

26. Sui X, Wei H, Wang D, Han Y, Deng J, Wang Y et al. Experimental research on the relationship between fit accuracy and fracture resistance of zirconia abutments. J Dent 2014;42:1353-9.

27. Wiest W, Zabler S, Rack A, Fella C, Balles A, Nelson K et al. In situ microradioscopy and microtomography of fatigue-loaded dental two-piece implants. J Synchrotron Radiat 2015;22:1492-7.

28. Prasad R, Al-Kheraif AA. Three-dimensional accuracy of CAD/CAM titanium and ceramic superstructures for implant abutments using spiral scan microtomography. Int J Prosthodont 2013;26:451-7.

29. Jemt T. Customized titanium single-implant abutments: 2-year follow-up pilot study. Int J Prosthodont 1998;11:312-6.

30. Kapos T, Evans C. CAD/CAM technology for implant abutments, crowns, and superstructures. Int J Oral Maxillofac Implants 2014;29 Suppl:117-36.

31. Torabi Ardekani K, Ahangari AH, Farahi L. Marginal and internal fit of CAD/CAM and slip-cast made zirconia copings. J Dent Res Dent Clin Dent Prospects 2012;6:42-8.

32. Papadiochou S, Pissiotis AL. Marginal adaptation and CAD-CAM technology: A systematic review of restorative material and fabrication techniques. J Prosthet Dent 2018;119:545-51.

33. Lops D, Meneghello R, Sbricoli L, Savio G, Bressan E, Stellini E. Precision of the Connection Between Implant and Standard or Computer-Aided Design/Computer-Aided Manufacturing Abutments: A Novel Evaluation Method. Int J Oral Maxillofac Implants 2018;33:23-30.

34. Alves DCC, de Carvalho PSP, Elias CN, Vedovatto E, Martinez EF. In vitro analysis of the microbiological sealing of tapered implants after mechanical cycling. Clin Oral Investig 2016;20:2437-45.

35. Coelho AL, Suzuki M, Dibart S, N DAS, Coelho PG. Cross-sectional analysis of the implant-abutment interface. J Oral Rehabil 2007;34:508-16.

36. Lorenzoni FC, Coelho PG, Bonfante G, Carvalho RM, Silva NR, Suzuki M et al. Sealing Capability and SEM Observation of the Implant-Abutment Interface. Int J Dent 2011;2011:864183.

37. Tsuge T, Hagiwara Y, Matsumura H. Marginal fit and microgaps of implant-abutment interface with internal anti-rotation configuration. Dent Mater J 2008;27:29-34.

38. Baggi L, Di Girolamo M, Mirisola C, Calcaterra R. Microbiological evaluation of bacterial and mycotic seal in implant systems with different implant-abutment interfaces and closing torque values. Implant Dent 2013;22:344-50.

39. Schmitt CM, Nogueira-Filho G, Tenenbaum HC, Lai JY, Brito C, Doring H et al. Performance of conical abutment (Morse Taper) connection implants: a systematic review. J Biomed Mater Res A 2014;102:552-74.

40. Kim MJ, Choi YJ, Kim SK, Heo SJ, Koak JY. Marginal Accuracy and Internal Fit of 3-D Printing Laser-Sintered Co-Cr Alloy Copings. Materials (Basel) 2017;10.

41. Oka Y, Sasaki J, Wakabayashi K, Nakano Y, Okamura SY, Nakamura T et al. Fabrication of a radiopaque fit-testing material to evaluate the three-dimensional accuracy of dental prostheses. Dent Mater 2016;32:921-8.

42. Moris ICM, Monteiro SB, Martins R, Ribeiro RF, Gomes EA. Influence of Manufacturing Methods of Implant-Supported Crowns on External and Internal Marginal Fit: A Micro-CT Analysis. Biomed Res Int 2018;2018:5049605.

2.2 ARTICLE 2

Implant-abutment fit influences the mechanical performance of single-crow prostheses

ABSTRACT

Objectives. To evaluate the three-dimensional fit of abutments fabricated by the industry to those either milled or cast by a commercial laboratory and to correlate the implant-abutment connection fit with stress at fatigue failure of prostheses. Probability of survival (reliability) and fractography to characterize failure modes were also performed for cemented and screw-retained prostheses.

Methods. One-hundred and twenty-six maxillary central incisor crowns were milled to restore implants and divided in 3 cemented and 3 screwed-retained groups (n=21/each), as follows: [Digital-Sc]: milled one-piece monolithic abutment/crown; [TiB-Sc]: milled crowns cemented onto Ti-base abutments; [UCLA]: screw-retained crown using UCLA abutments; [Digital-Ce]: milled two-piece assembly comprised by screwed monolithic abutment and a cemented crown; [TiB-Ce]: milled coping cemented onto Ti-base abutments to receive a cemented crown; [UCLA-Ce]: UCLA abutments that received an overcast coping and a cemented crown. Implant-abutment volume misfit was assessed by micro-computed tomography using the silicone replica technique. Implant/crown systems were subjected to step-stress accelerated life testing (SSALT) in water. The use-level probability Weibull curves and reliability for a mission of 50,000 cycles at calculated stress at failure of 2,300, 3,300 and 4,300 MPa were plotted. Fractographic analysis was performed with scanning electron microscopy. Internal misfit was analyzed through one-way ANOVA following post-hoc comparisons by Tukey test (*P*<0.05). Correlation between misfit volume and the stress at fatigue failure was assessed by Pearson test.

Results. Similar misfit volumes were observed for TiB-Sc (0.458 mm^3), TiB-Ce (0.461 mm^3), UCLA (0.471 mm^3) and UCLA-Ce (0.480 mm^3), which were significantly lower than Digital-Sc (0.676 mm^3) and Digital-Ce (0.633 mm^3). The mean β values were: 1.68, 1.39, 1.48, 2.41, 2.27 and 0.71 for Digital-Sc, TiB-Sc, UCLA, Digital-Ce, TiB-Ce and UCLA-Ce, respectively, indicating that fatigue was an accelerating factor for failure of all groups, except for UCLA-Ce. Higher stress at failure decreased the reliability of all groups, more significantly for screw compared to cement-retained groups, especially for Digital-Sc that demonstrated the lowest reliability. The failure mode was restricted to abutment screw fracture. A negative correlation was observed between misfit values and stress at failure ($r = -0.302$, $P=0.01$).

Conclusions. Abutments milled by a commercial lab presented higher misfit compared to those provided by the industry and a moderate correlation was observed between higher misfit and lower stress at failure during fatigue. Probability of survival decreased at higher stress, especially for screw compared to cement-retained groups, and failures were confined to abutment screws.

INTRODUCTION

Although high success rates are commonly reported for implant-supported prostheses,[1, 2] the less common report of cumulative survival rates suggest that success may be actually lower than reported and is therefore inflated.[3] Because complication rates increase over time,[4] indicating that the fatigue damage accumulation degrades prostheses strength, it is important to acknowledge that technical complications in implant dentistry are very common and the importance of their characterization in preclinical studies has been increasingly valued.[5, 6] According to a systematic review and meta-analysis, the most common complication is abutment screw fracture, with a cumulative rate of 10.4% in 5 years and a twofold increase to 20.4% in 10 years.[7] Such findings emphasize that treatment with implants, despite its advantages, should predict complications, additional time and cost for maintenance.[2]

The implant/abutment connection is one of the most important factors for prostheses stability.[8] Therefore, the selection of restorative components must be considered a paramount factor for long-term clinical success.[9] For improved performance, it is important that abutments present the best fit at the implant connection,[10] since higher values of misfit between such components may increase mechanical stress on connection structures and surrounding tissues, which may cause not only mechanical problems,[11, 12] such as screw preload loss or screw fracture, but also to biologic issues due to the bacterial contamination eventually participating in the multifactorial role of peri-implant tissue inflammation.[13-16]

Several 'prefabricated' or 'stock' abutments are available in the market, which vary in indication and design. Although the claimed best fit of stock abutments provided by the industry, which demand approval by regulatory agencies, their customization may be limited considering each patient's difference in peri-implant soft tissue emergence profile and prosthetic needs. Opportunities for individualization include the use of custom-made abutments fabricated through either a conventional casting procedure using universal casting long abutments (UCLA) or through a digital workflow. In the latter, two customization options are available: 1) not only the crown but also the entire abutment, may be designed and milled in a commercial laboratory (full digital lab fabrication process) by using the computer-aided design/computer-aided manufacturing (CAD/CAM) system (currently feasible for external or internal non-conical connections); or 2) an industrially manufactured abutment system (Ti-base) with libraries inserted in CAD/CAM systems receives custom CAD/CAM restoration fabricated by a commercial laboratory (final crown or custom core).

The benefits of employing a fully digital laboratory fabrication process for abutments and prostheses include customization and rapid chair-side or commercial laboratory fabrication regardless of industry abutment availability; however, the internal fit of such abutments is roughly dependent on several variables involved in the accuracy of milling of the CAD/CAM systems unit and the selected milling strategy. Also of concern is the fact that milling of abutments by commercial labs is not yet controlled by international standards or norms, as it is for industry-provided prefabricated abutments, which undergo standard quality assurance and quality control evaluation. A potential workaround has been recently introduced where industry-fabricated Ti-base abutments and their inclusion in CAD/CAM libraries allow the rapid fabrication of either a customized milled core (e.g: zirconia) or of the crown by commercial laboratories. This concept is based on a titanium connector featuring a female component that connects to the implant well and a external configuration with geometry available for insertion in most CAD/CAM systems where monolithic or bilayered restorations of any given material can be cemented chairside.[17-19] The main advantage and rationale for use of Ti-base abutments comprise the maintenance of industry provided fit of the female part, in contrast to UCLA abutments where overcasting and post processing (e.g. aluminum oxide blasting) change the titanium surface topography and fit.[20] Also, retrievablity is maintained when cementing the final prostheses directly to Ti-base since CAD/CAM blocks provided with screw access holes are used allowing extra-oral bonding and excess cement removal, which seems advantageous to reduce chances of potential cementation induced peri-implantitis.[21]

Along with the plethora of implant restorative components available, the fixation modes of the implant-supported restoration can be either screwed, cemented, or a combination of both. There is a rich literature on the advantages and disadvantages of each prosthesis retention systems.[22-29] A current consensus has been published [29] and, in general, the clinical recommendations for screw retention include: implants placed in a prosthetically ideal position, with the presence of minimal interarch space (4 mm); FDPs (fixed dental prostheses) with a cantilever design; long-span FDPs; in esthetic areas, where provisionalization of implants is required to enable soft tissue conditioning and emergence profile improvement or when retrievability is desired. Also, the cement retention is recommended in the following situations: for short-span prostheses with margins at or above the mucosa level, to compensate for improperly inclined implants, for cases where an easier control of occlusion without an access hole is desired (e.g. narrow-diameter crowns).[29] Although less technical complications of cement-retained relative to screw-retained crowns has been reported[30], the performance of hybrid systems that combine extra-orally cemented and screw-retained crowns warrants investigation.

Considering the increased use of customizable abutments in restorative dentistry and given that, once under function in the mouth, any restorative system's strength will degrade over time due to fatigue damage accumulation, the characterization of the internal fit at the implant/abutment connection of abutments fabricated by a commercial laboratory (milled or cast) compared to abutments provided by the industry, as well as the impact of misfit levels on the mechanical performance of prostheses still requires investigation. Therefore, the objective of this study was to evaluate the three-dimensional fit of abutments fabricated by the industry to those either milled or cast by a commercial laboratory and to correlate the implant-abutment connection misfit with stress at fatigue failure of prostheses. Probability of survival (reliability) and fractography to characterize failure modes were also performed for cemented and screw-retained prostheses. The null postulated hypotheses were: (i) the fabrication process of implant-supported prostheses has no influence on the internal misfit at the implant-abutment connection; (ii) the abutment fabrication method and crown fixation mode have no influence on the reliability; (iii) the internal misfit at the implant abutment interface has no influence on the stress at fatigue failure.

MATERIAL AND METHODS

Specimen preparation

One-hundred and twenty-six maxillary central incisor crowns were milled to restore implants and divided in 3 cemented and 3 screwed-retained groups (n=21/each), as follows: [Digital-Sc]: milled one-piece monolithic abutment/crown; [TiB-Sc]: milled crowns cemented onto Ti-base abutments; [UCLA]: screw-retained crown using UCLA abutments; [Digital-Ce]: milled two-piece assembly comprised by screwed monolithic abutment and a cemented crown; [TiB-Ce]: milled coping cemented onto Ti-base abutments to receive a cemented crown; [UCLA-Ce]: UCLA abutments that received an overcast coping and cemented crown (Table 1 and Figure 1).

