UNIVERSIDADE FEDERAL DE SANTA MARIA
CENTRO DE CIÊNCIAS DA SAÚDE
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS ODONTOLÓGICAS

Helder Callegaro Velho

AVALIAÇÃO DOS PARÂMETROS DE TESTES EMPREGADOS PARA INDUZIR FADIGA CÍCLICA EM MATERIAIS RESTAURADORES DENTÁRIOS

Santa Maria, RS
2021

Helder Callegaro Velho

AVALIAÇÃO DOS PARÂMETROS DE TESTES EMPREGADOS PARA INDUZIR FADIGA CÍCLICA EM MATERIAIS RESTAURADORES DENTÁRIOS

Dissertação apresentada ao Curso de Mestrado do Programa de Pós-Graduação em Ciências Odontológicas, área de concentração em Odontologia, ênfase em Prótese Dentária, da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para a obtenção do grau de **Mestre em Ciências Odontológicas**

Orientadora: Prof. Drª. Andressa Borin Venturini
Coorientador: Prof. Drº. Luiz Felipe Valandro

Santa Maria, RS
2021

This study was financied in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) – Finance Code 001

Velho, Helder Callegaro
Avaliação dos parâmetros de testes empregados para induzir fadiga cíclica em materiais restauradores dentários / Helder Callegaro Velho.- 2021.
98 p.; 30 cm

Orientadora: Andressa Borin Venturuni
Coorientador: Luiz Felipe Valandro
Dissertação (mestrado) - Universidade Federal de Santa Maria, Centro de Ciências da Saúde, Programa de Pós-graduação em Ciências Odontológicas, RS, 2021

1. Fadiga 2. Materiais restauradores dentários 3. Parâmetros de teste de fadiga I. Borin Venturuni, Andressa II. Valandro, Luiz Felipe III. Título.

Sistema de geração automática de ficha catalográfica da UFSM. Dados fornecidos pelo autor(a). Sob supervisão da Direção da Divisão de Processos Técnicos da Biblioteca Central. Bibliotecária responsável Paula Schoenfeldt Patta CRB 10/1728.

Declaro, HELDER CALLEGARO VELHO, para os devidos fins e sob as penas da lei, que a pesquisa constante neste trabalho de conclusão de curso (Dissertação) foi por mim elaborada e que as informações necessárias objeto de consulta em literatura e outras fontes estão devidamente referenciadas. Declaro, ainda, que este trabalho ou parte dele não foi apresentado anteriormente para obtenção de qualquer outro grau acadêmico, estando ciente de que a inveracidade da presente declaração poderá resultar na anulação da titulação pela Universidade, entre outras consequências legais.

Helder Callegaro Velho

AVALIAÇÃO DOS PARÂMETROS DE TESTES EMPREGADOS PARA INDUZIR FADIGA CÍCLICA EM MATERIAIS RESTAURADORES DENTÁRIOS

Dissertação apresentada ao Curso de Mestrado do Programa de Pós-Graduação em Ciências Odontológicas, área de concentração em Odontologia, ênfase em Prótese Dentária, da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para a obtenção do grau de **Mestre em Ciências Odontológicas**

Aprovado em 20 de fevereiro de 2021:

Andressa Borin Venturini, Drª. (UFSM)
(Orientadora / Presidente)

Camila da Silva Rodrigues, Drª. (UFSM)

Vinícius Felipe Wandscher, Dr. (CENEC)

Santa Maria, RS
2021

AGRADECIMENTOS

Chegar até este momento foi nada fácil, mas ao decorrer de minha trajetória sempre tive pessoas especiais ao meu lado que foram fundamentais para que eu chegasse até aqui. Por isso agradeço...

À Deus, por sempre me guiar pelo melhor caminho, por sempre fazer com que as coisas aconteçam no momento certo, por todas as pessoas especiais que têm colocado em meu caminho, por sempre me dar forças e coragem para encarar todas as dificuldades.

Aos meus pais Heliomar Velho e Aida Velho, por serem exemplos de caráter, honestidade, superação e dedicação total a família. Agradeço também pelos ensinamentos que vocês sempre me passaram, eles norteiam minha conduta e são alicerces para construção de minha vida pessoal e profissional. Obrigado por apoiarem todas as minhas escolhas, sempre me dando todo suporte necessário, se eu cheguei até aqui foi graças vocês!

Aos meus irmãos, obrigado pelo companheirismo e amizade, por estarem sempre dispostos a me ajudar, por compartilharem comigo os momentos bons e os momentos difíceis desta caminhada.

À minha namorada Jaqueline Tadiello, por ter estado sempre do meu lado desde o início, por sempre ter me dado apoio e me incentivado a seguir atrás dos meus objetivos, por ter estado do meu lado nos momentos de correria e cansaço, por cada palavra de carinho e acalento nos momentos difíceis. Muito obrigado por ser minha parceira, amiga e companheira de todas as horas.

À minha orientadora, Prof.ª Dra. Andressa Venturini, agradeço a confiança a mim depositada. Obrigado pela maestria com que conduziu a orientação dessa dissertação, pelos ensinamentos, por todo tempo e atenção a mim dirigidos. Obrigado por acreditar em mim e me incentivar sempre.

Ao meu coorientador, Prof. Dr. Luiz Felipe Valandro, agradeço a confiança a mim depositada. Obrigado, pelo apoio e por participar ativamente na concretização dos trabalhos.

Ao Prof. Dr. Gabriel Pereira, obrigado por contribuir ativamente na construção dos trabalhos, pelo tempo e atenção dispensados para revisão dos trabalhos. Obrigado pelos momentos de conversa e aconselhamentos.

À Kiara Dapieve, minha parceria na realização dos trabalhos. Muito obrigado por todo carinho, sensibilidade, atenção e disposição a mim dedicados durante a construção dos trabalhos. Obrigado por todos os momentos de conversa, risadas, pelas caronas até Jaguari. Obrigado por tornar essa trajetória mais leve.

À Prof.ª Dra. Sara Fraga, coautora do segundo estudo, muito obrigado pelas contribuições.

Aos colegas do grupo de pesquisa que me receberam de braços abertos, muito obrigado pela receptividade e por estarem sempre dispostos a me ajudar. À Simoni de Lima pelo suporte no laboratório e à Jéssica Dalcin pelo suporte nas questões burocráticas da pós-graduação.

Aos colegas de mestrado, em especial à Raquel Menezes, obrigado por ter sido minha parceira na realização dos seminários e por todos os momentos de conversa e desabafos. Também ao meu colega Eduardo Oliveira por todas as caronas até o centro e pelos momentos de conversa.

Aos professores da Pós-Graduação em Ciências Odontológicas (PPGCO). Prof.ª Dra. Marília Rippe, em especial, por ter colaborado com a presente dissertação durante o Exame de Qualificação. Aos demais professores do PPGCO, com quem tive a oportunidade de aprender. Nesse sentido, também agradeço a Prof.ª Dra. Catina Prochnow que também gentilmente contribuiu no Exame de Qualificação.

Aos membros da banca examinadora Prof.ª Dra. Camila da Silva Rodrigues, Prof. Dr. Vinícius Felipe Wandscher e Prof. Dr. Atais Bacchi por terem atendido ao convite para desempenhar este papel, dispondo de seu tempo e conhecimento na apreciação desse trabalho.

À Universidade Federal de Santa Maria, por me proporcionar um ensino público e de qualidade durante o mestrado, à CAPES, às empresas que doaram materiais para o desenvolvimento das pesquisas.

À Universidade Franciscana, por me proporcionar um ensino de qualidade durante a graduação. E neste sentido, reitero meus agradecimentos ao Prof. Dr. Vinícius Felipe Wandscher por ter sido meu incentivador, por ter me apresentado a iniciação científica, por todas as oportunidades que me deste durante toda a graduação. O senhor é parte fundamental desta trajetória, muito obrigado.

Enfim, agradeço imensamente as pessoas que acreditaram em mim, me apoiaram e que direta ou indiretamente contribuíram para a concretização dessa dissertação. Muito obrigado.

RESUMO

AVALIAÇÃO DOS PARÂMETROS DE TESTES EMPREGADOS PARA INDUZIR FADIGA CÍCLICA EM MATERIAIS RESTAURADORES DENTÁRIOS

AUTOR: Helder Callegaro Velho
ORIENTADORA: Andressa Borin Venturini
COORIENTADOR: Luiz Felipe Valandro

A presente dissertação está dividida em 2 estudos. O estudo 1 revisou sistematicamente a literatura para identificar os métodos e parâmetros de testes utilizados para induzir fadiga cíclica em espécimes não anatômicos de materiais restauradores dentários disponíveis comercialmente e discutir as indicações, limitações e implicações dos diferentes parâmetros de testes e métodos adotados. Foram selecionados estudos *in vitro* escritos em língua inglesa que avaliaram espécimes não anatômicos de materiais restauradores dentários disponíveis comercialmente, submetidos à fadiga cíclica. A busca foi realizada nas bases de dados *PubMed*, *Scopus* e *Web of Science* por 2 pesquisadores independentes. A busca inicial resultou em 1.848 artigos, dos quais 92 foram incluídos. Dentre os estudos incluídos, a maioria avaliou cerâmicas odontológicas, testadas sem a presença de um agente de cimentação ou substrato de suporte, utilizando ensaios de fadiga acelerados, frequências ≤2 Hz, pistões de aço inoxidável com ponta esférica, carregamento axial e ambiente de teste úmido. Assim, foi possível concluir que a definição da configuração do teste e do método de fadiga deve estar estritamente relacionada ao objetivo do estudo, e os achados devem ser compatíveis com o padrão de falha clínica ou conforme descrito nas diretrizes internacionais de testes mecânicos, onde a análise fractográfica é recomendada. O estudo 2 teve por objetivo avaliar a influência da frequência de carregamento no comportamento mecânico à fadiga de restaurações simplificadas de cerâmica infiltrada por polímeros (PICN) e dissilicato de lítio (LD). Trinta discos (Ø= 10 mm; espessura= 1,0 mm) de cada cerâmica foram cimentados adesivamente em discos de material análogo à dentina (Ø= 10 mm; espessura= 2,0 mm). Os espécimes foram alocados aleatoriamente em 4 grupos (n= 15) de acordo com o material cerâmico (LD ou PICN) e com a frequência de carregamento utilizada (2 ou 20 Hz). O teste de fadiga *stepstress* (carga inicial= 200 N; incremento= 100 N; 10.000 ciclos) foi executado e os dados foram analisados por testes de sobrevivência (Kaplan Meier e Mantel-Cox) e análise de Weibull. Nenhuma diferença estatística foi detectada em relação a carga para falha em fadiga e número de ciclos para falha entre os grupos do mesmo material cerâmico para as diferentes frequências avaliadas. Todas as falhas foram trincas radiais partindo da superfície de cimentação. Portanto, o uso de uma frequência de carregamento de 20 Hz é uma alternativa viável para acelerar os testes de fadiga, sem alterar os valores de carga para falha por fadiga, número de ciclos para falha e o padrão de falha de restaurações simplificadas de cerâmica infiltrada por polímeros e dissilicato de lítio.