Table 1. Detailed description of the groups used in this study.

Fixation Mode	Group	Fabrication Method	Description	Specification
Screwed (Sc)	**Digital-Sc**	**Fully Digital**	One-piece monolithic abutment and crown produced by CAD/CAM and screw-retained to the implants. The implant geometry previously stored in the CAD software was used to design the one-piece assembly, which were then milled using CoCr discs.	**CAD software** (Ceramill® mind, Amann Girrbach) **CoCr discs** (Ceramill sintron®, Amann Girrbach) **Ti-Base** (non-rotational Ti-Base, Colosso, Emfils, Itu, Brazil) **Resin cement** (RelyX™ Ultimate Adhesive Resin Cement, 3M) **Universal adhesive** (Scotchbond Universal, 3M) **Wax discs** (Ceramill® wax, Amann Girrbach, Curitiba, Brazil) **UCLA-Type abutments** (Castable non-rotational in CoCr base with plastic sleeve abutment, Colosso, Emfils, Itu, Brazil) **Temporary cement** (RelyX Temp® 3M Oral Care)
	TiB-Sc	**Partial Digital**	CAD/CAM produced crowns directly cemented onto prefabricated Ti-base abutments. The Ti-Base geometry previously stored in the CAD software was used to design the crowns, which were milled using CoCr discs and cemented onto Ti-Base abutment using a resin cement with universal adhesive for treatment of titanium substrates.	
	UCLA	**Conventional**	Screw-retained crown using custom-cast abutments (UCLA). For standardized crown anatomy, they were designed in the same CAD software and milled in wax pattern followed by conventional casting procedures using UCLA-Type abutments.	
Cemented (Ce)	**Digital-Ce**	**Fully Digital**	Two-piece assembly comprised by monolithic abutment produced by CAD/CAM and screwed to the implants to receive a cemented crown. The same CAD software was used to design the abutment and crown, which were milled using CoCr discs. CAD/CAM crowns were cemented onto digital abutments with a temporary cement.	
	TiB-Ce	**Partial Digital**	Coping produced by CAD/CAM system and cemented onto prefabricated standard Ti-Base abutments to receive a cemented crown. The Ti-Base geometry previously stored in the CAD software was used to design the copings, which were milled using CoCr discs and cemented onto Ti-Base abutment using a resin cement with universal adhesive for treatment of titanium substrates. CAD/CAM crowns were cemented onto abutments with a temporary cement.	
	UCLA-Ce	**Conventional**	Screw-retained abutment using custom-cast abutments (UCLA) to receive a cemented crown. For standardized abutment anatomy, they were designed in the same CAD software and milled in wax pattern followed by conventional casting procedures using UCLA-Type abutments. Crowns were cemented onto abutments with a temporary cement.	

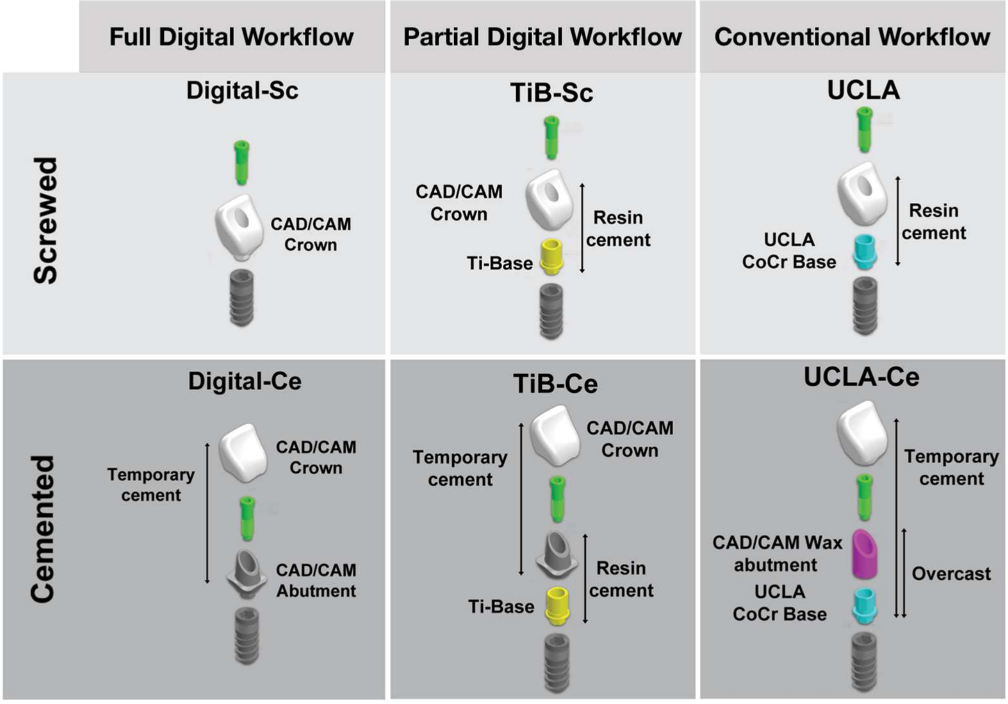


Fig. 1. Schematic diagram of experimental groups according to the abutment fabrication methods and crown fixation modes.

Prior to experimental tests, all implants were vertically embedded in an acrylic resin (Orthoresin, Degudent, Hanau-Wolfgang, Germany) and plastic tube (Ø25 mm x 35 mm) with the implant's platform positioned at the potting surface.

3-Dimensional misfit evaluation

Volume measurements were performed by one direct and another indirect micro-computed tomography scanning (μCT) technique to assess the internal misfit at the implant-abutment connection. First, direct volume scanning was performed for a single implant-abutment assembly of each group (μCT SkyScan 1272, Bruker, Belgium). Because of the low time-cost effectiveness of direct μCT scanning of metallic interfaces, an impression of the implant-abutment connection was made for μCT scanning comparison by means of the silicone replica technique. The implants were filled with a regular-body consistency polyvinyl-siloxane impression material (Express^{TM} XT Regular Body, 3M Oral Care, St. Paul, MN, USA) and the abutments were then torqued as per manufacturer's instructions (32 N.cm) using a digital torque gauge (Tohnichi BTG150CN-S, Tohnichi America, Northbrook, USA). After impression material setting, the abutment was untightened and carefully removed from the implant while the thin polyvinyl siloxane film remained in the inner surface of the implant. Then, the polyvinyl siloxane film was gently removed from the implant well. To avoid distortion of the replica specimen, the excess impression material drawn into the screw hole was not eliminated.

Each replica specimen was scanned using a µCT scanner (µCT 40, Scanco Medical, Basserdorf, Switzerland). Five specimens at a time were placed in the sample holder. The instrument was operated at medium resolution (16 µm/slice) using 70 kVp (114 µA) resulting in approximately 380 slices per sample. All data were exported in a DICOM-format and imported into Amira software (Amira, version 5.5.2, VSG, Burlington, MA, USA) for quantification of implant-abutment internal discrepancy, which was represented by the thickness of the regular-body polyvinyl siloxane. Three-dimensional (3D) rendering of the image set was performed using a standard “silicone mask” in Amira software. The same software was used to remove all silicone excess and define the region of interest (ROI). To ensure that the replica specimens of different groups and those directly scanned were all measured equally, the same ROI was defined by cropping the silicone replica image data at the equivalent height to the first implant thread (1.23 mm from the implant platform). A uniform threshold for silicone was determined across all groups using the Otsu algorithm ROIs. The volume of misfit was calculated using the ‘‘Material Statistics’’ software function after 3D reconstruction of the silicone replica.

Mechanical testing and reliability analysis

To design the profiles for the step-stress accelerated life testing (SSALT), three specimens of each group underwent single load-to failure (SLF) testing [6] in a universal testing machine (Model 5566, Instron, Norwood, MA, USA) equipped with a 10-kN load cell. A uniaxial compression load was applied at the incisal edge of the crown using a flat tungsten carbide indenter (r=3.18 mm), 30° off-axis at a crosshead speed of 1 mm/min following the ISO 14801:2007 (Dentistry-Implants-Dynamic fatigue test for endosseous dental implants). [6, 31-35]

Based on the mean load to failure from SLF results, the remaining 18 specimens of each group were randomly distributed into three step-stress profiles as follows: mild (n = 9), moderate (n = 6), and aggressive (n = 3) (aspect ratio distribution 3:2:1, respectively).[6] Such profiles refer to the increasingly step-wise rapidness in which a specimen is fatigued to reach a certain level of load, meaning that specimens assigned to a mild profile will be cycled longer to reach the same load of a specimen assigned to either moderate or aggressive profiles. A servo-all-electric system (TestResources 800L, Shakopee, MN, USA) was used for SSALT under water (load orientation and indenter as in SLF test) at 9 Hz. All specimens were subjected to fatigue until failure (fracture or bending of the abutment or implant), or suspension (no failure at the maximum 900 N load level). [6, 31-35]

Bending moment (M) and stress (σ) values were calculated as follows:

$$M = y \times F \qquad (1)$$

Where y is the moment arm, defined as l x sin θ (for most dental setting tests θ=30°), where l is the distance from the center of the crown to the clamping plane. Since force is expressed in N, bending moment is typically reported in N·mm. For determination of stress leading to failure (MPa), subsequent calculation included:

$$\sigma_{Stress} = \frac{My}{I}, \tag{2}$$

where M represents the bending moment, y is the perpendicular distance from the center of the inertia moment and I is the area moment of inertia, described by the area of the screw cross-section as:

$$I_{circle} = \frac{\pi.d^4}{64} \tag{3}$$

where d is the circle diameter.

Findings were recorded as stress, number of cycles, and step-stress profile in which the specimen failed during accelerated life testing for the reliability calculations.

Use-level probability Weibull curves (probability of failure versus number of cycles) using a cumulative damage and power law relationship were calculated (Alta Pro 7; Reliasoft, Tucson, AZ, USA) with use stress of 3300 MPa. The reliability (the probability of an item functioning for a given amount of time without failure) for completion of a mission of 50,000 cycles (using 90% two-sided confidence intervals) at 2300, 3300 and 4300MPa was determined for group comparisons. The use level probability Weibull analysis provides the beta (β) value, which describes the failure rate behavior over time. Beta value lower than 1 (β<1) indicates that the failure rate decreases over time and is associated with “early failures” or failures related to egregious flaws; β value approximately 1 (β~1) determines that failure rate does not vary over time and is associated with failures of a random nature; and, β higher than 1 (β>1) means that failure rate increases over time and is linked to fatigue damage. As per β<1 for one tested group, a probability Weibull 2-parameter contour plot (Weibull modulus [*m*] vs characteristic stress [η]) was calculated using final stress to failure or survival of groups (90% confidence intervals).[6, 36]

Failure mode analyses

Failed specimens were first inspected in a polarized-light stereomicroscope (MZ-APO Stereomicroscope, Leica Micro Imaging, Thornwood, NY, USA) to analyze and classify the modes of failure. Most representative failed samples were also imaged under a scanning electron microscope (SEM) (Hitachi S-3500, Hitachi Instruments, Tokyo, Japan) for qualitative fractography.

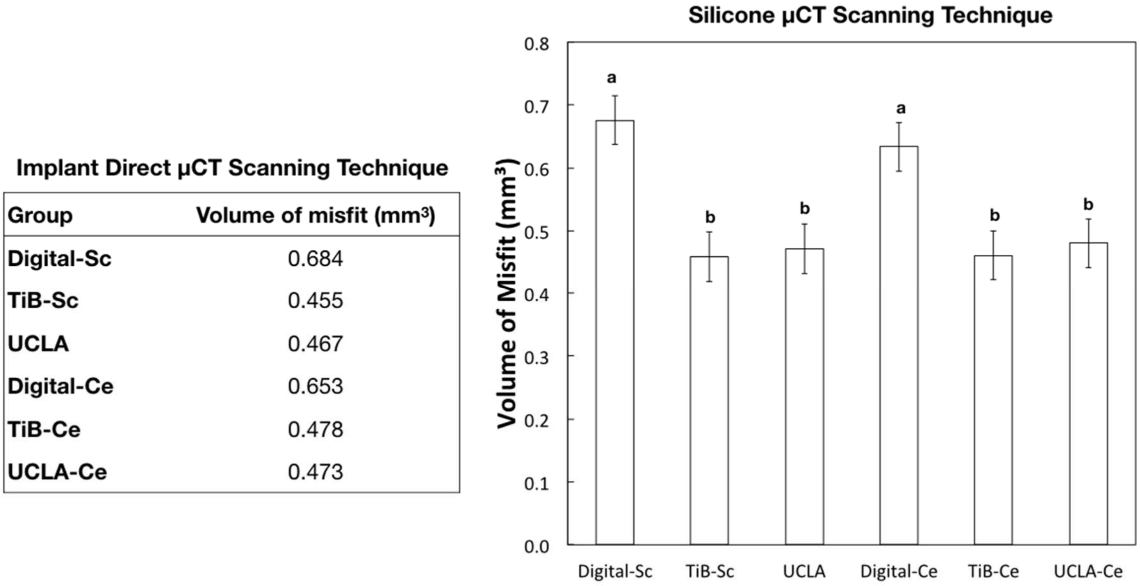
The statistical analyses from internal fit evaluation and fatigue load to failure were accomplished using SPSS (IBM SPSS 23, IBM Corp., Armonk, NY). Shapiro-Wilk statistical test for normality revealed normal distribution for data ($P>0.05$), which were statistically evaluated through one-way analysis of variance (ANOVA) following post-hoc comparisons by Tukey test. The level of significance was set at $P=0.05$ and data are presented as a function of mean values with the corresponding 95% confidence interval (CI). Also, the Pearson correlation test was used to assess the association between the volume of misfit at the implant-abutment interface and the load in which the specimens failed.

RESULTS

Fit evaluation

Regarding three-dimensional (3D) analysis of the internal fit at the implant-abutment interface, one-way ANOVA revealed that there was a statistically significant difference in volume of misfit between the different abutment fabrication methods (F=24.81, $P=0.000$). Results from post-hoc comparisons showed that TiB-Sc (0.458 mm^3, CI:0.039 mm^3), TiB-Ce (0.461 mm^3, CI:0.039 mm^3), UCLA (0.471 mm^3, CI:0.039 mm^3) and UCLA-Ce (0.480 mm^3, CI:0.039 mm^3) groups presented similar volume of misfit (all, $P>0.438$), which were significantly lower than Digital-Sc (0.676

mm^3, CI:0.039 mm^3) and Digital-Ce (0.633 mm^3, CI:0.039 mm^3)(not significantly different from each other, *P*=0.646)(Figure 2). Qualitative 3D image analysis and quantitative data from the direct and indirect μCT scanning techniques depicted similar results of internal misfit at the implant-abutment interface (Figure 2 and 3). It was observed higher internal gaps for groups produced with a full digital lab fabrication process (Digital-Sc and Digital-Ce) compared to a hybrid fabrication process (TiB-Sc and TiB-Ce) and a conventional (UCLA and UCLA-Ce) workflow, which can be observed due to thicker silicone layer and fewer empty spaces (correspondent to gaps inferior to 1 μm) (Figure 3).



Implant Direct μCT Scanning Technique

Group	Volume of misfit (mm³)
Digital-Sc	0.684
TiB-Sc	0.455
UCLA	0.467
Digital-Ce	0.653
TiB-Ce	0.478
UCLA-Ce	0.473

Fig. 2. Quantitative data from the direct and indirect Silicone μCT scanning techniques showing similar results of internal misfit at the implant-abutment interface. Column graphs showing misfit values as a function of mean and 95% confidence interval. Implant-retained prostheses fabrication methods have influenced the volume of misfit at the implant-abutment interface. *Different letters indicate significant difference between groups (P<0.05).

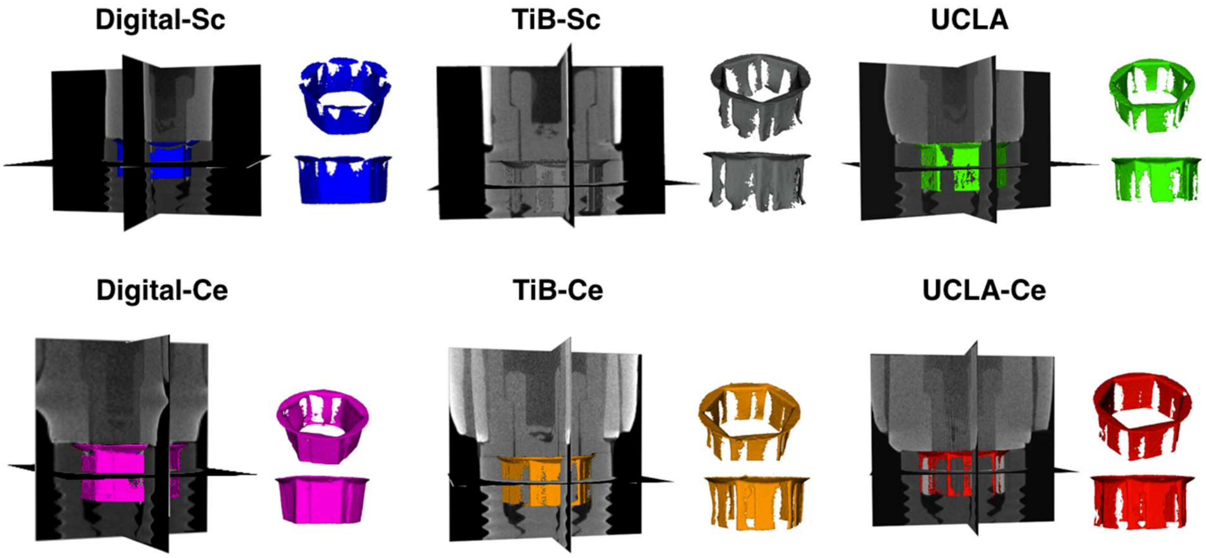


Fig. 3. Comparative images of the 3D reconstruction of one representative sample per group - from the direct and indirect silicone µCT scanning techniques - showing the presence of internal gaps and empty spaces (correspondent to gaps inferior to 1 µm).

Reliability analysis

All samples failed after SSALT. The failure mode was similar for all groups, restricted to abutment screw. The use level probability Weibull (90% confidence bounds) showing the probability of failure vs. number of cycles at 3300 MPa of set stress is presented in Figure 4. The mean β values (confidence interval range) derived from use level probability Weibull calculation were: 1.68 (1.13-2.49) for Digital-Sc, 1.39 (0.93-2.07) for TiB-Sc, 1.48 (0.89-2.46) for UCLA, 2.41 (1.64-3.53) for Digital-Ce, 2.27 (1.56-3.31) for TiB-Ce and 0.71 (0.41-1.23) for UCLA-Ce (Table 2). Except for the latter, such values indicated that for all groups, failure rate increases over time, associated with fatigue damage accumulation. For UCLA-Ce, failure is commonly associated with "early failures" or failures that occur due to egregious flaws.

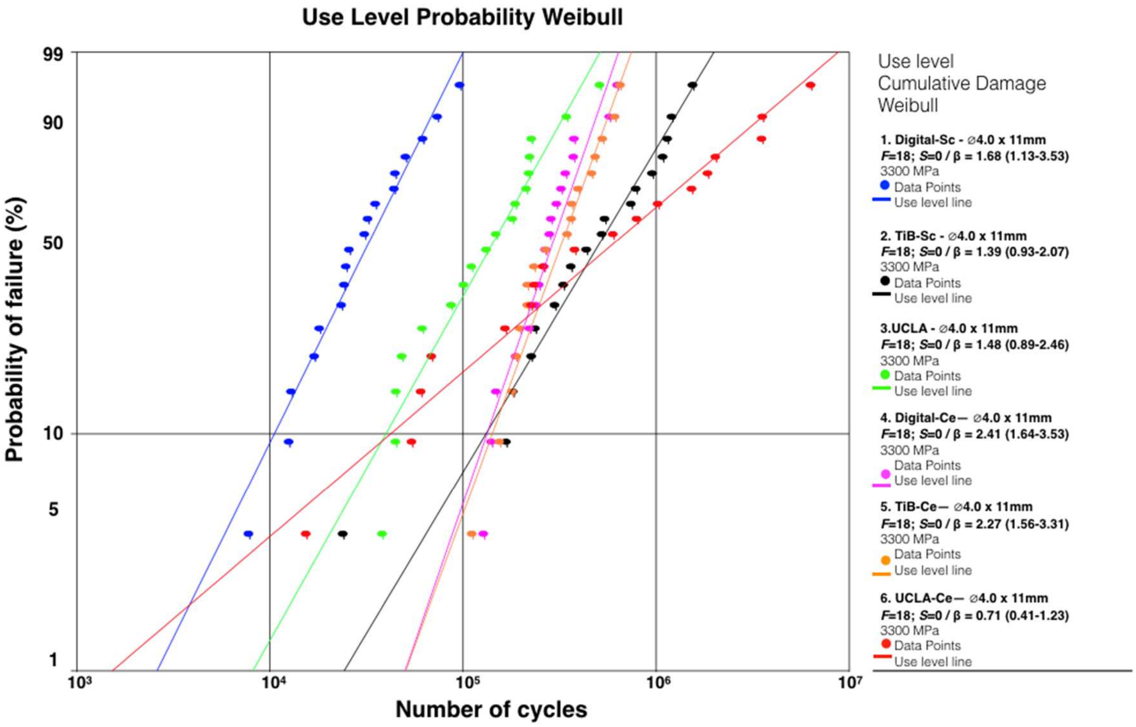
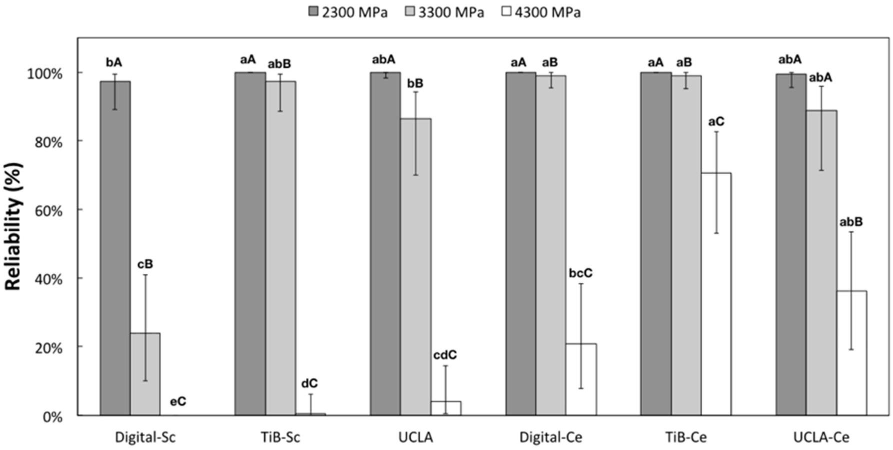


Fig. 4. Use level probability Weibull (90% confidence interval) showing the probability of failure versus time at 3300 MPa of set stress.

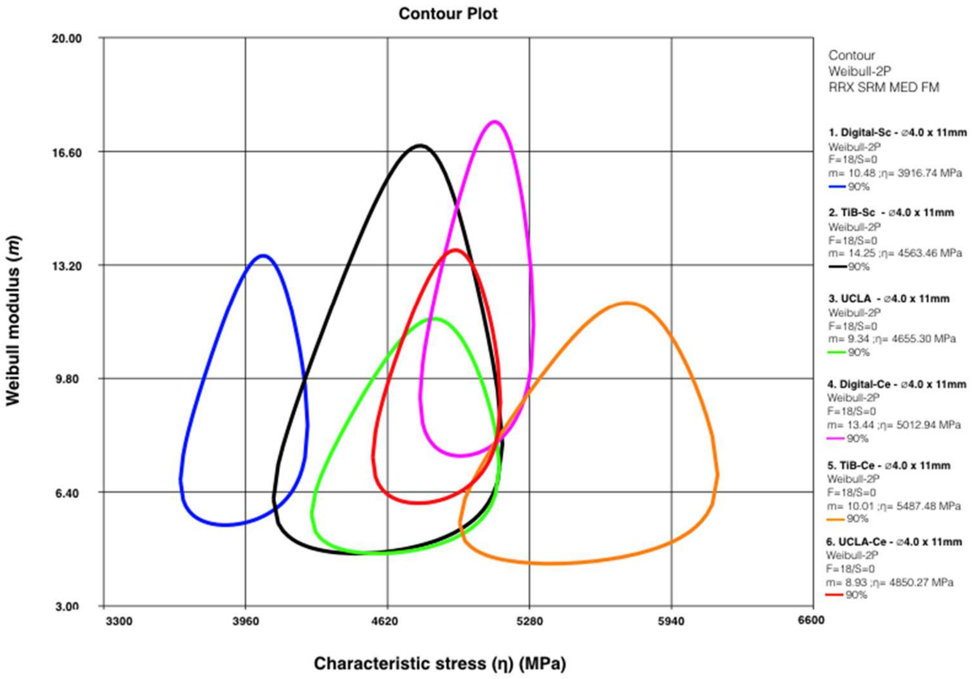
The calculated reliability (probability of the implant-supported incisor operating for a given amount of time without failure) with 90% confidence intervals for a mission of 50,000 cycles at 2300, 3300 and 4300 MPa are shown in Figure 5. At 2300 MPa, all groups showed high reliability (above 97%), with Digital-Sc (97.32%) presenting the lowest values (statistically similar to UCLA-Ce). While all groups kept their survivability higher than 86% at a set stress of 3300 MPa, a significantly reduced reliability was demonstrated by Digital-Sc (~24%). An increase in stress to 4300 MPa significantly decreased the reliability to 0%, 0.49% and 4.12% for screwed groups (Digital-Sc, TiB-Sc and UCLA, respectively) and 20.93%, 70.68% and 36.08% for cemented groups (Digital-Ce, TiB-Ce and UCLA-Ce, respectively) with statistically lower and higher survival for Digital-Sc and TiB-Ce, respectively, compared to all other groups (without difference between TiB-Ce and UCLA-Ce). At such stress scenario, the pairwise comparisons between cemented and screwed crowns presenting the same fabrication method depicted that the cemented systems always presented higher reliability than screwed ones.