Palavras-chave: Análise de sobrevivência. Cerâmicas odontológicas. Fadiga. Materiais dentários. Parâmetros de testes de fadiga. Resina composta.

ABSTRACT

EVALUATION OF TESTS PARAMETERS USED TO INDUCE CYCLIC FATIGUE IN DENTAL RESTORATIVE MATERIALS

AUTHOR: Helder Callegaro Velho
PROMOTER: Andressa Borin Venturini
CO-PROMOTER: Luiz Felipe Valandro

The present dissertation is divided into two studies. Study 1 systematically reviewed the literature to identify what are the methods and testing parameters used to induce fatigue on non-anatomic specimens of commercially available dental restorative materials, to discuss their indication, limitations, and implications. In vitro studies written in English which evaluated commercially available non-anatomic dental restorative material samples subjected to mechanical cyclic fatigue were selected. The search was performed in the PubMed, Scopus, and Web of Sciences databases by 2 independent researchers. The initial search yielded 1,848 articles, of which 92 were included. Among the studies included, most evaluated dental ceramic materials, tested without the presence of a luting agent, or supporting substrate, evaluated the materials using accelerated fatigue tests, frequencies ≤2 Hz, stainless steel indenters with a spherical tip, axial loading, and a wet test environment. Thus, it was possible to conclude that the definition of the test configuration and the fatigue method must be strictly related to the objective of the study, and the findings must be compatible with the clinical failure pattern or as described in the international standards for mechanical tests, in which fractographic analysis is recommended. Study 2 aimed to evaluate the influence of loading frequency on the mechanical fatigue behavior of polymer-infiltrated ceramic-network (PICN) and lithium disilicate (LD) simplified restorations. Thirty discs (Ø= 10 mm; thickness= 1.0 mm) of each ceramic material were adhesive cemented onto dentin analogue discs (Ø= 10 mm; thickness= 2.0 mm). The specimens were randomly allocated in 4 groups (n= 15) according to the ceramic (LD or PICN) and the loading frequency used (2 Hz or 20 Hz). Stepstress fatigue test (initial load= 200 N; increment= 100 N; 10,000 cycles) was performed and the data were analyzed by survival tests (Kaplan Meier and Mantel-Cox) and Weibull analysis. No statistical difference was detected in relation to fatigue failure load and number of cycles for failure between the groups of the same ceramic for the different frequencies evaluated. All failures were radial cracks in the cementation surface. Therefore, the use of a 20 Hz loading frequency shows to be a viable alternative to accelerate fatigue tests without changing the fatigue failure load values, number of cycles for failure and the failure pattern of simplified restorations made of lithium disilicate glass ceramic or polymer infiltrated ceramic network.

Keywords: Dental ceramics. Dental Materials. Fatigue. Fatigue test parameters. Resin composite. Survival analysis.

SUMÁRIO

1 INTRODUÇÃO GERAL

Os materiais restauradores dentários estão em constante evolução, visto que os avanços da odontologia adesiva e a demanda por estética têm favorecido o desenvolvimento de novos compósitos para substituir o amálgama, assim como cerâmicas reforçadas por partículas em troca das restaurações metalocerâmicas (BAYNE et al., 2019). Aliado a isso, a incorporação da tecnologia CAD/CAM (*Computer-Aided Design/Computer-Aided Manufacturing*) e o desenvolvimento de materiais restauradores em blocos manufaturados industrialmente para usinagem têm permitido a confecção de restaurações com maior confiabilidade mecânica devido à redução da presença de defeitos e poros no interior do material (ZHANG; KELLY, 2017).

No ambiente bucal, os materiais restauradores estão expostos à presença de umidade, cargas mastigatórias, alterações de temperatura e de pH (DENRY; HOLLOWAY, 2010). Além disso, esses materiais geralmente são submetidos à cargas muito abaixo de sua carga crítica, de forma contínua ou repetitiva, estando sujeitos à falha por fadiga (KELLY et al., 2017). Neste sentido, a avaliação *in vitro* prévia dos materiais restauradores dentários por meio de ensaios em fadiga é importante para estimar os valores de resistência, risco de falha ou comparar as variantes do material, e assim, estimar a capacidade mecânica destes e a sua compatibilidade com as demandas exigidas quando em função na cavidade oral (KELLY, 1999).

Fadiga pode ser definida como um processo de degradação (enfraquecimento) de um material, sob a influência de estresse mecânico, químico ou biológico, ou uma combinação destes (KELLY et al., 2017). O processo de falha por fadiga inicia com o aparecimento da trinca a partir de defeitos estruturais do material ou superficiais (desgaste com pontas abrasivas ou padrão topográfico promovido pelo processamento), resultando no crescimento dessa trinca e por fim, a falha catastrófica do material (ROSENTRITT; BEHR; PREIS, 2016). Dois mecanismos relevantes estão envolvidos neste processo, decorrentes ou do crescimento 'subcrítico' ou 'lento' de trincas (SCG) e/ou de efeitos cíclicos adicionais (KELLY et al., 2017). SCG é um processo que envolve o crescimento de trincas a partir de defeitos pré-existentes em níveis de tensão inferiores ao necessário para levar à fratura do material (TASKONAK et al., 2008). No que diz respeito ao processo de corrosão sob tensão assistido quimicamente por água, a difusão de moléculas de água na ponta de uma trinca causa hidrólise das ligações de siloxano (Si-O-Si) nas cerâmicas vítreas (CHARLES, 1958; FREIMAN; WIEDERHORN; MECHOLSKY, JR., 2009; MICHALSKE; FREIMAN, 1993; WIEDERHORN, 1967;

WIEDERHORN; BOLZ, 1970). Considerando as resinas compostas, a absorção de água da matriz resinosa pode levar à hidrólise das interfaces carga-matriz, acelerando o processo de falha (TAKESHIGE et al., 2007).

Neste sentido, os ensaios de fadiga são uma alternativa para a avaliação do comportamento mecânico dos materiais restauradores dentários a longo prazo, pois eles simulam um cenário mais próximo do que ocorre clinicamente (WISKOTT; NICHOLLS; BELSER, 1995). Os ensaios de fadiga podem ser classificados de acordo com o modo de aplicação de tensão ou deformação em: estático (permanecendo constante com o tempo), dinâmico (aplicado com uma taxa constante) ou cíclico (tensão ou magnitude de deformação variando com o tempo) (BARAN; BOBERICK; MCCOOL, 2001). No entanto, o carregamento cíclico é o teste de fadiga mais clinicamente relevante, pois produz uma melhor percepção sobre a resposta do material para uma vida útil completa (KELLY et al., 2017). Diversos ensaios de fadiga cíclica podem ser executados utilizando diferentes geometrias de teste e metodologias de ensaio de fadiga dependendo do objetivo do estudo em questão.

Geometrias de teste de flexão (resistência flexural 3-pontos, 4-pontos ou biaxial) são importantes para a caracterização e avaliação da confiabilidade dos materiais por meio da determinação de fadiga e limites de resistência, quando submetidos a fatores específicos (por exemplo, como um tratamento de superfície afeta uma propriedade do material, ou um método de processamento, entre outros) (KELLY et al., 2017). Por outro lado, o uso de geometrias de teste com espécimes no formato de coroas anatômicas ou não anatômicas (discos, placas ou coroas planas) cimentadas em um substrato de suporte (dentina, material análogo à dentina, metal) são uma alternativa para a aproximação dos ensaios laboratoriais com a realidade clínica, onde variáveis como cimentação adesiva passam a ser consideradas. Um ponto importante a ser observado neste tipo de geometria cimentada, é que os modos de falha sejam semelhantes aos padrões encontrados clinicamente(KELLY et al., 2010).

A respeito das metodologias de ensaios de fadiga, métodos como a determinação de gráficos de ciclos de tensões até a falha (curvas S-N) são notoriamente os que consomem mais tempo para aquisição dos dados, apesar de produzirem melhores percepções sobre a resposta do material para uma vida útil completa em relação aos ensaios de fadiga acelerados (KELLY et al., 2017). Uma alternativa a esses testes é o uso de métodos de fadiga acelerados como *Staircase*, *Stepstress* ou *Boundary*. Nesses ensaios, as amostras são submetidas a condições de teste mais severas (níveis de tensões superiores aos encontrados clinicamente) de forma a acelerar a falha, porém mantendo os modos de falha observados clinicamente (BONFANTE; COELHO, 2016; NELSON, 2004).

Após a definição da geometria do teste e do método de ensaio de fadiga, algumas variáveis do teste precisam ser definidas, como o pistão a ser utilizado para aplicar carga (material, formato e dimensão), frequência de carregamento (número de ciclos por segundo), número de ciclos e ambiente de teste (úmido ou seco). Em especial, a frequência de carregamento é uma das variáveis que pode influenciar no tempo necessário para a execução dos ensaios de fadiga cíclica. Na perspectiva de aproximação com a realidade clínica, onde a frequência mastigatória varia de 0,95 Hz a 2,15 Hz (PO et al., 2011), o uso de frequências próximas a 2 Hz parece ser a escolha ideal. No entanto, a aquisição dos dados torna-se muito lenta ao utilizar estas frequências. Neste sentido, alguns estudos vêm avaliando o uso que frequências de carregamento mais altas (10, 20 e 40 Hz) como alternativa para acelerar os ensaios de fadiga em diferentes materiais cerâmicos (FRAGA et al., 2016, 2020; JOSHI et al., 2014; KELLY et al., 2010). Maiores valores de carga para falha por fadiga foram encontrados para uma frequência de 20 Hz em comparação a 2 Hz em uma cerâmica a base de alumina infiltrada por vidro (KELLY et al., 2010). Por outro lado, Fraga et al. (2016) constataram que é possível acelerar os ensaios de fadiga em uma zircônia parcialmente estabilizada por óxido de ítrio (Y-TZP) utilizando uma frequência de 20 Hz sem influenciar os valores de resistência a fadiga. No que diz respeito às cerâmicas vítreas de fluorapatita (JOSHI et al., 2014) e reforçada por leucita (FRAGA et al., 2020), a frequência de carregamento não influenciou os valores de resistência à fadiga nem o tempo necessário para falha em testes de sobrevivência. No entanto, a adoção de frequências de carregamento mais altas para os demais materiais cerâmicos ainda requer investigação.