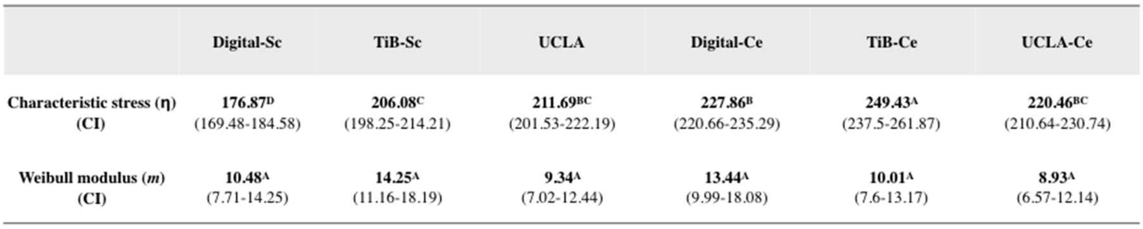


	Digital-Sc			TiB-Sc			UCLA			Digital-Ce			TiB-Ce			UCLA-Ce		
	Lower Bound	**Reliability**	**Upper Bound**	**Lower Bound**	**Reliability**	**Upper Bound**	**Lower Bound**	**Reliability**	**Upper Bound**	**Lower Bound**	**Reliability**	**Upper Bound**	**Lower Bound**	**Reliability**	**Upper Bound**	**Lower Bound**	**Reliability**	**Upper Bound**
2300 MPa	89.10	**97.32**^{bA}	99.36	99.92	**100**^{aA}	100	98.31	**99.78**^{abA}	99.97	99.97	**100**^{aA}	100	99.83	**99.99**^{aA}	100	95.51	**99.37**^{abA}	99.91
3300 MPa	10.07	**23.87**^{cB}	40.91	88.59	**97.29**^{abB}	99.38	70.02	**86.35**^{bB}	94.13	95.33	**99.01**^{aB}	99.79	95.16	**99.02**^{aB}	99.8	71.39	**88.81**^{abA}	95.91
4300 MPa	0	**0**^{eC}	0	0	**0.49**^{dC}	6.23	0.52	**4.12**^{cdC}	14.45	7.84	**20.93**^{bcC}	38.27	52.95	**70.68**^{aC}	82.75	19.06	**36.08**^{abB}	53.42
Beta	1.13	**1.68**	2.49	0.93	**1.39**	2.07	0.89	**1.48**	2.46	1.64	**2.41**	3.53	1.56	**2.27**	3.31	0.41	**0.71**	1.23

Fig. 5. Calculated reliability (%) for a given mission of 50,000 cycles at a set stress of 2300, 3300 and 4300 MPa. *Different lowercase letters mean statistical difference between groups at the same load level. Different uppercase letters mean statistical difference between load levels. Differences between groups were identified based on the non-overlap of 90% two-sided confidence interval.

As one group showed β value lower than 1, the probability Weibull distribution was determined using fatigue stress to failure data of the groups. The calculated Weibull modulus (m) and characteristic stress (η), which indicates the stress in which 63.2% of the specimens may fail, are depicted in the contour plot (Figure 6). The probability Weibull distribution presented values of 10.48 (7.71-14.25) for Digital-Sc, 14.25 (11.16-18.19) for TiB-Sc, 9.34 (7.02-12.44) for UCLA, 13.44 (9.99-18.08) for Digital-Ce, 10.01 (7.6-13.17) for TiB-Ce, and 8.93 (6.57-12.14) for UCLA-Ce, without significant differences between each other. While Digital-Sc demonstrated the lowest characteristic stress values (3916 MPa), TiB-Ce showed the highest values (5487.48 MPa), both significantly different from others. Furthermore, UCLA, UCLA-Ce and TiB-Sc displayed statistically similar characteristic stress values (Figure 6).





	Digital-Sc	TiB-Sc	UCLA	Digital-Ce	TiB-Ce	UCLA-Ce
Characteristic stress (η) (CI)	**176.87^{D}** (169.48-184.58)	**206.08^{C}** (198.25-214.21)	**211.69^{BC}** (201.53-222.19)	**227.86^{B}** (220.66-235.29)	**249.43^{A}** (237.5-261.87)	**220.46^{BC}** (210.64-230.74)
Weibull modulus (*m*) (CI)	**10.48^{A}** (7.71-14.25)	**14.25^{A}** (11.16-18.19)	**9.34^{A}** (7.02-12.44)	**13.44^{A}** (9.99-18.08)	**10.01^{A}** (7.6-13.17)	**8.93^{A}** (6.57-12.14)

Fig. 6. Contour plot showing “m” as an indicator of reliability (Weibull modulus) vs. characteristic stress (η), which indicates the stress in which 63.2% of the specimens of each group may fail. Differences between groups were identified based on the non-overlap of 90% two-sided confidence interval.

The Pearson correlation coefficient value illustrated that there is a negative correlation between the volume of misfit and the stress in which the specimens failed (r = -0.302, P=0.01), which means that the higher the volume of misfit, the lower the fatigue stress to failure (Figure 7).

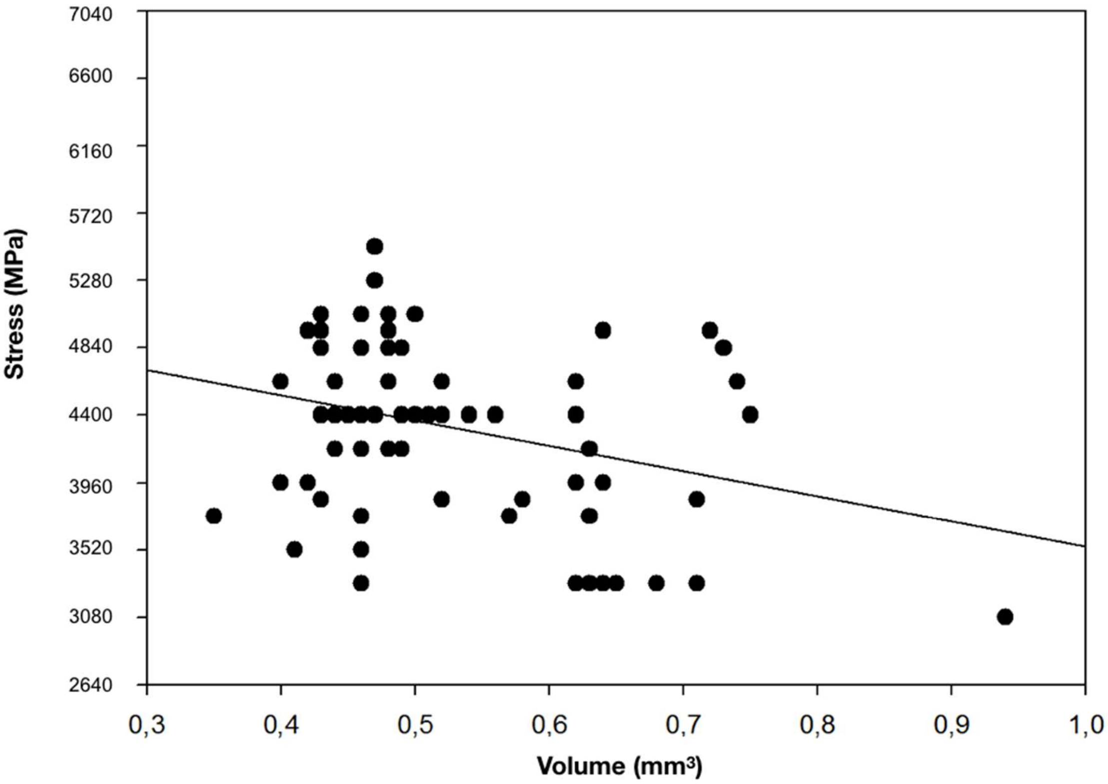


Fig. 7. Scatter plot of stress and volume of misfit, r = -0.302, P=0.01.

Failure mode

For all groups, failure mode chiefly comprised abutment screw fracture. Observation of the polarized light and scanning electron microscope (SEM) micrographs of the fractured surface of the abutment screws allowed the consistent identification of fractographic marks, such as compression curl, fatigue striations, dimples, which indicated the fracture origin and the direction of crack propagation (Figure 8).

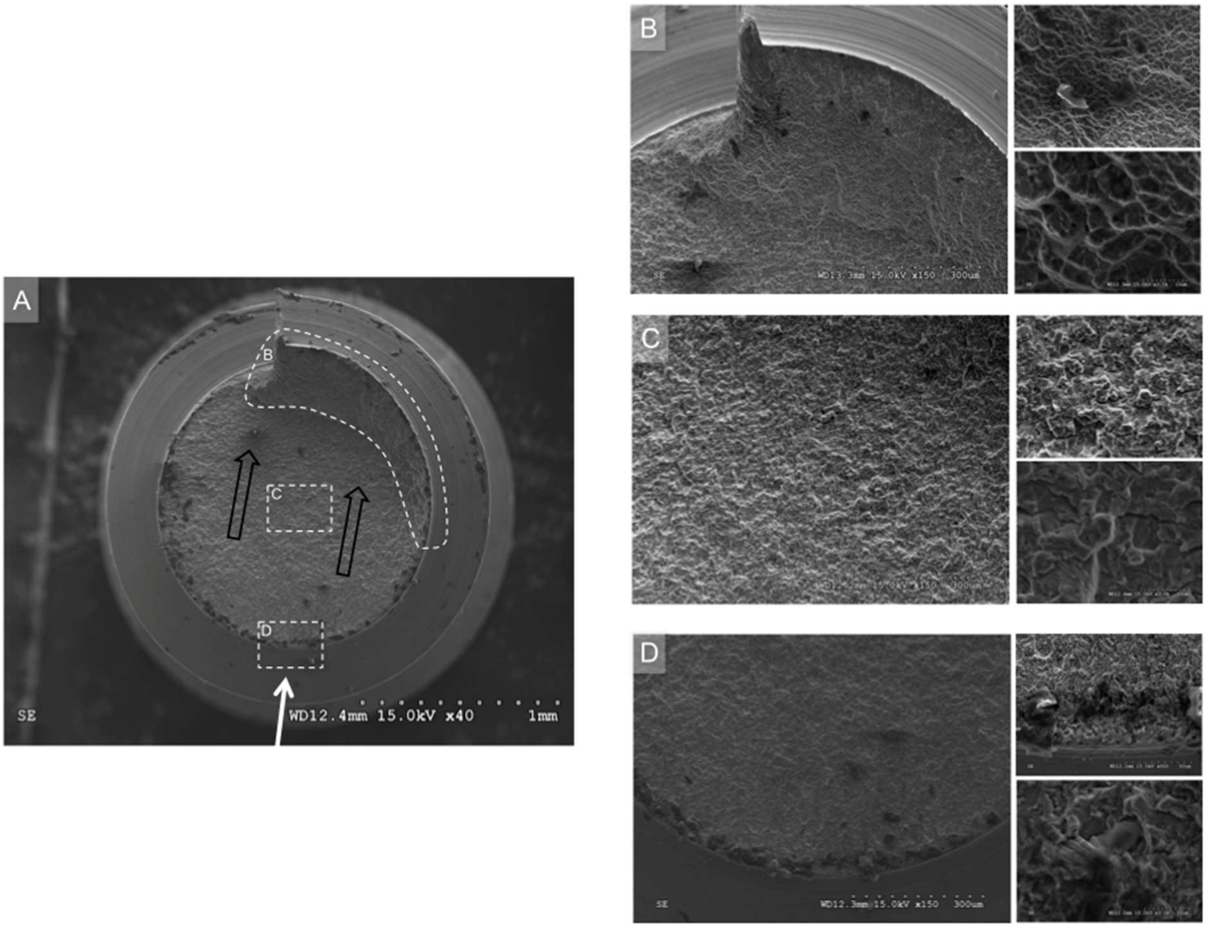


Fig. 8. (A) SEM micrograph (40x magnification) of a representative failed abutment screw after SSALT. The main dotted marked area (top) shows a compression curl, which evidences fracture origin (dotted bottom square-D) at the opposite tensile side (white arrow), indicating the direction of crack propagation (dcp) (black arrows) from lingual to buccal. (B, C and D) Higher magnification (150x, 350x and 2,500x) of the fractured surface shows fractographic features of ductile metals such as dimples created by microvoid coalescence (B) and fatigue striations (pointer in D) that mark the crack-front position with its successive stress cycles.

DISCUSSION

The present study sought to evaluate the three-dimensional fit of abutments fabricated by the industry compared to those either milled or cast by a commercial laboratory and to correlate the implant-abutment connection misfit with stress at fatigue failure of prostheses. Also, the probability of survival (reliability) and fractography to characterize failure modes were performed for cemented and screw-retained prostheses. The results demonstrated that the three-dimensional internal fit at the implant/abutment interface was influenced by the fabrication method of implant-retained restorations. An impact on the mechanical performance was also observed, since the higher the volume of misfit between the implant and the abutment, the lower the strength of the implant-supported rehabilitations. Besides, the results of this study showed that fatigue accelerated the failures of all groups, except for UCLA-Ce, as evidenced by the resulting β value. The reliability of such systems was influenced by the fabrication method and crown fixation mode. Therefore, all postulated null hypotheses were rejected.

The need for custom abutments is gradually increasing over the years. To achieve aesthetic, biological and functional success in implant rehabilitation, it is often necessary to improve prostheses emergence profile, by customization of the abutment to the anatomical needs of the respective implant site[37-39] and/or compensate for inadequate implant angulation. In this study, two customized restoration designs fabricated through different process were investigated: (a) monolithic-abutment-crown, where the abutment and crown are manufactured as one-piece that is directly screwed to implant (Digital-Sc and UCLA) or bonded to a titanium base then screwed to the implant (TiB-Sc) or (b) a core with a separate crown, where the abutment is screwed to implant (Digital-Ce and UCLA- Ce) or bonded to titanium base first (TiB-Ce), then screwed to the implant followed by cementation of a crown. While the former design would be better indicated for implants placed in an ideal three-dimensional position, the latter would be indicated for implants in a not ideal position. Regarding the fabrication process, besides the custom castable abutments fabricated through a conventional casting workflow (by using UCLA-type abutments), customized abutments can also be fabricated out of different materials such as metal alloys or ceramics using CAD/CAM manufacturing systems.[37, 39] Such a technology has been suggested as an improvement over the conventional methods since numerous advantages in the fabrication of implant-supported rehabilitations were introduced, which include reduced clinical time, high precision machining of prefabricated blocks of any given material, reduced laboratory technique sensitivity and, consequently, high capacity of customization.[36, 37] However, despite the advantages mentioned above of employing a fully digital workflow, the control of internal misfit is not yet controlled by international standards or norms (as it is for prefabricated abutments) and is dependent on several variables involved in the milling strategies of the CAD/CAM systems.[40-42] In this scenario, recently introduced abutments, known as Ti-base, have been designed to be CAD/CAM-friendly and to allow rapid fabrication of prostheses with maximal fit at the implant-abutment connection. [37] In essence, Ti-base is a prefabricated abutment with a hybrid concept of cemented and screwed fixation in the same prostheses where the implant-abutment connection is used with the precision as delivered from the manufacturer.

The literature on the fit accuracy of abutments milled in commercial laboratory CAD/CAM systems is controversial, either supporting or not a comparable internal fit relative to prefabricated ones. [43-46] In this study, the qualitative and quantitative findings of the three-dimensional internal fit evaluation demonstrated that groups produced by a complete laboratory digital workflow (Digital-Sc and Digital-Ce) depicted higher values of internal misfit relative to groups produced by hybrid digital (TiB-Sc and TiB-Ce) and conventional (UCLA and UCLA-Ce) workflows (not significantly different from each other). While the reasons for the worse fit found in the Digital-Sc and Digital-Ce group can be explained by several factors relative to the milling parameters and strategies, [40-42] the similarity between the misfit values of the TiB-Sc, TiB-Ce, UCLA, and UCLA-Ce can be explained by the well-controlled conditions in which such abutments were industrially manufactured.

The existence of micro gaps between implant and abutment has been described in several studies. [14, 16, 47-51] Such interface comprises a paramount factor in the long-term success of any implant rehabilitation. [8] Biological implications of the micro gap at the implant-abutment connection are related to the bacterial colonization which, as a bacterial reservoir, could influence the remodelling of the peri-implant bone and the long-term health of the peri-implant tissues. [13-16] It must be recognized that as of now, there are no endosseous dental implant systems that can provide a complete seal at the implant–abutment interface [52] and so this is still an important clinical issue. Mechanical implications are more related to micro-movements and possible loosening or fracturing of abutment screws. [11, 12] In the present study, the volumetric results of internal fit affected the mechanical performance of the investigated systems since the volume of misfit between the implant and abutment was negatively related to the fatigue stress of the implant-supported rehabilitation, which means that specimens with higher internal gaps failed at lower fatigue stress. The impairment of the mechanical resistance according to different levels of internal misfit, although seldom investigated, was confirmed by other authors using different methods. [11, 53, 54]

Several measuring analytical techniques for gap determination in implant-supported rehabilitations are described in the literature. [55, 56, 40, 57, 20, 58] Although many of these techniques are well established, most authors agree that these methodologies provide limited information, [43, 59, 60] and it is impossible to use these methods *in vivo* considering their destructive approach. Accordingly, with the development of digital technology, three-dimensional analysis methods have been explored, such as microcomputed tomography, as used in our study. [55, 61] By using the silicone replica technique we have demonstrated that microgaps up to 1 μm width could be measured and reconstructed in a three-dimensional rendering image, providing insight into the most critical volumes of misfit. Besides, qualitative and quantitative data from the direct implant scanning and the silicone replica scanning techniques showed similar values. Statistical analysis was not performed to compare direct and the indirect silicone replica techniques, given that only one sample for each group was evaluated in the former technique. However, our findings of similar measurements between these two techniques are in agreement with Oka et al.[60] that evaluated the fitting accuracy of prostheses three-dimensionally using a combination of the silicone replica technique and μCT in comparison with a conventional 2D silicone replica method (stereomicroscopy). Their study showed that 3D virtual images of the replica accurately reflected their *in situ* misfit.

In addition to the implant-retained prostheses fabrication method, the fixation mode influenced the reliability of the groups at higher stress scenario. A general trend was observed for increased reliability of cement-retained prostheses at higher stress, regardless of the fabrication method. From a mechanical standpoint, the finding concerning higher reliability for cement-retained implant-supported prostheses compared to screw-retained prostheses has been previously reported in fatigue studies[32, 62, 63] and was confirmed by a clinical study[64]. It can be inferred that the presence of the cement between the crown and abutment increases the interaction due to the intimate contact created by the filling cementing media, which potentially reduces misfit and micromotion between parts. A review of clinical studies showed the survival of cement-retained single crowns was 93%, compared to 83% for implant-supported screwed crowns for follow-up periods commonly longer than 6 years. [65]

Based on fractographic features of failed specimens observed in polarized-light and scanning electron microscopy, all fractures were characterized by plastic deformation, suggesting ductile fractures. From a clinical standpoint, failure modes of all groups could be considered repairable, since they did not affect the implant integrity, as observed in previous *in vitro* [62] and clinical studies. [66, 67] As a consequence, expected long-term maintenance of the investigated systems would likely be limited to the abutment screws. Considering that at 3300 MPa (equivalent to 150 N) all groups kept their survivability higher than 86%, except for the screwed monolithic digital abutment/crown (Digital-Sc = 24%), the investigated systems showed sufficient resistance required for the clinical application under loadings within the maximum bite force for incisors (65N [68] to 100N). [69] However, long-term randomized clinical trials are always highly desired to obtain information on the longevity and complication modes of new implant-abutment restorative systems.

CONCLUSIONS

Within the limitations of this study, the following conclusions may be drawn:

- Implant-supported prostheses milled by a commercial laboratory (Digital-Sc and Digital-Ce) exhibited poorer internal fit at the implant/abutment connection compared to those either cast or fabricated by the industry (TiB-Sc, TiB-Ce, UCLA and UCLA-Ce);
- All groups presented high reliability at 2300 MPa. At higher stress TiB-Ce demonstrated the highest reliability;
- Failure mode chiefly comprised abutment screw fracture;
- Higher misfit values negatively influenced the stress in which the specimens failed.

REFERENCES

1. Pjetursson BE, Zarauz C, Strasding M, Sailer I, Zwahlen M, Zembic A. A systematic review of the influence of the implant-abutment connection on the clinical outcomes of ceramic and metal implant abutments supporting fixed implant reconstructions. Clin Oral Implants Res 2018;29 Suppl 18:160-83.
2. Jung RE, Pjetursson BE, Glauser R, Zembic A, Zwahlen M, Lang NP. A systematic review of the 5-year survival and complication rates of implant-supported single crowns. Clin Oral Implants Res 2008;19:119-30.
3. Griggs JA. Dental Implants. Dent Clin North Am 2017;61:857-71.
4. Jung RE, Zembic A, Pjetursson BE, Zwahlen M, Thoma DS. Systematic review of the survival rate and the incidence of biological, technical, and aesthetic

complications of single crowns on implants reported in longitudinal studies with a mean follow-up of 5 years. Clin Oral Implants Res 2012;23 Suppl 6:2-21.

5. Papaspyridakos P, Chen CJ, Singh M, Weber HP, Gallucci GO. Success criteria in implant dentistry: a systematic review. J Dent Res 2012;91:242-8.
6. Bonfante EA, Coelho PG. A Critical Perspective on Mechanical Testing of Implants and Prostheses. Adv Dent Res 2016;28:18-27.
7. Papaspyridakos P, Chen CJ, Chuang SK, Weber HP, Gallucci GO. A systematic review of biologic and technical complications with fixed implant rehabilitations for edentulous patients. Int J Oral Maxillofac Implants 2012;27:102-10.
8. Sailer I, Philipp A, Zembic A, Pjetursson BE, Hammerle CH, Zwahlen M. A systematic review of the performance of ceramic and metal implant abutments supporting fixed implant reconstructions. Clin Oral Implants Res 2009;20 Suppl 4:4-31.
9. Zarone F, Sorrentino R, Traini T, Di Iorio D, Caputi S. Fracture resistance of implant-supported screw- versus cement-retained porcelain fused to metal single crowns: SEM fractographic analysis. Dent Mater 2007;23:296-301.
10. Steinebrunner L, Wolfart S, Bossmann K, Kern M. In vitro evaluation of bacterial leakage along the implant-abutment interface of different implant systems. Int J Oral Maxillofac Implants 2005;20:875-81.
11. al-Turki LE, Chai J, Lautenschlager EP, Hutten MC. Changes in prosthetic screw stability because of misfit of implant-supported prostheses. Int J Prosthodont 2002;15:38-42.
12. Binon PP. The effect of implant/abutment hexagonal misfit on screw joint stability. Int J Prosthodont 1996;9:149-60.

13. Alqutaibi AY, Aboalrejal AN. Microgap and Micromotion at the Implant Abutment Interface Cause Marginal Bone Loss Around Dental Implant but More Evidence is Needed. J Evid Based Dent Pract 2018;18:171-2.
14. Mishra SK, Chowdhary R, Kumari S. Microleakage at the Different Implant Abutment Interface: A Systematic Review. J Clin Diagn Res 2017;11:ZE10-ZE5.
15. Broggini N, McManus LM, Hermann JS, Medina R, Schenk RK, Buser D et al. Peri-implant inflammation defined by the implant-abutment interface. J Dent Res 2006;85:473-8.
16. Liu Y, Wang J. Influences of microgap and micromotion of implant-abutment interface on marginal bone loss around implant neck. Arch Oral Biol 2017;83:153-60.
17. Silva CEP, Soares S, Machado CM, Bergamo ETP, Coelho PG, Witek L et al. Effect of CAD/CAM Abutment Height and Cement Type on the Retention of Zirconia Crowns. Implant Dent 2018;27:582-7.
18. Lopes ACO, Machado CM, Bonjardim LR, Bergamo ETP, Ramalho IS, Witek L et al. The Effect of CAD/CAM Crown Material and Cement Type on Retention to Implant Abutments. J Prosthodont 2018.
19. Nouh I, Kern M, Sabet AE, Aboelfadl AK, Hamdy AM, Chaar MS. Mechanical Behavior of Posterior All-Ceramic Hybrid-Abutment-Crowns Versus Hybrid-Abutments with Separate Crowns - A Laboratory Study. Clin Oral Implants Res 2018.
20. Byrne D, Houston F, Cleary R, Claffey N. The fit of cast and premachined implant abutments. J Prosthet Dent 1998;80:184-92.