Frente ao exposto em relação a importância da avaliação do comportamento à fadiga de materiais restauradores dentários, conhecer os principais métodos utilizados e a influência dos diferentes parâmetros de teste na obtenção dos dados, configura-se como uma temática relevante que requer investigação. Neste sentido a presente dissertação está fragmentada em 2 artigos.

ARTIGO 1: *What are the methods and testing parameters used to induce mechanical fatigue in non-anatomic dental restorative material specimens? A scoping review.* Apresenta como objetivo revisar sistematicamente a literatura a fim de identificar os métodos, parâmetros de testes e características usadas para induzir fadiga cíclica em espécimes não anatômicos de materiais restauradores dentários, e discutir as indicações, limitações e implicações dos diferentes parâmetros de testes e métodos adotados.

ARTIGO 2: *Accelerated loading frequency does not influence the fatigue behavior of polymer infiltrated ceramic network or lithium disilicate glass-ceramic restorations.* O estudo visa avaliar se é possível acelerar os ensaios de fadiga aumentando a frequência de carregamento sem influenciar o comportamento mecânico à fadiga de restaurações de cerâmica infiltrada por polímeros e de dissilicato de lítio.

2 ARTIGO 1: WHAT ARE THE METHODS AND TESTING PARAMETERS USED TO INDUCE MECHANICAL FATIGUE IN NON-ANATOMIC DENTAL RESTORATIVE MATERIAL SPECIMENS? A SCOPING REVIEW.

Este artigo será submetido ao periódico *Materials Science and Engineering C: Materials for Biological Applications*, ISSN: 0928-4931. Fator de impacto: 5.88, Qualis CAPES A2. As normas para publicação estão descritas no Anexo A.

What are the methods and testing parameters used to induce mechanical fatigue in non-anatomic dental restorative material specimens? A scoping review

Helder Callegaro Velho[a], Kiara Serafini Dapieve[a], Gabriel Kalil Rocha Pereira[a], Luiz Felipe Valandro[a], Andressa Borin Venturini[a*]

[a]*MSciD and PhD Post-Graduate Program in Oral Science, Faculty of Dentistry, Federal University of Santa Maria (UFSM), Santa Maria, Rio Grande do Sul State, Brazil*

Authors' e-mail addresses

Helder Callegaro Velho (heldercvelho@hotmail.com)
Kiara Serafini Dapieve (kiara_s_d@hotmail.com)
Gabriel Kalil Rocha Pereira (gabrielkrpereira@hotmail.com)
Luiz Felipe Valandro (valandrolf@gmail.com)
Andressa Borin Venturini (andressa.venturini@hotmail.com)

***Corresponding author:** Andressa Borin Venturini, D.D.S, M.S.D., Ph.D., Assistant Researcher, Federal University of Santa Maria, Faculty of Odontology, MSciD-PhD Graduate Programs in Oral Science, Prosthodontics Unit, 1000 Roraima Av, T Street, Building 26F, Room 2360, UFSM Campus, 97105-900, Santa Maria, Brazil. E-mail: andressa.venturini@hotmail.com

Abstract

The aim of the present scoping review was to identify the methods, testing parameters, and characteristics used to induce cyclic fatigue on non-anatomic dental restorative material specimens, to discuss their indications, limitations, and implications. The protocol of this study, available online (https://osf.io/m95cz/), followed the Joana Briggs Institute guidelines, and the reporting was based on PRISMA Extension for Scoping Reviews. In vitro studies written in English which evaluated commercially available non-anatomic dental restorative material samples subjected to mechanical cyclic fatigue were selected. The search was performed in PubMed, Scopus and Web of Science databases by 2 independent researchers. Study screening was also undertaken by 2 independent researchers using the EndNote program. Next, a descriptive analysis was performed considering dental restorative material, luting agent, type of supporting substrate, test geometry, fatigue method, test parameters (loading frequency, material and shape/dimension of indenter, direction of load application), test environment conditions (dry or wet) and fractographic analysis (present or absent). The initial search yielded 1,848 articles, of which 92 were included. Based on the collected data, most of the included studies evaluated dental ceramic materials (n= 60, 65.2%); tested materials without the presence of a luting agent or supporting substrate (n= 60, 65.2%); used staircase (n= 52, 55.9%) or step-stress (n= 22, 23.7%) accelerated fatigue tests, loading frequencies below 2 Hz (n= 43, 42.6%), stainless steel (n= 19, 19.2%) or tungsten carbide (n= 14, 14.1%) load applicators with spherical shaped tip 40 mm diameter (n= 17, 18.3%) or <7 mm diameter (n= 12, 12.9%); applied only axial loads (n= 87, 92.6%); and considered a wet testing environment (n= 73, 75.3%). Although the flexural test configurations, axial loading and accelerated fatigue tests are the most used, the definition of test configuration, loading direction and fatigue method must be strictly related to the study objective. Loading frequencies below 2 Hz are the most used. Despite that, higher frequencies (e.g. 20 Hz) can be an alternative to accelerate the tests of materials such as Y-TZP ceramic, polymer infiltrated ceramic network and lithium disilicate glass-ceramic. Load applicators of different materials and shape/dimensions are described in the literature, but they should not alter the failure mode that the setup is mimicking, thus a careful fractographic analysis is essential. A wet test environment was described in most of the studies, which is an important tool to simulate the hydrolytic degradation of materials observed in clinical scenarios.

Keywords: Cyclic fatigue. Dental ceramics. Resin composites. Test variables.

1. Introduction

In vitro evaluation of dental restorative materials is essential to access their mechanical capacity and compatibility with the physiological demands when in function in the oral cavity. Hence, material's resistance values, risk of failure or comparing the material variants [1]. Dental restorative materials in the oral environment are subjected to challenging conditions such as humidity, temperature and pH variations [2]. In addition, these materials are usually loaded far below their critical load, either continuously or repetitively, meaning they are subjected to fatigue [3].

Fatigue is often defined as the degradation (weakening) of a structural component under the influence of mechanical, chemical, or biological stress, and in most cases a combination of them. This process mostly involves two major relevant mechanisms, arising either from 'subcritical' or 'slow' crack growth (SCG) and/or cyclic effects [3]. SCG is a process that involves the stable growth of pre-existing flaws at stress intensity factor (KI) levels lower than that necessary for the flaw to become unstable (KIc) [4]. In relation to the stress-corrosion process chemically assisted by water, the diffusion of water molecules at the tip of a crack causes hydrolysis of the siloxane bonds (Si-O-Si) in glass ceramics [5–9]. In addition, the mechanical degradation in ceramic materials is favored by the friction between crack walls during cyclic loading due to the change in the stress concentrated at the crack tip from tensile to compression (cyclic effects) [10]. Considering resin composite materials, water absorption from the resin matrix may lead to the hydrolysis of filler-matrix interfaces, accelerating the failure process [11].

Fatigue-induced failure mechanisms depend on the type of material [12]. Pre-existing flaws in ceramics originating from processing serve as nuclei for crack propagation. The crack propagates catastrophically when has grown to a critical size and the stress states at the crack tip exceeds the materials' fracture toughness [13]. The direct measurement of the crack velocity as a function of stress intensity factor is a way to determine SCG [14]. Several mechanisms may participate in fatigue-induced damage in composites. Among them, filler type [15], matrix cracking, matrix deformation, void formation, multidirectional cracking, filler debonding and filler failure [12]. A crack will start in either the matrix or the filler particles (or the interface), with the crack propagation and direction being continuously modified during the fatigue process, due to changes in the distribution of internal stresses [12].

In this sense, fatigue tests are an alternative for assessing the long-term behavior of dental restorative materials [16]. The mode of stress or strain application in fatigue tests may be static (remaining constant with time), dynamic (applied at some constant rate), or cyclic (stress or strain magnitude varying with time) [12]. However, the cyclic loading is the most clinically relevant fatigue test as they produce the best insight in the material response for a complete service life [3]. Thus, it is necessary that the tests are planned to simulate the different aspects to which dental restorative materials are subjected in order to accurately predict the clinical behavior and failure modes that occur clinically [1]. It is also necessary to define the test geometry, fatigue method and some test parameters such as, loading frequency, load applicator type (shape and dimension), test environment conditions and fractographic analysis. So far, there is no standardization for choosing these fatigue test parameters. Furthermore, the effect of using different parameters in cyclic fatigue tests on the mechanical behavior and failure mode of dental restorative materials is not completely clear. In addition, a compiled of literature would help to discuss the existing methods and guide future studies.

As mentioned, a wide range of variables which characterize cyclic fatigue tests associated with the large number of studies found in the literature makes the variability among studies very large, which in turn makes it difficult to compare their findings. Thus, the aim of the present scoping review was to systematically review the literature to identify the methods, testing parameters, and characteristics used to induce cyclic fatigue on non-anatomic restorative dental material specimens, to discuss their indications, limitations, and implications.

2. Materials and methods

The protocol of this study was based on the framework proposed by Peters et al. [17] according to the Joana Briggs Institute and is available at the following link: (https://osf.io/m95cz/). In addition, the reporting of this scoping review was based on PRISMA Extension for Scoping Reviews [18].

2.1 Inclusion criteria

In vitro studies which evaluated commercially available dental restorative material samples induced to mechanical cyclic fatigue were selected. Studies which evaluated single-unit restorations with simplified geometry (non-anatomic) were included, regardless of the type of dental restorative material or the presence of luting agents, and/or the type of adopted supporting substrate (e.g., tooth remnant tissues: enamel, dentin; or even simplified in vitro assemblies using resin composite, epoxy resin, metal alloys, ceramic alloys; among others). Studies which evaluated the mechanical fatigue performance of the restorative material following normative guidelines were also considered (i.e. disc- or bar- shaped tested under bending tests, among other methods). Studies which did not conduct a fatigue test until failure were not considered, for example studies which used mechanical cycling for aging, and then executed a static test.

2.2 Search

The search was performed in three databases (PubMed, Scopus and Web of Science) without date restrictions (last executed on May 07, 2020) and was limited to articles written in the English language. The search strategy was based on Mesh terms and free-text specific terms of PubMed and adapted for the Scopus and Web of Science databases (Table 1).

2.3 Screening

The search was initially undertaken using the EndNote program (EndNote X9, Thomson Reuters, New York, NY). Two researchers (H.C.V. and K.S.D.) independently identified articles by first analyzing titles and abstracts for relevance and the presence of the eligibility criteria. Retrieved records was classified as include, exclude, or uncertain. The full-text articles of the included and uncertain records were selected for further eligibility screening by 2 reviewers (H.C.V. and G.K.R.P) (acting independently). Discrepancies in screening of titles/abstracts and full text articles were resolved through a discussion.

2.4 Charting the results

A form was created using the Excel program (Microsoft Excel, Redmond, WA), which was tested by four reviewers to reach a consensus for data collections. Then, two reviewers (H.C.V. and K.S.D.) extracted the data and the other two reviewers (A.B.V. and G.K.R.P.) checked it. The following data were collected: dental restorative material, luting agent and type of supporting substrate (if present), test geometry, fatigue method, test parameters (loading frequency, type of load applicator – material and shape/dimension, load application direction), in accordance with normative guidelines (ISOs, ASTMs, or other), test environment conditions (dry or wet), and fractographic analysis (present or absent). Each data was considered separately in data collection for studies which used more than one restorative material, test method or parameter. Meanwhile, only new information was considered for studies in which data were based on previous studies (i.e. duplicate data were excluded).

2.5 Data analysis

The synthesis focused on describing the main characteristics of the studies regarding the collected data. In addition, qualitative analysis was performed and presented using tables and illustrations.

3. Results

The initial search resulted in 1848 studies. A total of 157 articles were considered eligible for full-text assessment after duplicate removal and assessment of titles and abstracts, from which 92 records were included for qualitative analysis (Figure 1). The bibliographic references of the included studies can be consulted in the supplementary material (List of included studies). The studies by Joshi et al. [19] and Joshi et al. [20] presented data which appeared to have been collected from the same group of specimens. Therefore, the data from the study by Joshi et al. [20] were excluded from the qualitative analysis to avoid the risk of duplicates.

Regarding the main characteristics of the included studies, most studies evaluated dental ceramics (n= 60; 65.2% – Table 2), whereas the remaining studies considered resin composites (n= 28; 30.4% - Table 2) or glass ionomer as restorative material (n= 4; 4.4% – Table 2). Most cyclic fatigue studies only tested the restorative material as test geometry (n= 57; 62% – Table 3), and only a few studies used simplified cemented geometries such as disc on disc (trilayer cemented assembly) (n= 25; 27.2% – Table 3) or simplified non-anatomic crowns (n= 7; 7.6% – Table 3). Figure 2 illustrates the specimen format used for each test geometry.

It is important to highlight that changes have been detected in the execution of cyclic fatigue tests over time. The use of support substrates and luting agents become more common after 2007 (Figure 3A). Regarding the fatigue methods, only the staircase approach (n= 14; 66.7%) and fatigue cycling until failure (n= 7; 33.3%) were reported until 2007. Other reported methods (e.g. step stress approach and boundary technique) have been used (Figure 3B) from that time forward. It can be emphasized that accelerated fatigue tests such as the staircase (n= 52; 55.9% - Table 4) and step-stress approaches (n= 22; 23.7% - Table 4) were the most used until 2020. The cycling until failure methods were only used in 16.1% (n= 15) of the studies (Table 4). A detailed description of the test methodologies performed by each study including fatigue method, loading frequency, material and shape of the load applicator, load application direction, test environment conditions, and use of normative guidelines are described in Table 4.

The load applicator material was not reported in 44.4% (n= 44) of the included studies, and the format/dimension was not reported in 46.2% studies (n= 43). Stainless steel (n= 19; 19.2%) and tungsten carbide (n= 14; 14.1%) were the most reported materials used for the load applicator. Different load applicator materials were compared in only two studies: Anderson et al. [21] compared load applicators made of nanohybrid composite resin dentures, unfilled acrylic resin dentures, tungsten carbide and a pressed leucite glass ceramic; meanwhile, Stijacic et al. [22] considered an interpenetrating polymer network resin-based dentures, heat-pressed leucite glass-ceramic on supporting a high noble alloy substructure, heat-pressed lithium disilicate and a zirconium dioxide load applicator. Spherical/hemispherical-shaped tip load applicator with a diameter of 40 mm in diameter were the most used (n= 17; 18.3%). The cylinder/circular-shaped tips (<3 mm) were used by 14.0% (n= 13) and spherical-shaped tips (<7 mm) by 12.9% (n= 12) of the studies.

Regarding load application mode, axial load application was reported by most studies (n= 87; 92.6%), while rotary was reported in 3.2% (n= 3) and sliding by 4.3% (n= 4) of the studies, respectively. A wet test environment was the most reported by the studies (n= 73; 75.3%). A dry test environment was reported for only 7.2% (n= 7) of the studies. Information about the test environment was not reported in 17.5% (n= 17) of studies. A fractographic analysis was performed by 78.5% (n= 73) of studies. A description of implementing normative guidelines for the fatigue test design was not reported in most of the included studies (n= 65; 69.8%). The ISO 6872 normative guideline was the most cited (n= 26; 28.0%).

4. Discussion

The present study is the first which attempts to provide a synthesis of information considering the test characteristics, parameters and methods used to induce cyclic fatigue in non-anatomical restorative dental material specimens. The data collected highlight that several test parameters and methodologies have been used to conduct fatigue tests on dental restorative materials. Therefore, it is important to discuss the methodological implications and the accurate approximation of the clinical reality.

In vitro tests grant the researcher the possibility of isolating factors and addressing specific parameters which may influence a desired outcome. On the other hand, in vitro tests may also enable adopting more complex testing scenarios which attempt to simulate almost all factors that a restoration may be exposed to in the clinical environment. This latter scenario is undeniably more complex [23]. Thus, the researcher should consider which experimental design and method are suitable to the study objective in order to access the outcome, isolating the desired study factors or associating them to do so. The use of non-anatomical specimens avoids the influence of different thicknesses of restorative material on the cusps, facilitating the control of the loads to predict stress distribution. In addition, the reduced time for sample preparation and the low cost are advantages of using non-anatomical specimens. In this sense, we believe that this is the main reason for the common use of non-anatomical specimens, and why this scoping review attempts to collect data and guide future research of such scenarios. Undoubtedly, a scoping review of anatomic samples may further contribute to the knowledge of this specific scientific field in the future.

4.1 Test geometry

The International Standardization Guidelines are available to guide the execution of mechanical tests in specimens of strict restorative materials with specific formats, such as the International Organization for Standardization - ISO 6872 (2015) for ceramic materials, ISO 10477 (2018) for polymer-based crown and veneering materials, and the American Society for Testing and Materials - ASTM e-647-93 (1994), which describe standard methods to estimate fatigue crack growth rates. Despite the existence of International Standardization Guidelines for non-anatomic specimens in flexural test configurations, only 26 studies reported the use of such guidelines from the

46 included studies which explored this scenario. Compliance with the guidelines outlined by an international association ensures that all factors of the fracture mechanics of the material are respected, avoiding potential masking of the effect of the studied factor on the outcome. It also enhances the reproducibility and comparability between studies. Therefore, it is mandatory to obey these guidelines when using such geometries. However, there are no guidelines to be followed when considering cemented specimens which involve more complex testing geometries. Thus, the recommendation that has been widely followed is that the mechanical tests should induce failures observed in a clinical scenario, which highlights the importance of fractographic analysis in both scenarios [13,23].

Most of the studies in non-anatomic specimens have evaluated materials in flexural test configurations (e.g. 3-point, 4-point, or biaxial flexural strength) (Table 3). These tests are important in characterizing and assessing the reliability of materials through determining fatigue, endurance limits and S-N curves submitted to specific factors (i.e. how a surface treatment affects a material property, or a processing method, among others) [3]. However, the specimens are loaded without being supported by any substrate in these tests, being exposed to more aggressive conditions than would occur clinically [24]. Restorations in the clinical setting are bonded to a support substrate (i.e. dental structure or metal core) and different stress distributions can be expected, depending on the modulus of elasticity of the restorative and substrate materials [25–27]. In addition, fatigue tests using cemented specimens can also evaluate the role of adhesive cementation in the mechanical behavior of restorations, since appropriate resin adhesion improves the fracture strength [28,29].

4.2 Fatigue method

Although cyclic fatigue tests are time-consuming experiments for data acquisition, they are the most clinically relevant approach and produce a better perception of the material’s response for a complete useful life [3]. Most studies have used accelerated fatigue tests (i.e. staircase, step-stress or boundary technique) (Table 4), which are an alternative to obtain data more quickly. The samples are subjected to more aggressive test conditions in these tests to accelerate the failure. Although they may be carefully executed to promote failure modes which occur clinically [23,30], it is important to consider the obtained data, the method used and its limitations. The staircase method determines the average fatigue limit value of the material for a determined useful life (number of cycles). However, the pre-defined number of cycles does not allow for predictions on different amounts of cycles and this test is not conducted in a wide force range or extreme stress values, which could mask performance under worst case scenarios [23]. On the other hand, each specimen in the step-stress method is loaded with increasing levels of load, meaning that after a certain period (number of cycles) the load is increased step-by-step until its failure or end of the test profiles. This method considers the cumulative effect of the applied stresses, estimating the probability of survival over time and predicting the reliability for a specific period [31,32]. Another accelerated fatigue test reported was the boundary technique. In this method, two groups of specimens are evaluated for each number of determined cycles, using two stress levels, one corresponding to a low probability of failure and the other with a stress amplitude corresponding to a high probability of failure. An advantage of this methodology is that the data obtained may be used to predict stresses corresponding to low probabilities of failure, providing more precision on estimating the stress range of clinical interest [33–35]. Despite being more efficient approaches (in terms of time and effort), the accelerated methods may limit any phenomenological insight of the material's behavior. In addition, they provide a limited image of the S-N curve and the slow crack growth parameters (n and A) [3]. In this case, the most comprehensive approach is to determine stress-cycles-to-failure plots (S–N, Wöhler curve) [3]. Thus, the choice of the fatigue method must consider the necessary parameters to answer the study objectives.

4.3 Test parameters

The test parameters must then be defined after choosing the test geometry and the fatigue method, including the loading frequency, the type of load applicator (material, shape, and dimension), the load application direction and the test environment. The researcher should consider the material microstructure, the way the crack propagates into it and the influence mechanism of each of these parameters in the fatigue induction to select these parameters.

Regarding the loading frequency, it was observed herein that frequencies below 2 Hz were the most reported by the studies (Table 4), with these values being close to the masticatory frequency (1-2 Hz) [36]. However, the use of low loading frequencies can make data acquisition very time consuming. As mentioned, the friction between the crack walls during cyclic loading can contribute to the crack propagation (mechanical degradation) [10]. This mechanism can be influenced by the loading frequency adopted by the cyclic testing, since the time available for opening and closing the crack may vary according to the frequency adopted.