21. Staubli N, Walter C, Schmidt JC, Weiger R, Zitzmann NU. Excess cement and the risk of peri-implant disease - a systematic review. Clin Oral Implants Res 2016.
22. Goodacre CJ, Kan JY, Rungcharassaeng K. Clinical complications of osseointegrated implants. J Prosthet Dent 1999;81:537-52.
23. Hebel KS, Gajjar RC. Cement-retained versus screw-retained implant restorations: achieving optimal occlusion and esthetics in implant dentistry. J Prosthet Dent 1997;77:28-35.
24. Lee A, Okayasu K, Wang HL. Screw- versus cement-retained implant restorations: current concepts. Implant Dent 2010;19:8-15.
25. Michalakis KX, Hirayama H, Garefis PD. Cement-retained versus screw-retained implant restorations: a critical review. Int J Oral Maxillofac Implants 2003;18:719-28.
26. Pauletto N, Lahiffe BJ, Walton JN. Complications associated with excess cement around crowns on osseointegrated implants: a clinical report. Int J Oral Maxillofac Implants 1999;14:865-8.
27. Pjetursson BE, Tan K, Lang NP, Bragger U, Egger M, Zwahlen M. A systematic review of the survival and complication rates of fixed partial dentures (FPDs) after an observation period of at least 5 years. Clin Oral Implants Res 2004;15:667-76.
28. Schiessl C, Schaefer L, Winter C, Fuerst J, Rosentritt M, Zeman F et al. Factors determining the retentiveness of luting agents used with metal- and ceramic-based implant components. Clin Oral Investig 2013;17:1179-90.

29. Wittneben JG, Joda T, Weber HP, Bragger U. Screw retained vs. cement retained implant-supported fixed dental prosthesis. Periodontol 2000 2017;73:141-51.

30. Sailer I, Muhlemann S, Zwahlen M, Hammerle CH, Schneider D. Cemented and screw-retained implant reconstructions: a systematic review of the survival and complication rates. Clin Oral Implants Res 2012;23 Suppl 6:163-201.

31. Almeida EO, Freitas AC, Jr., Bonfante EA, Marotta L, Silva NR, Coelho PG. Mechanical testing of implant-supported anterior crowns with different implant/abutment connections. Int J Oral Maxillofac Implants 2013;28:103-8.

32. Bonfante EA, Almeida EO, Lorenzoni FC, Coelho PG. Effects of implant diameter and prosthesis retention system on the reliability of single crowns. Int J Oral Maxillofac Implants 2015;30:95-101.

33. Bordin D, Bergamo ETP, Fardin VP, Coelho PG, Bonfante EA. Fracture strength and probability of survival of narrow and extra-narrow dental implants after fatigue testing: In vitro and in silico analysis. J Mech Behav Biomed Mater 2017;71:244-9.

34. Bordin D, Bergamo ETP, Bonfante EA, Fardin VP, Coelho PG. Influence of platform diameter in the reliability and failure mode of extra-short dental implants. J Mech Behav Biomed Mater 2018;77:470-4.

35. Freitas-Junior AC, Rocha EP, Bonfante EA, Almeida EO, Anchieta RB, Martini AP et al. Biomechanical evaluation of internal and external hexagon platform switched implant-abutment connections: An in vitro laboratory and three-dimensional finite element analysis. Dent Mater 2012;28:e218-28.

36. Nelson W. Accelerated testing: statistical models, test plans and data analysis.: John Wiley & Sons; 2004.

37. Kurbad A, Kurbad S. CAD/CAM-based implant abutments. Int J Comput Dent 2013;16:125-41.
38. Jemt T. Customized titanium single-implant abutments: 2-year follow-up pilot study. Int J Prosthodont 1998;11:312-6.
39. Kapos T, Evans C. CAD/CAM technology for implant abutments, crowns, and superstructures. Int J Oral Maxillofac Implants 2014;29 Suppl:117-36.
40. Mobilio N, Fasiol A, Franceschetti G, Catapano S. Marginal Vertical Fit along the Implant-Abutment Interface: A Microscope Qualitative Analysis. Dent J (Basel) 2016;4.
41. Papadiochou S, Pissiotis AL. Marginal adaptation and CAD-CAM technology: A systematic review of restorative material and fabrication techniques. J Prosthet Dent 2018;119:545-51.
42. Torabi Ardekani K, Ahangari AH, Farahi L. Marginal and internal fit of CAD/CAM and slip-cast made zirconia copings. J Dent Res Dent Clin Dent Prospects 2012;6:42-8.
43. Lops D, Meneghello R, Sbricoli L, Savio G, Bressan E, Stellini E. Precision of the Connection Between Implant and Standard or Computer-Aided Design/Computer-Aided Manufacturing Abutments: A Novel Evaluation Method. Int J Oral Maxillofac Implants 2018;33:23-30.
44. Hamilton A, Judge RB, Palamara JE, Evans C. Evaluation of the fit of CAD/CAM abutments. Int J Prosthodont 2013;26:370-80.
45. Vigolo P, Fonzi F, Majzoub Z, Cordioli G. Evaluation of gold-machined UCLA-type abutments and CAD/CAM titanium abutments with hexagonal external connection and with internal connection. Int J Oral Maxillofac Implants 2008;23:247-52.

46. Park JI, Lee Y, Lee JH, Kim YL, Bae JM, Cho HW. Comparison of fracture resistance and fit accuracy of customized zirconia abutments with prefabricated zirconia abutments in internal hexagonal implants. Clin Implant Dent Relat Res 2013;15:769-78.

47. Coelho AL, Suzuki M, Dibart S, N DAS, Coelho PG. Cross-sectional analysis of the implant-abutment interface. J Oral Rehabil 2007;34:508-16.

48. Kano SC, Bonfante G, Hussne R, Siqueira AF. Use of base metal casting alloys for implant framework: marginal accuracy analysis. J Appl Oral Sci 2004;12:337-43.

49. Bondan JL, Oshima HM, Segundo RM, Shinkai RS, Mota EG, Meyer KR. Marginal fit analysis of premachined and castable UCLA abutments. Acta Odontol Latinoam 2009;22:139-42.

50. Lorenzoni FC, Coelho PG, Bonfante G, Carvalho RM, Silva NR, Suzuki M et al. Sealing Capability and SEM Observation of the Implant-Abutment Interface. Int J Dent 2011;2011:864183.

51. Meleo D, Baggi L, Di Girolamo M, Di Carlo F, Pecci R, Bedini R. Fixture-abutment connection surface and micro-gap measurements by 3D micro-tomographic technique analysis. Ann Ist Super Sanita 2012;48:53-8.

52. Schmitt CM, Nogueira-Filho G, Tenenbaum HC, Lai JY, Brito C, Doring H et al. Performance of conical abutment (Morse Taper) connection implants: a systematic review. J Biomed Mater Res A 2014;102:552-74.

53. Gil FJ, Herrero-Climent M, Lazaro P, Rios JV. Implant-abutment connections: influence of the design on the microgap and their fatigue and fracture behavior of dental implants. J Mater Sci Mater Med 2014;25:1825-30.

54. Sui X, Wei H, Wang D, Han Y, Deng J, Wang Y et al. Experimental research on the relationship between fit accuracy and fracture resistance of zirconia abutments. J Dent 2014;42:1353-9.

55. Jorn D, Kohorst P, Besdo S, Borchers L, Stiesch M. Three-Dimensional Nonlinear Finite Element Analysis and Microcomputed Tomography Evaluation of Microgap Formation in a Dental Implant Under Oblique Loading. Int J Oral Maxillofac Implants 2016;31:e32-42.

56. Rismanchian M, Hatami M, Badrian H, Khalighinejad N, Goroohi H. Evaluation of microgap size and microbial leakage in the connection area of 4 abutments with Straumann (ITI) implant. J Oral Implantol 2012;38:677-85.

57. Wiest W, Zabler S, Rack A, Fella C, Balles A, Nelson K et al. In situ microradioscopy and microtomography of fatigue-loaded dental two-piece implants. J Synchrotron Radiat 2015;22:1492-7.

58. Soo S, Garriga-Majo D, Palmer RM, Curtis RV. The longitudinal accuracy of fit of titanium implant superstructures superplastically formed on investment models. Dent Mater 2004;20:269-76.

59. Kim MJ, Choi YJ, Kim SK, Heo SJ, Koak JY. Marginal Accuracy and Internal Fit of 3-D Printing Laser-Sintered Co-Cr Alloy Copings. Materials (Basel) 2017;10.

60. Oka Y, Sasaki J, Wakabayashi K, Nakano Y, Okamura SY, Nakamura T et al. Fabrication of a radiopaque fit-testing material to evaluate the three-dimensional accuracy of dental prostheses. Dent Mater 2016;32:921-8.

61. Moris ICM, Monteiro SB, Martins R, Ribeiro RF, Gomes EA. Influence of Manufacturing Methods of Implant-Supported Crowns on External and Internal Marginal Fit: A Micro-CT Analysis. Biomed Res Int 2018;2018:5049605.

62. Freitas AC, Jr., Bonfante EA, Rocha EP, Silva NR, Marotta L, Coelho PG. Effect of implant connection and restoration design (screwed vs. cemented) in reliability and failure modes of anterior crowns. Eur J Oral Sci 2011;119:323-30.
63. Almeida EO, Freitas Junior AC, Bonfante EA, Rocha EP, Silva NR, Coelho PG. Effect of microthread presence and restoration design (screw versus cemented) in dental implant reliability and failure modes. Clin Oral Implants Res 2013;24:191-6.
64. Nissan J, Narobai D, Gross O, Ghelfan O, Chaushu G. Long-term outcome of cemented versus screw-retained implant-supported partial restorations. Int J Oral Maxillofac Implants 2011;26:1102-7.
65. Weber HP, Sukotjo C. Does the type of implant prosthesis affect outcomes in the partially edentulous patient? Int J Oral Maxillofac Implants 2007;22 Suppl:140-72.
66. Piattelli A, Piattelli M, Scarano A, Montesani L. Light and scanning electron microscopic report of four fractured implants. Int J Oral Maxillofac Implants 1998;13:561-4.
67. Velasquez-Plata D, Lutonsky J, Oshida Y, Jones R. A close-up look at an implant fracture: a case report. Int J Periodontics Restorative Dent 2002;22:483-91.
68. Kampe T, Haraldson T, Hannerz H, Carlsson GE. Occlusal perception and bite force in young subjects with and without dental fillings. Acta Odontol Scand 1987;45:101-7.
69. Fontijn-Tekamp FA, Slagter AP, Van Der Bilt A, Van THMA, Witter DJ, Kalk W et al. Biting and chewing in overdentures, full dentures, and natural dentitions. J Dent Res 2000;79:1519-24.

3 DISCUSSION

3 DISCUSSION

The overall objective of this study was to evaluate the influence of abutment fabrication method on the reliability and the three-dimensional fit at the implant-abutment interface of implant-supported prostheses. The correlation between misfit levels with stress at fatigue failure of prostheses was also performed. The results demonstrated that not only the three-dimensional internal fit at the implant/abutment interface but also the reliability of the studied systems was influenced by the fabrication method of implant-retained restorations. An impact on the mechanical performance was observed, since the higher the volume of misfit between the implant and the abutment, the lower the strength of the implant-supported rehabilitations. Therefore, all postulated null hypotheses were rejected.

The rationale behind the selection of the abutments used in this study is based on the increasing need of custom abutments to attend the multifaceted and highly complex set of clinical scenarios. Custom abutments are individually shaped according to the anatomical needs of the respective implant site [52-54] and allow the clinician to improve prostheses emergence profile, and to compensate for inadequate implant angulation. In this study, two customized restoration designs fabricated through different process were investigated: (a) monolithic-abutment-crown, where the abutment and crown are manufactured as one-piece that is directly screwed to implant (Digital-Sc and UCLA) or bonded to a titanium base then screwed to the implant (TiB-Sc) or (b) a core with a separate crown, where the abutment is screwed to implant (Digital-Ce and UCLA-Ce) or bonded to titanium base first (TiB-Ce), then screwed to the implant followed by cementation of a crown. While the former design would be better indicated for implants placed in an ideal three-dimensional position, the latter would be indicated for implants in a not ideal position.