It is important to highlight that the way the crack propagates changes according to the material's microstructure [3,37,38]. In this sense, adopting higher frequencies (e.g. 10, 20 or 40 Hz) must be carefully considered. It was possible to accelerate the fatigue tests in yttria-stabilized polycrystalline tetragonal zirconia (Y-TZP), polymer infiltrated ceramic network and lithium disilicate glass-ceramic using a frequency of up to 20 Hz [39,40]. However, no differences were observed in the time required for failure using frequencies of 2 or 10 Hz in fluoropatite glass-ceramic [20]. Likewise, a frequency of 20 Hz did not decrease the time required for failure in a leucite-reinforced glass-ceramic, since it required a greater number of cycles for failure for a frequency of

20 Hz compared to 2 Hz [41]. Higher fatigue failure load values were also observed when a glass-infiltrated alumina ceramic was tested using a frequency of 20 Hz compared to 2 Hz [42]. In addition, loading frequencies below 5 Hz have been adopted for resin composites, it is advocated that, due to their viscoelastic properties, high loading frequencies could lead to internal heating during fatigue testing, which may affect results [15,43]. Despite that we did not find conclusive data comparing different loading frequencies for resin composite or other ceramic materials. Therefore, future studies evaluating and comparing this factor are still suggested.

In addition to frequency, the load applicator choice is also a factor which influences the fatigue tests, since the material, shape and dimensions are important variables for failure modes and stress distribution [1]. Despite this, data regarding the load applicator used were not presented in most of the studies (Table 4), which makes reproducibility and comparison between studies difficult. The use of materials with a high modulus of elasticity (i.e. stainless steel and tungsten carbide) for the load applicator may overestimate resistance values [1,44], as it may induce greater contact pressure and consequently higher stress concentrations [42]. Another factor which can also influence the test results is the shape and dimension of load applicator. According to Kelly et al. [1], spheres which are 40 mm to 1 m in diameter would be necessary to generate clinically realistic occlusal contact areas. It is important to pay attention to this aspect, because in decreasing the load applicator diameter, the contact area between load applicator and restorative material is consequently also reduced, generating very high contact pressures which are not reflected in clinically relevant failures [1]. Moreover, flat load applicators should be avoided because they can become edge-loading applicators when the tested material deforms slightly beneath the load applicator [1], with the exception of studies that adopt the International Standardization Guidelines, such as ISO 6872(2015) which standardizes the use of a flat load applicators (1.4 ± 0.2 mm).

Sliding load application was little explored by the included studies when the load application direction is considered, whereas the majority used only axial loads (Table 4). This finding is completely expected, since anatomical specimens are commonly used with this complex loading scenario, but which were excluded from this scoping review limiting the discussion on this topic. Even so, the purpose of using sliding loads is to simulate inclination of the posterior dental cusp and the occlusal contacts assumed during chewing [45]. Among the included studies herein, only one compared axial loading and sliding loading on the reliability and fracture patterns of zirconia cores veneered with pressable porcelain. In this study they concluded that the reliability was not influenced by the load orientation (uni-axial vs. off-axis/sliding), but incorporation of sliding resulted in more aggressive damage to the veneer (partial cone cracks) [46].

Another important aspect is the test environment, as the presence of humidity may influence the fatigue phenomena through a chemical degradation process [3], which reinforces the necessity of a wet environment during testing. A wet environment was the most used by studies in the current scoping review (Table 4), which denotes the authors' attention in this regard. It should be noted that this chemical degradation process occurs in conjunction with the mechanical degradation caused by cyclic loading over time. In this sense, the use of higher frequencies decreases the action time of the water, which can hinder the chemical degradation process [47].

We highlight the importance of the fractographic analysis of failed specimens throughout this review, replicating and enabling comparison with the clinically found flaws or predicted in the fractography guidance. Additionally, the guidance for fractographic analysis by Scherrer et al. [13] highlights the importance of fractographic analysis to characterize the observed flaws, serving to elucidate the failure origin, failure causes, loading conditions and the crack direction. Cracks in specimens tested in flexural test configurations are expected to start from defects on the tensile side (bottom) towards the compression side (top), where a compression curl is found [13]. Non-anatomical cemented test geometries simulate a scenario closer to that of clinical restorations to predict mechanical performance, where failure modes should mimic those which are clinically reported [3]. Some of the commonly observed clinical fracture modes include cracks initiating from the cementation interface surface opposite the load application [42] and in the crown margin region, juxtaposed at the end of the restoration preparation [48]. Defects introduced by processing in both scenarios would be responsible for triggering stress concentrations during mechanical loading that would induce the coalescence of these defects and subsequently catastrophic crack propagation [49]. Another region responsible for the origin of failures is the occlusal surface [50], as these failures would start from defects introduced by milling and grinding procedures, which are part of the fabrication and fitting/adjusting processes restorations [51,52]. In addition, failures can also initiate from wear facets, where wear related microcracks can form [53].

The limitations of this scoping review mainly include the great heterogeneity among the studies included regarding the considered materials, the specimen formats, testing characteristics, parameters and methods. Even though, this allows a discussion and guidance for future studies, the absence of primary studies comparing the influence of such factors in acquiring fatigue data makes it difficult to indicate one parameter or another. In this sense, further studies are required. In addition, we did not conduct a risk of bias assessment of the included studies, because this is a scoping review. In the future, a risk of bias assessment may become feasible when a systematic review and meta-analysis of the influence of each factor is possible. Despite this, our scoping review successfully points out that researchers have given importance to assessing the fatigue behavior of dental restorative materials and that studies have explored different methods and test configurations as an alternative to predict the clinical reality. Furthermore, our scoping review is the first to provide a discussion of the effects of each testing parameter and method and provides tools for the researcher to select the best method and parameters which suit the study objective.

5. Conclusion

- Flexural test configurations, axial loading and accelerated fatigue tests are the most used. However, the definition of test configuration, loading direction and fatigue method must be strictly related to the study objective.
- Loading frequencies below 2 Hz are the most used. Despite that, higher loading frequencies (i.e., 20 Hz) prove to be an alternative to accelerate the tests of materials such as Y-TZP ceramic, polymer infiltrated ceramic network and lithium disilicate glass-ceramic.
- Load applicators of different materials and shape/dimensions are described in the literature, but they should not alter the failure mode that the setup is mimicking, thus a careful fractographic analysis is essential.
- A wet test environment was described in most of the studies, which is an important tool to simulate the hydrolytic degradation of materials observed in clinical scenarios.

Acknowledgements

This study was partly supported by: the Brazilian Federal Agency for Coordination of Improvement of Higher Education Personnel – CAPES, Brazil (Finance code 001, H.C.V. Master’s scholarship); the Foundation for Research Support of the Rio Grande do Sul State, Brazil – FAPERGS (A.B.V. post-doctorate scholarship; grants # 18/2551-0000520-7). This study is part of the Master’s Dissertation by (H.C.V.). The authors declare no conflicts of interest.

References

[1] J.R. Kelly, Clinically relevant approach to failure testing of all-ceramic restorations, J. Prosthet. Dent. 81 (1999) 652–661. https://doi.org/10.1016/S0022-3913(99)70103-4.

[2] I. Denry, J. Holloway, Ceramics for Dental Applications: A Review, Materials (Basel). 3 (2010) 351–368. https://doi.org/10.3390/ma3010351.

[3] J.R. Kelly, P.F. Cesar, S.S. Scherrer, A. Della Bona, R. van Noort, M. Tholey, A. Vichi, U. Lohbauer, ADM guidance-ceramics: Fatigue principles and testing, Dent. Mater. 33 (2017) 1192–1204. https://doi.org/10.1016/j.dental.2017.09.006.

[4] B. Taskonak, J.A. Griggs, J.J.J. Mecholsky, J.-H. Yan, Analysis of subcritical crack growth in dental ceramics using fracture mechanics and fractography., Dent. Mater. 24 (2008) 700–707. https://doi.org/10.1016/j.dental.2007.08.001.

[5] R. Charles, Static fatigue of glass, J. Appl. Phys. (1958) 1549–60.

[6] S.W. Freiman, S.M. Wiederhorn, J.J. Mecholsky, Jr., Environmentally Enhanced Fracture of Glass: A Historical Perspective, J. Am. Ceram. Soc. 92 (2009) 1371–1382. https://doi.org/10.1111/j.1551-2916.2009.03097.x.

[7] S.M. Wiederhorn, Influence of Water Vapor on Crack Propagation in Soda-Lime Glass, J. Am. Ceram. Soc. 50 (1967) 407–414. https://doi.org/10.1111/j.1151-2916.1967.tb15145.x.

[8] S.M. Wiederhorn, L.H. Bolz, Stress Corrosion and Static Fatigue of Glass, J. Am. Ceram. Soc. 53 (1970) 543–548. https://doi.org/10.1111/j.1151-2916.1970.tb15962.x.

[9] T.A. Michalske, S.W. Freiman, A Molecular Mechanism for Stress-Corrosion in Vitreous Silica, J. Am. Ceram. Soc. 66 (1993) 284–288.

[10] W. Jian, J. Zhihao, W. Xiaotian, A comparison of failure predictions by dynamic bending and cyclic bending fatigue techniques for Y2O3ZrO2 ceramics, Int. J. Fatigue. 15 (1993) 37–40. https://doi.org/10.1016/0142-1123(93)90075-2.

[11] F. Takeshige, Y. Kawakami, M. Hayashi, S. Ebisu, Fatigue behavior of resin composites in aqueous environments, Dent. Mater. 23 (2007) 893–899. https://doi.org/10.1016/j.dental.2006.06.031.

[12] G. Baran, K. Boberick, J. McCool, Fatigue of restorative materials., Crit. Rev. Oral Biol. Med. an Off. Publ. Am. Assoc. Oral Biol. 12 (2001) 350–360. https://doi.org/10.1177/10454411010120040501.

[13] S.S. Scherrer, U. Lohbauer, A. Della Bona, A. Vichi, M.J. Tholey, J.R. Kelly, R. van Noort, P.F. Cesar, ADM guidance-Ceramics: guidance to the use of fractography in failure analysis of brittle materials., Dent. Mater. 33 (2017) 599–620. https://doi.org/10.1016/j.dental.2017.03.004.

[14] M. Borba, M.D. de Araújo, K.A. Fukushima, H.N. Yoshimura, P.F. Cesar, J.A. Griggs, Á. Della Bona, Effect of the microstructure on the lifetime of dental ceramics, Dent. Mater. 27 (2011) 710–721. https://doi.org/10.1016/j.dental.2011.04.003.

[15] M.B. Shah, J.L. Ferracane, J.J. Kruzic, Mechanistic aspects of fatigue crack growth behavior in resin based dental restorative composites., Dent. Mater. 25 (2009) 909–916. https://doi.org/10.1016/j.dental.2009.01.097.

[16] H.W. Wiskott, J.I. Nicholls, U.C. Belser, Stress fatigue: basic principles and prosthodontic implications., Int. J. Prosthodont. 8 (1995) 105–16.

[17] M.D. Peters, C.M. Godfrey, H.K. Bpharm, P. Mcinerney, D. Parker, C.B. Soares, Guidance for conducting systematic scoping reviews, Int J Evid Basead Heal. 13 (2015) 141–146. https://doi.org/10.1097/XEB.0000000000000050.

[18] A.C. Tricco, E. Lillie, W. Zarin, K.K.O. Brien, H. Colquhoun, D. Levac, D. Moher, M.D.J. Peters, T. Horsley, L. Weeks, L. Hartling, A. Aldcroft, M.G. Wilson, C. Garritty, Research and reporting methods PRISMA Extension for Scoping Reviews (PRISMA-ScR): checklist and explanation, Ann Interm Med. 169 (2018) 467–473. https://doi.org/10.7326/M18-0850.

[19] G. V Joshi, Y. Duan, A. Della Bona, T.J. Hill, K. St John, J.A. Griggs, Fatigue loading and R-curve behavior of a dental glass-ceramic with multiple flaw distributions., Dent. Mater. 29 (2013) 1123–1131. https://doi.org/10.1016/j.dental.2013.08.208.

[20] G. V. Joshi, Y. Duan, A. Della Bona, T.J. Hill, K. St. John, J.A. Griggs, Contributions of stress corrosion and cyclic fatigue to subcritical crack growth in a dental glass-ceramic, Dent. Mater. 30 (2014) 884–890. https://doi.org/10.1016/j.dental.2014.05.026.

[21] M.R. Anderson, K.-H. Chung, B.D. Flinn, A.J. Raigrodski, An in vitro study of the effect of different restorative materials on the reliability of a veneering porcelain, J. Prosthet. Dent. 110 (2013) 521–528. https://doi.org/10.1016/j.prosdent.2013.09.009.

[22] T. Stijacic, K.-H. Chung, B.D. Flinn, A.J. Raigrodski, Effect of Tooth-Colored Restorative Materials on Reliability of Heat-Pressed Lithium Disilicate, J. Prosthodont. 24 (2015) 475–483. https://doi.org/10.1111/jopr.12243.

[23] E.A. Bonfante, P.G. Coelho, A Critical Perspective on Mechanical Testing of Implants and Prostheses., Adv. Dent. Res. 28 (2016) 18–27. https://doi.org/10.1177/0022034515624445.

[24] C.B. Vicari, B. de O. Magalhães, J.A. Griggs, M. Borba, Fatigue Behavior of Crystalline-Reinforced Glass-Ceramics, J. Prosthodont. 28 (2018) e297–e303. https://doi.org/10.1111/jopr.12739.

[25] R. Ottoni, J.A. Griggs, P.H. Corazza, Á. Della Bona, M. Borba, Precision of different fatigue methods for predicting glass-ceramic failure., J. Mech. Behav. Biomed. Mater. 88 (2018) 497–503. https://doi.org/10.1016/j.jmbbm.2018.09.004.

[26] J.C. Facenda, M. Borba, P. Benetti, A. Della Bona, P.H. Corazza, Effect of supporting substrate on the failure behavior of a polymer-infiltrated ceramic network material., J. Prosthet. Dent. 121 (2019) 929–934. https://doi.org/10.1016/j.prosdent.2018.08.008.

[27] A.M. de O. Dal Piva, J.P.M. Tribst, A.L.S. Borges, R.O. de A. e Souza, M.A. Bottino, CAD-FEA modeling and analysis of different full crown monolithic restorations, Dent. Mater. 34 (2018) 1342–1350. https://doi.org/10.1016/j.dental.2018.06.024.

[28] P.C. Guess, J.R. Strub, N. Steinhart, M. Wolkewitz, C.F.J. Stappert, All-ceramic partial coverage restorations—Midterm results of a 5-year prospective clinical splitmouth study, J. Dent. 37 (2009) 627–637. https://doi.org/10.1016/j.jdent.2009.04.006.

[29] M.B. Blatz, M. Vonderheide, J. Conejo, The Effect of Resin Bonding on Long-Term Success of High-Strength Ceramics, J. Dent. Res. 97 (2018) 132–139. https://doi.org/10.1177/0022034517729134.

[30] W.B. Nelson, Accelerated Testing: Statistical Models, Test Plans, and Data Analysis, Hoboken, New Jersey, 2004.

[31] A. Mettas, P. Vassiliou, Modeling and analysis of time-dependent stress accelerated life data, in: Annu. Reliab. Maintainab. Symp. 2002 Proc. (Cat. No.02CH37318), IEEE, 2002: pp. 343–348. https://doi.org/10.1109/RAMS.2002.981665.

[32] W. Nelson, Accelerated Life Testing - Step-Stress Models and Data Analyses, IEEE Trans. Reliab. R-29 (1980) 103–108. https://doi.org/10.1109/TR.1980.5220742.

[33] W. Maennig, Statistical planning and evaluation of fatigue tests. A survey of recent results, Int J Fract. 11

(1975) 123–129.

[34] Y. Zhang, J.A. Griggs, Evaluation of failure probability estimators for cyclic fatigue using boundary technique, J. Mater. Sci. Lett. 22 (2003) 1775–1777. https://doi.org/10.1023/B:JMSL.0000005418.37199.f7.

[35] M.C.D.N.J.M. Huysmans, P.G.T. Van Der Varst, R. Schäfer, M.C.R.B. Peters, A.J.M. Plasschaert, U. Soltesz, Fatigue Behavior of Direct Post-and-core-restored Premolars, J. Dent. Res. 71 (1992) 1145–1150. https://doi.org/10.1177/00220345920710050301.

[36] J.M.C. Po, J.A. Kieser, L.M. Gallo, A.J. Tésenyi, P. Herbison, M. Farella, Time-Frequency Analysis of Chewing Activity in the Natural Environment, J. Dent. Res. 90 (2011) 1206–1210. https://doi.org/10.1177/0022034511416669.

[37] J. Chevalier, L. Gremillard, S. Deville, Low-Temperature Degradation of Zirconia and Implications for Biomedical Implants, Annu. Rev. Mater. Res. 37 (2007) 1–32. https://doi.org/10.1146/annurev.matsci.37.052506.084250.

[38] J.J. Kruzic, J.A. Arsecularatne, C.B. Tanaka, M.J. Hoffman, P.F. Cesar, Recent advances in understanding the fatigue and wear behavior of dental composites and ceramics, J. Mech. Behav. Biomed. Mater. 88 (2018) 504–533. https://doi.org/10.1016/j.jmbbm.2018.08.008.

[39] S. Fraga, G.K.R. Pereira, M. Freitas, C.J. Kleverlaan, L.F. Valandro, L.G. May, Loading frequencies up to 20Hz as an alternative to accelerate fatigue strength tests in a Y-TZP ceramic., J. Mech. Behav. Biomed. Mater. 61 (2016) 79–86. https://doi.org/10.1016/j.jmbbm.2016.01.008.

[40] H.C. Velho, K.S. Dapieve, G.K. Rocha Pereira, S. Fraga, L.F. Valandro, A.B. Venturini, Accelerated loading frequency does not influence the fatigue behavior of polymer infiltrated ceramic network or lithium disilicate glass-ceramic restorations, J. Mech. Behav. Biomed. Mater. 110 (2020) 103905. https://doi.org/10.1016/j.jmbbm.2020.103905.

[41] S. Fraga, C. da S. Rodrigues, C.P. Zucuni, G.K.R. Pereira, M.N. Barbosa, L.F. Valandro, L.G. May, High load frequency at 20Hz: Its effects on the fatigue behavior of a leucite-reinforced glass-ceramic, J. Mech. Behav. Biomed. Mater. 107 (2020) 103769. https://doi.org/10.1016/j.jmbbm.2020.103769.

[42] J.R. Kelly, P. Rungruanganunt, B. Hunter, F. Vailati, Development of a clinically validated bulk failure test for ceramic crowns, J. Prosthet. Dent. 104 (2010) 228–238. https://doi.org/10.1016/S0022-3913(10)60129-1.

[43] G.M. Loughran, A. Versluis, W.H. Douglas, Evaluation of sub-critical fatigue crack propagation in a restorative composite, Dent. Mater. 21 (2005) 252–261. https://doi.org/10.1016/j.dental.2004.04.005.

[44] R. Yang, D. Arola, Z. Han, X. Zhang, A comparison of the fracture resistance of three machinable ceramics after thermal and mechanical fatigue, J. Prosthet. Dent. 112 (2014) 878–885. https://doi.org/10.1016/j.prosdent.2014.03.005.

[45] T. Santana, Y. Zhang, P. Guess, V.P. Thompson, E.D. Rekow, N.R.F.A. Silva, Off-axis sliding contact reliability and failure modes of veneered alumina and zirconia., Dent. Mater. 25 (2009) 892–898. https://doi.org/10.1016/j.dental.2009.01.093.

[46] E.A. Bonfante, P.G. Coelho, P.C. Guess, V.P. Thompson, N.R.F.A. Silva, Fatigue and damage accumulation of veneer porcelain pressed on Y-TZP., J. Dent. 38 (2010) 318–324. https://doi.org/10.1016/j.jdent.2009.12.004.

[47] I. ASM, Fatigue, in: F.C. Campbell (Ed.), Elem. Metall. AndE Ngineering Alloy., ASM International, United States, 2008: pp. 243–264.

[48] M. Øilo, A.D. Hardang, A.H. Ulsund, N.R. Gjerdet, Fractographic features of glass-ceramic and zirconia-based dental restorations fractured during clinical function, Eur. J. Oral Sci. 122 (2014) 238–244. https://doi.org/10.1111/eos.12127.

[49] Y. Zhang, I. Sailer, B.R. Lawn, Fatigue of dental ceramics., J. Dent. 41 (2013) 1135–1147. https://doi.org/10.1016/j.jdent.2013.10.007.

[50] I. Sailer, J. Gottnerb, S. Kanelb, C.H.F. Hammerle, Randomized controlled clinical trial of zirconia-ceramic and metal-ceramic posterior fixed dental prostheses: a 3-year follow-up., Int. J. Prosthodont. 22 (2009) 553–60. http://www.ncbi.nlm.nih.gov/pubmed/19918588.

[51] A. Della Bona, J.R. Kelly, The Clinical Success Of All-Ceramic Restorations, J. Am. Dent. Assoc. 139 (2008) S8–S13. https://doi.org/10.14219/jada.archive.2008.0361.

[52] C. Taufer, A. Della Bona, Edge chipping resistance of ceramics bonded to a dentine analogue, J. Mech. Behav. Biomed. Mater. 90 (2019) 587–590. https://doi.org/10.1016/j.jmbbm.2018.11.010.