Considering that the abutment/implant interface exerts remarkable influence on the future success and long-term stability of implant-supported rehabilitations, it becomes paramount to investigate the effect of different abutment fabrication methods on the internal fit at the implant-abutment connection. As regards the fit accuracy of abutments milled in commercial laboratory CAD/CAM systems, the literature is controversial, either supporting or not a comparable internal fit relative to the prefabricated ones.[55-58] In this study, the qualitative and quantitative findings of the three-dimensional internal fit evaluation demonstrated that groups produced by a fully digital laboratory fabrication process (Digital-Sc and Digital-Ce) depicted higher values of internal misfit relative to groups produced by a hybrid fabrication process (TiB-Sc and TiB-Ce) and conventional (UCLA and UCLA-Ce) workflow (not significantly different from each other). Possible explanations for the worse fit found in the fully digital groups could be associated to several factors relative to the milling process, such as the wear of milling instruments, the change in the radius of the instruments during the milling procedure,[59] the incompatible size of the milling drill with the corresponding implant angles[60] and, more importantly, tolerances set in producing CAD/CAM screw-retained abutments/crowns, which can play a key role in the final fit.[24] Mobilio et al.[24] evaluated the marginal vertical fit along implant/abutment interface of a prefabricated abutment and three customized CAD/CAM screw-retained crowns with three different “tolerance” values. The results of such investigation demonstrated that reducing the tolerance of 10 microns lower than the manufacturer values is equal to increasing the attrition and, consequently, the vertical gap between the components.

The similarity between the misfit values of the Ti-Base and UCLA abutments can be explained by the well-controlled conditions in which such abutments were industrially produced. It is worthwhile to mention that, in the current study, UCLA abutments with metallic base were used and the customized wax patterns were milled in the CAD/CAM system followed by conventional casting procedures, which could contribute to the favorable internal fit depicted in this group. Previous investigations[25, 34] showed that prefabricated abutments, which include UCLA abutments with a CoCr base that are customized in a laboratory, are superior in adaptation to those cast from plastic burnout patterns.

In contrast to studies reporting data on marginal/internal gaps between two different surfaces, a volume of misfit (mm^3) at the implant/abutment interface was also measured in this study. Similarly, Lops et al.[55] calculated the volume of contact (mm^3) to investigate the accuracy of fit between an internal conical connection implant and prefabricated and CAD/CAM abutments, using a multisensored opto-mechanical coordinate measuring machine. In contrast to our results, lower mean values of volume of interference for the CAD/CAM abutments (0.108 mm^3) were found in comparison to the prefabricated abutments (0.134 mm^3). Although direct comparison is not feasible, given the different implant geometry and methodology used in such investigation, the authors emphasized the 3D measurement method as a more helpful approach compared to the 2D measurement for the comparison between different abutment groups.

Several measuring analytical techniques for gap determination in implant-supported rehabilitations are described in the literature, which include measurement of the specimens by direct visualization under a microscope; or embedded and sectioned specimens and silicone replica analyzed under scanning electron microscopy (SEM),[22, 23] optical microscopy,[24] microtomography,[22, 31] travelling microscope,[25, 26] among others. Although such techniques are well established, most authors agree that these methodologies provide limited information,[55, 61, 62] and it is impossible to use these methods *in vivo* considering their destructive approach. Accordingly, with the development of digital technology, three-dimensional analysis methods has been explored, such as 3D nonlinear finite element analysis (FEA)[22] and microcomputed tomography.[22, 63] By using this technique we have demonstrated that microgaps up to 1 µm width could be measured in two and three dimensions; in the latter case, the microgaps at the implant/abutment interface could be reconstructed onto a three-dimensional rendering image, which can provide insight into the most critical areas of misfit. Besides, qualitative and quantitative data from the direct implant scanning and the silicone replica scanning techniques showed similar values. Statistical analysis was not performed to compare direct and the indirect silicone replica techniques, given that only one sample for each group was evaluated in the former technique. However, our findings of similar measurements between these two techniques are in agreement with Oka et al.[62] that evaluated the fitting accuracy of prostheses three-dimensionally using a combination of the silicone replica technique and µCT in comparison with a conventional 2D silicone replica method (stereomicroscopy). Their study showed that 3D virtual images of the replica accurately reflected their *in situ* misfit.

From a technical standpoint, gaps between the implant and the abutment are inevitable in fitting the different parts. Such components cannot be accurately matched because of the precision limit during manufacturing process and therefore, some amount of microleakage will unavoidably occur regardless of the type of connection and the size of the microgaps.[20, 23, 64] Accordingly, the magnitude of these gaps and its clinical significance has been receiving significant attention[18, 20, 29, 34, 35, 65, 66] and different methodologies have been utilized for such investigation.[16, 19, 24, 29, 31, 34, 55, 65] The size of the microgap at implant/abutment connection has been reported as a wide range of 1 to 60 µm,[24, 25, 34, 67] and it is dependent, among other factors, on the implant system and the torque used to fix abutments.[20, 68] Although gaps from different magnitudes have been identified along with proportional levels of microleakage at different implant abutment configurations, it is important to bear in mind that no internal or external implant-abutment screwed connection has 100% bacterial seal [69] and so this is still an important clinical issue. Biological implications of the micro gap at the implant-abutment connection are related to the bacterial colonization in the apical portion of the abutment screw, which, as a bacterial reservoir, could influence the remodelling of the peri-implant bone and the long-term health of the peri-implant tissues.[17, 18, 20, 21] Mechanical implications are more related to micro-movements and possible loosening or fracturing of abutment screws. [16, 19] In the present study, the volumetric results of internal fit affected the mechanical performance of the investigated systems since the volume of misfit between the implant and abutment was negatively related to the fatigue stress of the implant-supported rehabilitation, which means that specimens with higher internal gaps failed at lower fatigue stress.

Additionally, when evaluating the calculated reliability for the tested groups, all groups showed comparable reliability (above 97%) at 2300 MPa. However, at higher stress (3300 MPa) while all groups kept their survivability higher than 86%, significantly lower reliability was demonstrated by Digital-Sc (~24%). Within the same fixation mode, the full digital groups presented the lowest reliability values (0% - Digital-Sc and 20.93% - Digital-Ce) at 4300 MPa of set stress. The impairment of the mechanical resistance according to different levels of internal misfit, although seldom investigated, was confirmed by other authors.[16, 30, 70]

In addition to the implant-retained prostheses fabrication method, the fixation mode influenced the reliability of the groups at higher stress scenario. It was observed a general trend for better reliability of cement-retained prostheses at higher stress, regardless of the fabrication method. From a mechanical standpoint, the finding concerning higher reliability for cement-retained implant-supported prostheses compared to screw-retained prostheses has been previously reported in fatigue studies[10, 11, 71] and was confirmed by a clinical study[72]. It can be inferred that the presence of the cement between the crown and abutment increases the interaction due to the intimate contact created by the filling cementing media, which potentially reduces misfit and motion between parts and thereby improving the mechanical performance of cement-retained systems. In an extensive review, the survival of cement-retained single crowns was 93%, compared to 83% for implant-supported screwed crowns for follow-up periods commonly longer than 6 years.[73]

Based on fractographic features of failed specimens observed in polarized-light and scanning electron microscopy, all fractures were characterized by material tearing and exhibited gross plastic deformation, suggesting ductile fractures. From a clinical standpoint, failure modes of all groups could be considered repairable, since they did not affect the implant integrity, as observed in previous *in vitro*[71] and clinical studies.[74, 75] As a consequence, expected long-term maintenance of the investigated systems would likely be limited to the abutment screws. Considering that at 3300 MPa of set stress (equivalent to 150 N) all groups kept their survivability higher than 86%, except for the screwed monolithic digital abutment/crown (Digital-Sc = 24%), the investigated systems showed sufficient resistance required for the clinical application under loadings within the physiologic range for incisor area, where the loads are reported to be approximately 65 N [76] to 100 N. [77] However, long-term randomized clinical trials are always highly desired to obtain information on the longevity and complication modes of new implant abutments.

4 CONCLUSION

4 CONCLUSION

Within the limitations of this study, the following conclusions may be drawn:

- Implant-supported prostheses milled by a commercial laboratory (Digital-Sc and Digital-Ce) exhibited poorer internal fit at the implant/abutment connection compared to those either cast or fabricated by the industry (TiB-Sc, TiB-Ce, UCLA and UCLA-Ce);
- All groups presented high reliability at 2300 MPa (up to 97%), however at higher stress Digital-Sc decreased the reliability to 0% and TiB-Ce (71%) demonstrated higher reliability than other groups;
- Failure mode chiefly comprised abutment screw fracture;
- Higher misfit values negatively influenced the load in which the specimens failed.

REFERENCES

REFERENCES

1. Jung RE, Pjetursson BE, Glauser R, Zembic A, Zwahlen M, Lang NP. A systematic review of the 5-year survival and complication rates of implant-supported single crowns. Clin Oral Implants Res 2008;19:119-30.

2. Sailer I, Philipp A, Zembic A, Pjetursson BE, Hammerle CH, Zwahlen M. A systematic review of the performance of ceramic and metal implant abutments supporting fixed implant reconstructions. Clin Oral Implants Res 2009;20 Suppl 4:4-31.

3. Griggs JA. Dental Implants. Dent Clin North Am 2017;61:857-71.

4. Pjetursson BE, Zarauz C, Strasding M, Sailer I, Zwahlen M, Zembic A. A systematic review of the influence of the implant-abutment connection on the clinical outcomes of ceramic and metal implant abutments supporting fixed implant reconstructions. Clin Oral Implants Res 2018;29 Suppl 18:160-83.

5. Papaspyridakos P, Chen CJ, Chuang SK, Weber HP, Gallucci GO. A systematic review of biologic and technical complications with fixed implant rehabilitations for edentulous patients. Int J Oral Maxillofac Implants 2012;27:102-10.

6. Jung RE, Zembic A, Pjetursson BE, Zwahlen M, Thoma DS. Systematic review of the survival rate and the incidence of biological, technical, and aesthetic complications of single crowns on implants reported in longitudinal studies with a mean follow-up of 5 years. Clin Oral Implants Res 2012;23 Suppl 6:2-21.

7. Papaspyridakos P, Chen CJ, Singh M, Weber HP, Gallucci GO. Success criteria in implant dentistry: a systematic review. J Dent Res 2012;91:242-8.

8. Bonfante EA, Coelho PG. A Critical Perspective on Mechanical Testing of Implants and Prostheses. Adv Dent Res 2016;28:18-27.

9. Almeida EO, Freitas AC, Jr., Bonfante EA, Marotta L, Silva NR, Coelho PG. Mechanical testing of implant-supported anterior crowns with different implant/abutment connections. Int J Oral Maxillofac Implants 2013;28:103-8.

10. Almeida EO, Freitas Junior AC, Bonfante EA, Rocha EP, Silva NR, Coelho PG. Effect of microthread presence and restoration design (screw versus cemented) in dental implant reliability and failure modes. Clin Oral Implants Res 2013;24:191-6.

11. Bonfante EA, Almeida EO, Lorenzoni FC, Coelho PG. Effects of implant diameter and prosthesis retention system on the reliability of single crowns. Int J Oral Maxillofac Implants 2015;30:95-101.

12. Bordin D, Bergamo ETP, Bonfante EA, Fardin VP, Coelho PG. Influence of platform diameter in the reliability and failure mode of extra-short dental implants. J Mech Behav Biomed Mater 2018;77:470-4.

13. Bordin D, Bergamo ETP, Fardin VP, Coelho PG, Bonfante EA. Fracture strength and probability of survival of narrow and extra-narrow dental implants after fatigue testing: In vitro and in silico analysis. J Mech Behav Biomed Mater 2017;71:244-9.

14. Zarone F, Sorrentino R, Traini T, Di Iorio D, Caputi S. Fracture resistance of implant-supported screw- versus cement-retained porcelain fused to metal single crowns: SEM fractographic analysis. Dent Mater 2007;23:296-301.

15. Steinebrunner L, Wolfart S, Bossmann K, Kern M. In vitro evaluation of bacterial leakage along the implant-abutment interface of different implant systems. Int J Oral Maxillofac Implants 2005;20:875-81.

16. al-Turki LE, Chai J, Lautenschlager EP, Hutten MC. Changes in prosthetic screw stability because of misfit of implant-supported prostheses. Int J Prosthodont 2002;15:38-42.