[53] Z. Pang, A. Chughtai, I. Sailer, Y. Zhang, A fractographic study of clinically retrieved zirconia–ceramic and metal–ceramic fixed dental prostheses, Dent. Mater. 31 (2015) 1198–1206. https://doi.org/10.1016/j.dental.2015.07.003.

TABLES

Table 1. Search strategy according to each database.

PUBMED
*("Composite Resins"[Mesh] OR Composite resin OR resin-ceramic OR ceramic/polymer material OR polymer-infiltrated ceramic OR hybrid ceramic OR resin nano ceramic OR polymer-infiltrated-ceramic-network material OR CAD/CAM composite OR "ceramics" [Mesh] OR ceramic OR "dental porcelain" [Mesh] OR porcelain OR Glass ceramic OR polycrystalline ceramic OR Feldspathic OR Lithium disilicate OR lithium silicate OR zirconia OR yttrium polycrystalline tetragonal zirconia OR Leucite OR CAD/CAM OR CAD-CAM OR computer aided design OR computer aided machine) AND (Fatigue[*Mesh*] OR Fatigue) NOT (review OR wear OR shear OR retention OR tensile)*
SCOPUS   *("Composite resin" OR "resin-ceramic" OR "ceramic/polymer material" OR "polymer-infiltrated ceramic" OR "hybrid ceramic" OR "resin nano ceramic" OR "polymer-infiltrated-ceramic-network material" OR "CAD/CAM composite" OR "ceramics" OR "ceramic" OR "porcelain" OR "Glass ceramic" OR "polycrystalline ceramic" OR "Feldspathic" OR "Lithium disilicate" OR "lithium silicate" OR "zirconia" OR "yttrium polycrystalline tetragonal zirconia" OR "Leucite" OR "CAD/CAM" OR "CAD-CAM" OR "computer aided design" OR "computer aided machine") AND ("Fatigue") AND NOT ("review" OR "wear" OR "shear" OR "retention" OR "tensile") AND (LIMIT-TO (SUBJAREA , "DENT"))*
Web of Science   *(TS=(Composite resin) OR TS=(resin-ceramic) OR TS=(ceramic/polymer material) OR TS=(polymer-infiltrated ceramic OR TS=(hybrid ceramic) OR TS=(resin nano ceramic) OR TS=(polymer-infiltrated-ceramic-network material) OR TS=(CAD/CAM composite) OR TS=(ceramic) OR TS=(porcelain) OR TS=(Glass ceramic) OR TS=(polycrystalline ceramic) OR TS=(Feldspathic) OR TS=(Lithium disilicate) OR TS=(lithium silicate) OR TS=(zirconia) OR TS=(yttrium polycrystalline tetragonal zirconia) OR TS=(Leucite) OR TS=(CAD/CAM) OR TS=(CAD-CAM) OR TS=(computer aided design) OR TS=(computer aided machine)) AND (TS=(fatigue)) NOT (TS=(review) OR TS=(wear) OR TS=(shear) OR TS=(retention) OR TS=(tensile)) AND SU=(Dentistry)*

Table 2. Description of the materials used in the included studies.

Materials	**n (%)**
Dental restorative material*	
Dental ceramics	60 (65.2)
Resin composites	28 (30.4)
Glass ionomer as restorative material	4 (4.4)
Luting agent	
Not applicable	60 (65.2)
Resin cement	31 (33.7)
Zinc phosphate	1 (1.1)
Supporting substrate	
Not applicable	60 (65.2)
Dentin analogue	24 (26.1)
Resin composite	8 (8.7)

Table 3. Description of the test geometries used in the included studies.

Test geometry	**n (%)**
Only restorative material	**57 (62.0)**
Biaxial flexural strength	20 (21.7)
3-point flexure strength	14 (15.2)
4-point flexure strength	12 (13.0)
Rotating cantilever beam test	3 (3.3)
Flexural Strength according Bream et al. (1994)	2 (2.2)
Diametral compression	2 (2.2)
Compressive loading	2 (2.2)
Compact-tension	1 (1.1)
Bending cantilever beam test	1 (1.1)
Restorative material cemented on substrate	**32 (34.8)**
Trilayer cemented assembly*	25 (27.2)
Simplified non-anatomic crowns	7 (7.6)
Unclear geometry	**3 (3.2)**

Table 4. Description of the fatigue methods and test parameters used by the included studies.

Fatigue method	**n (%)**
Staircase	52 (55.9)
Step stress	22 (23.7)
Fatigue cycling until failure	15 (16.1)
Boundary technique	3 (3.2)
Unclear	1 (1.1)
Fatigue test parameters*	
Material of load applicator	
Not reported	44 (44.4)
Stainless Steel	19 (19.2)
Tungsten Carbide	14 (14.1)
G10 epoxy resin	5 (5.1)
Not applicable	5 (5.1)
Other materials	5 (5.1)
Ceramic	4 (4.0)
Steel	3 (3.0)
Shape/dimension of load applicator	
Not reported	43 (46.2)
Spherical > 40mm diameter	17 (18.3)
Cylinder/circular > 3mm diameter	13 (14.0)
Spherical < 7mm diameter	12 (12.9)
Not applicable	5 (5.4)
Unclear	3 (3.2)
Loading Frequency	
≤ 2Hz	43 (42.6)
>2 and ≤10Hz	25 (24.8)
> 10Hz	24 (23.8)
Not reported	5 (5.0)
Unclear	3 (3.0)
Load contact was 0-7s out of a 2s cycle	1 (1.0)
Type/Direction of load application	
Axial	87 (92.6)
Sliding	4 (4.3)
Rotary	3 (3.2)
Test environment conditions	
Wet	73 (75.3)
Not reported	17 (17.5)
Dry	7 (7.2)
Fractographic analysis	
Present	73(78.5)
Absent	20(21.5)
In accordance to normative guidelines	
Not reported	65 (69.9)
ISO 6872	26 (28.0)
ISO 10477	1 (1.0)
ASTM E647-93	1 (1.0)

*Each data was considered separately in studies that used more than one parameter.

FIGURES

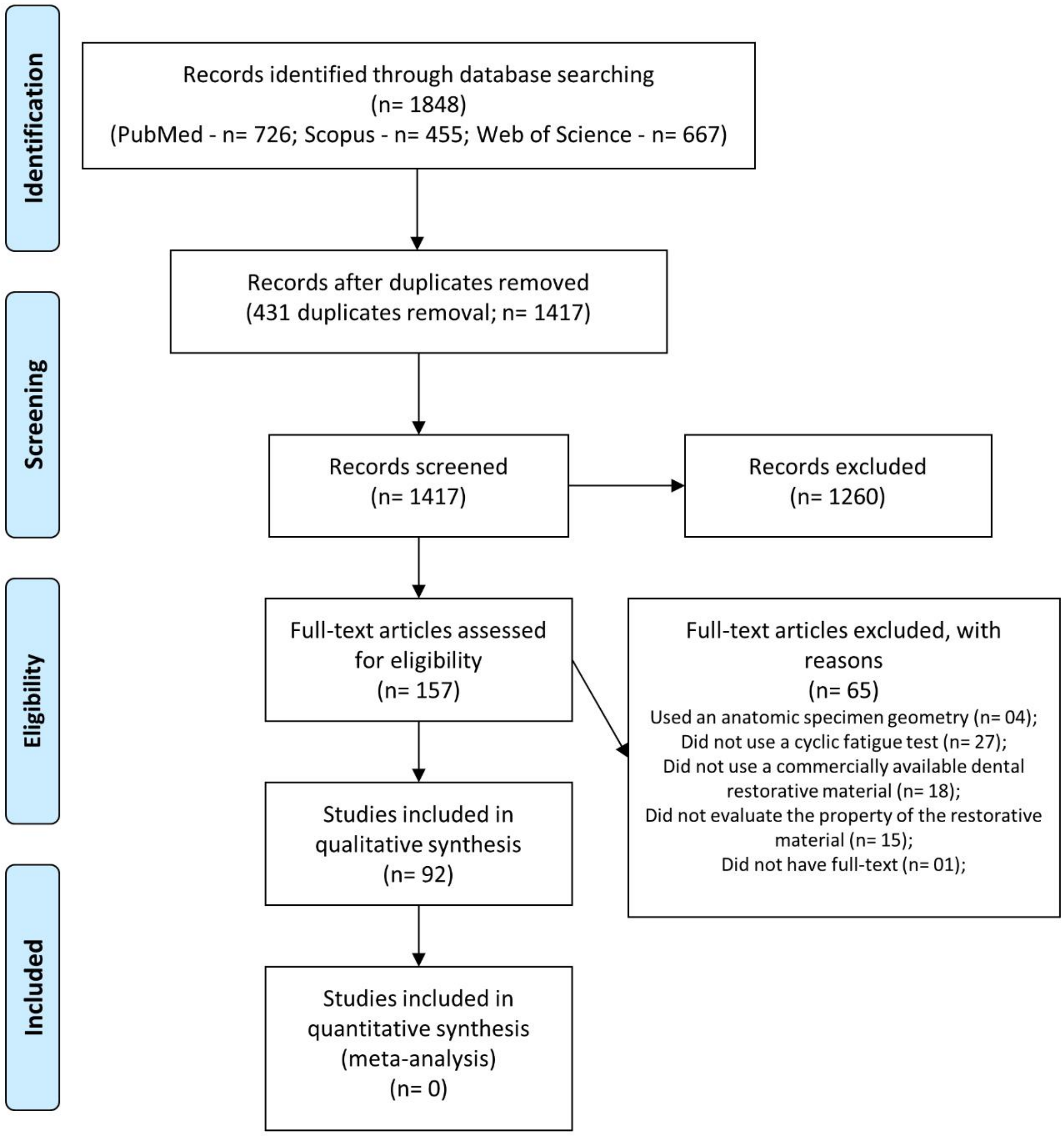


Figure 1. Flowchart of study selection.

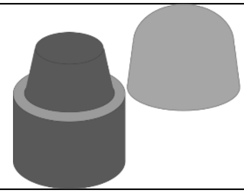
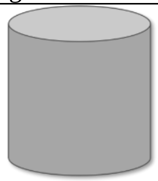
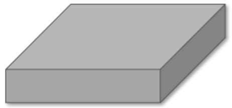
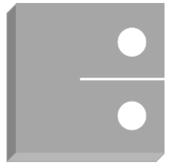
			
-3-point flexure strength; -4-point flexure strength; -Flexural strength; -Bending cantilever beam test	-Biaxial flexural strength	-Trilayer cemented assembly	-Simplified non-anatomic crowns
			
-Diametral compression	-Rotating cantilever beam test	-Compressive loading	-Compact-tension

Figure 2. Specimens format illustrations for each test geometry (dimensions differed among studies). In simplified trilayer assembly and simplified crowns, the restorative material was cemented in a dentin analogue material represented in the image by the darker color.