17. Alqutaibi AY, Aboalrejal AN. Microgap and Micromotion at the Implant Abutment Interface Cause Marginal Bone Loss Around Dental Implant but More Evidence is Needed. J Evid Based Dent Pract 2018;18:171-2.

18. Liu Y, Wang J. Influences of microgap and micromotion of implant-abutment interface on marginal bone loss around implant neck. Arch Oral Biol 2017;83:153-60.

19. Binon PP. The effect of implant/abutment hexagonal misfit on screw joint stability. Int J Prosthodont 1996;9:149-60.

20. Mishra SK, Chowdhary R, Kumari S. Microleakage at the Different Implant Abutment Interface: A Systematic Review. J Clin Diagn Res 2017;11:ZE10-ZE5.

21. Broggini N, McManus LM, Hermann JS, Medina R, Schenk RK, Buser D et al. Peri-implant inflammation defined by the implant-abutment interface. J Dent Res 2006;85:473-8.

22. Jorn D, Kohorst P, Besdo S, Borchers L, Stiesch M. Three-Dimensional Nonlinear Finite Element Analysis and Microcomputed Tomography Evaluation of Microgap Formation in a Dental Implant Under Oblique Loading. Int J Oral Maxillofac Implants 2016;31:e32-42.

23. Rismanchian M, Hatami M, Badrian H, Khalighinejad N, Goroohi H. Evaluation of microgap size and microbial leakage in the connection area of 4 abutments with Straumann (ITI) implant. J Oral Implantol 2012;38:677-85.

24. Mobilio N, Fasiol A, Franceschetti G, Catapano S. Marginal Vertical Fit along the Implant-Abutment Interface: A Microscope Qualitative Analysis. Dent J (Basel) 2016;4.

25. Byrne D, Houston F, Cleary R, Claffey N. The fit of cast and premachined implant abutments. J Prosthet Dent 1998;80:184-92.

26. Soo S, Garriga-Majo D, Palmer RM, Curtis RV. The longitudinal accuracy of fit of titanium implant superstructures superplastically formed on investment models. Dent Mater 2004;20:269-76.

27. Contrepois M, Soenen A, Bartala M, Laviole O. Marginal adaptation of ceramic crowns: a systematic review. J Prosthet Dent 2013;110:447-54 e10.

28. Holmes JR, Bayne SC, Holland GA, Sulik WD. Considerations in measurement of marginal fit. J Prosthet Dent 1989;62:405-8.

29. Meleo D, Baggi L, Di Girolamo M, Di Carlo F, Pecci R, Bedini R. Fixture-abutment connection surface and micro-gap measurements by 3D micro-tomographic technique analysis. Ann Ist Super Sanita 2012;48:53-8.

30. Sui X, Wei H, Wang D, Han Y, Deng J, Wang Y et al. Experimental research on the relationship between fit accuracy and fracture resistance of zirconia abutments. J Dent 2014;42:1353-9.

31. Wiest W, Zabler S, Rack A, Fella C, Balles A, Nelson K et al. In situ microradioscopy and microtomography of fatigue-loaded dental two-piece implants. J Synchrotron Radiat 2015;22:1492-7.

32. Prasad R, Al-Kheraif AA. Three-dimensional accuracy of CAD/CAM titanium and ceramic superstructures for implant abutments using spiral scan microtomography. Int J Prosthodont 2013;26:451-7.

33. Binon PP, McHugh MJ. The effect of eliminating implant/abutment rotational misfit on screw joint stability. Int J Prosthodont 1996;9:511-9.

34. Bondan JL, Oshima HM, Segundo RM, Shinkai RS, Mota EG, Meyer KR. Marginal fit analysis of premachined and castable UCLA abutments. Acta Odontol Latinoam 2009;22:139-42.

35. Kano SC, Bonfante G, Hussne R, Siqueira AF. Use of base metal casting alloys for implant framework: marginal accuracy analysis. J Appl Oral Sci 2004;12:337-43.

36. Blatz MB, Conejo J. The Current State of Chairside Digital Dentistry and Materials. Dent Clin North Am 2019;63:175-97.

37. Alghazzawi TF. Advancements in CAD/CAM technology: Options for practical implementation. J Prosthodont Res 2016;60:72-84.

38. Silva CEP, Soares S, Machado CM, Bergamo ETP, Coelho PG, Witek L et al. Effect of CAD/CAM Abutment Height and Cement Type on the Retention of Zirconia Crowns. Implant Dent 2018;27:582-7.

39. Lopes ACO, Machado CM, Bonjardim LR, Bergamo ETP, Ramalho IS, Witek L et al. The Effect of CAD/CAM Crown Material and Cement Type on Retention to Implant Abutments. J Prosthodont 2018.

40. Nouh I, Kern M, Sabet AE, Aboelfadl AK, Hamdy AM, Chaar MS. Mechanical Behavior of Posterior All-Ceramic Hybrid-Abutment-Crowns Versus Hybrid-Abutments with Separate Crowns - A Laboratory Study. Clin Oral Implants Res 2018.

41. Staubli N, Walter C, Schmidt JC, Weiger R, Zitzmann NU. Excess cement and the risk of peri-implant disease - a systematic review. Clin Oral Implants Res 2016.

42. Pauletto N, Lahiffe BJ, Walton JN. Complications associated with excess cement around crowns on osseointegrated implants: a clinical report. Int J Oral Maxillofac Implants 1999;14:865-8.

43. Rodriguez LC, Saba JN, Chung KH, Wadhwani C, Rodrigues DC. In vitro effects of dental cements on hard and soft tissues associated with dental implants. J Prosthet Dent 2017;118:31-5.

44. Goodacre CJ, Kan JY, Rungcharassaeng K. Clinical complications of osseointegrated implants. J Prosthet Dent 1999;81:537-52.

45. Hebel KS, Gajjar RC. Cement-retained versus screw-retained implant restorations: achieving optimal occlusion and esthetics in implant dentistry. J Prosthet Dent 1997;77:28-35.

46. Lee A, Okayasu K, Wang HL. Screw- versus cement-retained implant restorations: current concepts. Implant Dent 2010;19:8-15.

47. Michalakis KX, Hirayama H, Garefis PD. Cement-retained versus screw-retained implant restorations: a critical review. Int J Oral Maxillofac Implants 2003;18:719-28.

48. Pjetursson BE, Tan K, Lang NP, Bragger U, Egger M, Zwahlen M. A systematic review of the survival and complication rates of fixed partial dentures (FPDs) after an observation period of at least 5 years. Clin Oral Implants Res 2004;15:667-76.

49. Schiessl C, Schaefer L, Winter C, Fuerst J, Rosentritt M, Zeman F et al. Factors determining the retentiveness of luting agents used with metal- and ceramic-based implant components. Clin Oral Investig 2013;17:1179-90.

50. Wittneben JG, Joda T, Weber HP, Bragger U. Screw retained vs. cement retained implant-supported fixed dental prosthesis. Periodontol 2000 2017;73:141-51.

51. Sailer I, Muhlemann S, Zwahlen M, Hammerle CH, Schneider D. Cemented and screw-retained implant reconstructions: a systematic review of the survival and complication rates. Clin Oral Implants Res 2012;23 Suppl 6:163-201.

52. Kurbad A, Kurbad S. CAD/CAM-based implant abutments. Int J Comput Dent 2013;16:125-41.

53. Jemt T. Customized titanium single-implant abutments: 2-year follow-up pilot study. Int J Prosthodont 1998;11:312-6.

54. Kapos T, Evans C. CAD/CAM technology for implant abutments, crowns, and superstructures. Int J Oral Maxillofac Implants 2014;29 Suppl:117-36.

55. Lops D, Meneghello R, Sbricoli L, Savio G, Bressan E, Stellini E. Precision of the Connection Between Implant and Standard or Computer-Aided

Design/Computer-Aided Manufacturing Abutments: A Novel Evaluation Method. Int J Oral Maxillofac Implants 2018;33:23-30.

56. Hamilton A, Judge RB, Palamara JE, Evans C. Evaluation of the fit of CAD/CAM abutments. Int J Prosthodont 2013;26:370-80.

57. Vigolo P, Fonzi F, Majzoub Z, Cordioli G. Evaluation of gold-machined UCLA-type abutments and CAD/CAM titanium abutments with hexagonal external connection and with internal connection. Int J Oral Maxillofac Implants 2008;23:247-52.

58. Park JI, Lee Y, Lee JH, Kim YL, Bae JM, Cho HW. Comparison of fracture resistance and fit accuracy of customized zirconia abutments with prefabricated zirconia abutments in internal hexagonal implants. Clin Implant Dent Relat Res 2013;15:769-78.

59. Torabi Ardekani K, Ahangari AH, Farahi L. Marginal and internal fit of CAD/CAM and slip-cast made zirconia copings. J Dent Res Dent Clin Dent Prospects 2012;6:42-8.

60. Papadiochou S, Pissiotis AL. Marginal adaptation and CAD-CAM technology: A systematic review of restorative material and fabrication techniques. J Prosthet Dent 2018;119:545-51.

61. Kim MJ, Choi YJ, Kim SK, Heo SJ, Koak JY. Marginal Accuracy and Internal Fit of 3-D Printing Laser-Sintered Co-Cr Alloy Copings. Materials (Basel) 2017;10.

62. Oka Y, Sasaki J, Wakabayashi K, Nakano Y, Okamura SY, Nakamura T et al. Fabrication of a radiopaque fit-testing material to evaluate the three-dimensional accuracy of dental prostheses. Dent Mater 2016;32:921-8.

63. Moris ICM, Monteiro SB, Martins R, Ribeiro RF, Gomes EA. Influence of Manufacturing Methods of Implant-Supported Crowns on External and Internal Marginal Fit: A Micro-CT Analysis. Biomed Res Int 2018;2018:5049605.

64. Alves DCC, de Carvalho PSP, Elias CN, Vedovatto E, Martinez EF. In vitro analysis of the microbiological sealing of tapered implants after mechanical cycling. Clin Oral Investig 2016;20:2437-45.

65. Coelho AL, Suzuki M, Dibart S, N DAS, Coelho PG. Cross-sectional analysis of the implant-abutment interface. J Oral Rehabil 2007;34:508-16.

66. Lorenzoni FC, Coelho PG, Bonfante G, Carvalho RM, Silva NR, Suzuki M et al. Sealing Capability and SEM Observation of the Implant-Abutment Interface. Int J Dent 2011;2011:864183.

67. Tsuge T, Hagiwara Y, Matsumura H. Marginal fit and microgaps of implant-abutment interface with internal anti-rotation configuration. Dent Mater J 2008;27:29-34.

68. Baggi L, Di Girolamo M, Mirisola C, Calcaterra R. Microbiological evaluation of bacterial and mycotic seal in implant systems with different implant-abutment interfaces and closing torque values. Implant Dent 2013;22:344-50.

69. Schmitt CM, Nogueira-Filho G, Tenenbaum HC, Lai JY, Brito C, Doring H et al. Performance of conical abutment (Morse Taper) connection implants: a systematic review. J Biomed Mater Res A 2014;102:552-74.

70. Gil FJ, Herrero-Climent M, Lazaro P, Rios JV. Implant-abutment connections: influence of the design on the microgap and their fatigue and fracture behavior of dental implants. J Mater Sci Mater Med 2014;25:1825-30.

71. Freitas AC, Jr., Bonfante EA, Rocha EP, Silva NR, Marotta L, Coelho PG. Effect of implant connection and restoration design (screwed vs. cemented) in reliability and failure modes of anterior crowns. Eur J Oral Sci 2011;119:323-30.

72. Nissan J, Narobai D, Gross O, Ghelfan O, Chaushu G. Long-term outcome of cemented versus screw-retained implant-supported partial restorations. Int J Oral Maxillofac Implants 2011;26:1102-7.

73. Weber HP, Sukotjo C. Does the type of implant prosthesis affect outcomes in the partially edentulous patient? Int J Oral Maxillofac Implants 2007;22 Suppl:140-72.

74. Piattelli A, Piattelli M, Scarano A, Montesani L. Light and scanning electron microscopic report of four fractured implants. Int J Oral Maxillofac Implants 1998;13:561-4.

75. Velasquez-Plata D, Lutonsky J, Oshida Y, Jones R. A close-up look at an implant fracture: a case report. Int J Periodontics Restorative Dent 2002;22:483-91.

76. Kampe T, Haraldson T, Hannerz H, Carlsson GE. Occlusal perception and bite force in young subjects with and without dental fillings. Acta Odontol Scand 1987;45:101-7.

77. Fontijn-Tekamp FA, Slagter AP, Van Der Bilt A, Van THMA, Witter DJ, Kalk W et al. Biting and chewing in overdentures, full dentures, and natural dentitions. J Dent Res 2000;79:1519-24.