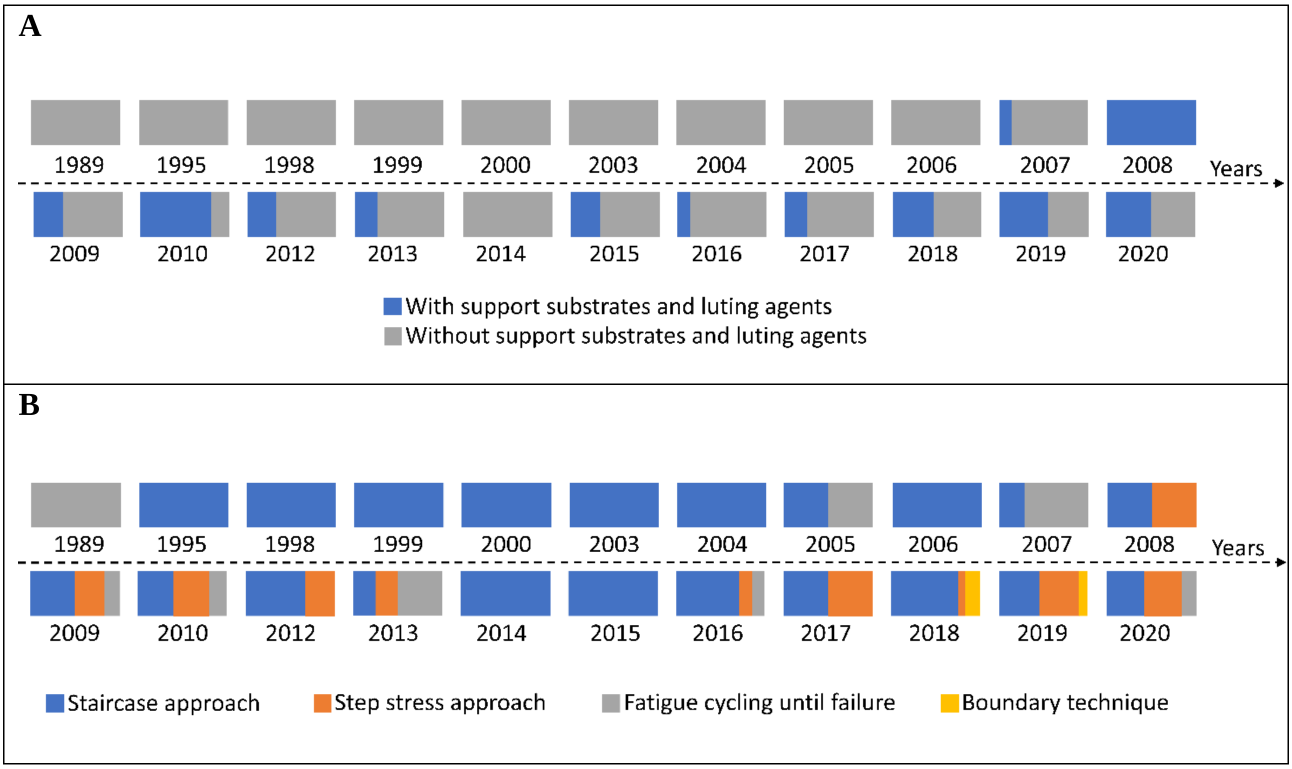


Figure 3. Changes in the execution of the cyclic fatigue test over time. **A** – Use of support substrates and luting agents; **B** – Fatigue methods adopted by studies.

SUPPLEMENTARY MATERIAL

LIST OF INCLUDED STUDIES

[1] M.N. Aboushelib, H. Wang, C.J. Kleverlaan, A.J. Feilzer, Fatigue behavior of zirconia under different loading conditions., Dent. Mater. 32 (2016) 915–920. https://doi.org/10.1016/j.dental.2016.03.012.

[2] J. Aghadazeh Mohandesi, M.A. Rafiee, V. Barzegaran, F. Shafiei, Compressive fatigue behavior of dental restorative composites., Dent. Mater. J. 26 (2007) 827–837. https://doi.org/10.4012/dmj.26.827.

[3] E.Q.H. Al Twal, R.G. Chadwick, Fibre reinforcement of two temporary composite bridge materials—Effect upon flexural properties, J. Dent. 40 (2012) 1044–1051. https://doi.org/10.1016/j.jdent.2012.08.012.

[4] R. Alessandretti, M. Borba, A. Della Bona, Cyclic contact fatigue resistance of ceramics for monolithic and multilayer dental restorations., Dent. Mater. 36 (2020) 535–541. https://doi.org/10.1016/j.dental.2020.02.006.

[5] A.A. Alshamrani, G.M. De Souza, Effect of ionizing radiation on mechanical properties and translucency of monolithic zirconia., J. Biomed. Mater. Res. B. Appl. Biomater. 108 (2020) 1068–1076. https://doi.org/10.1002/jbm.b.34458.

[6] M. Amaral, P.F. Cesar, M.A. Bottino, U. Lohbauer, L.F. Valandro, Fatigue behavior of Y-TZP ceramic after surface treatments, J. Mech. Behav. Biomed. Mater. 57 (2016) 149–156. https://doi.org/10.1016/j.jmbbm.2015.11.042.

[7] L.C. Anami, J.M.C. Lima, L.F. Valandro, C.J. Kleverlaan, A.J. Feilzer, M.A. Bottino, Fatigue Resistance of Y-TZP/Porcelain Crowns is Not Influenced by the Conditioning of the Intaglio Surface., Oper. Dent. 41 (2016) E1-12. https://doi.org/10.2341/14-166-L.

[8] M.R. Anderson, K.-H. Chung, B.D. Flinn, A.J. Raigrodski, An in vitro study of the effect of different restorative materials on the reliability of a veneering porcelain, J. Prosthet. Dent. 110 (2013) 521–528. https://doi.org/10.1016/j.prosdent.2013.09.009.

[9] C.P. Assis, M.R. Moyses, H.M. Teixeira, J.C.R. Ribeiro, J.G.R. Ribeiro, S.C. Dias, Fatigue limits for composite restorations with and without glass ionomer cement liners., Gen. Dent. 57 (2009) 481-485,535-536.

[10] I.L. Aurélio, C. Prochnow, L.F. Guilardi, G.F. Ramos, M.A. Bottino, L.G. May, The effect of extended glaze firing on the flexural fatigue strength of hard-machined ceramics., J. Prosthet. Dent. 120 (2018) 755–761. https://doi.org/10.1016/j.prosdent.2018.01.030.

[11] M.L. Auzani, K.S. Dapieve, C.P. Zucuni, G.K. Rocha Pereira, L.F. Valandro, Influence of shading technique on mechanical fatigue performance and optical properties of a 4Y-TZP ceramic for monolithic restorations., J. Mech. Behav. Biomed. Mater. 102 (2019) 103457. https://doi.org/10.1016/j.jmbbm.2019.103457.

[12] J.-M. Bae, K.-N. Kim, M. Hattori, K. Hasegawa, M. Yoshinari, E. Kawada, Y. Oda, Fatigue strengths of particulate filler composites reinforced with fibers., Dent. Mater. J. 23 (2004) 166–174. https://doi.org/10.4012/dmj.23.166.

[13] R. Belli, E. Geinzer, A. Muschweck, A. Petschelt, U. Lohbauer, Mechanical fatigue degradation of ceramics versus resin composites for dental restorations., Dent. Mater. 30 (2014) 424–432. https://doi.org/10.1016/j.dental.2014.01.003.

[14] R. Belli, A. Petschelt, U. Lohbauer, Are linear elastic material properties relevant predictors of the cyclic fatigue resistance of dental resin composites?, Dent. Mater. 30 (2014) 381–391. https://doi.org/10.1016/j.dental.2014.01.009.

[15] E.A. Bonfante, P.G. Coelho, P.C. Guess, V.P. Thompson, N.R.F.A. Silva, Fatigue and damage accumulation of veneer porcelain pressed on Y-TZP., J. Dent. 38 (2010) 318–324. https://doi.org/10.1016/j.jdent.2009.12.004.

[16] M.J. Braem, P. Lambrechts, S. Gladys, G. Vanherle, In vitro fatigue behavior of restorative composites and glass ionomers., Dent. Mater. 11 (1995) 137–141. https://doi.org/10.1016/0109-5641(95)80049-2.

[17] F. Campos, L.F. Valandro, S.A. Feitosa, C.J. Kleverlaan, A.J. Feilzer, N. de Jager, M.A. Bottino, Adhesive Cementation Promotes Higher Fatigue Resistance to Zirconia Crowns., Oper. Dent. 42 (2017) 215–224. https://doi.org/10.2341/16-002-L.

[18] S. Chen, C. Öhman, S.R. Jefferies, H. Gray, W. Xia, H. Engqvist, Compressive fatigue limit of four types of dental restorative materials., J. Mech. Behav. Biomed. Mater. 61 (2016) 283–289. https://doi.org/10.1016/j.jmbbm.2016.03.031.

[19] A.M. de O. Dal Piva, J.P.M. Tribst, A.B. Venturini, L.C. Anami, E.A. Bonfante, M.A. Bottino, C.J. Kleverlaan, Survival probability of zirconia-reinforced lithium silicate ceramic: Effect of surface condition and fatigue test load profile, Dent. Mater. 36 (2020) 808–815. https://doi.org/10.1016/j.dental.2020.03.029.

[20] K.S. Dapieve, L.S.F. Guilardi, T. Silvestri, M.P. Rippe, G.K.R. Pereira, L.F. Valandro, Mechanical performance of Y-TZP monolithic ceramic after grinding and aging: Survival estimates and fatigue strength., J. Mech. Behav. Biomed. Mater. 87 (2018) 288–295. https://doi.org/10.1016/j.jmbbm.2018.07.041.

[21] K.S. Dapieve, R.V. Machry, R.O. Pilecco, C.J. Kleverlaan, G.K. Rocha Pereira, A.B. Venturini, L.F. Valandro, One-step ceramic primer as surface conditioner: Effect on the load-bearing capacity under fatigue of bonded lithium disilicate ceramic simplified restorations, J. Mech. Behav. Biomed. Mater. 104 (2020) 103686. https://doi.org/10.1016/j.jmbbm.2020.103686.

[22] J.L. Drummond, Cyclic fatigue of composite restorative materials., J. Oral Rehabil. 16 (1989) 509–520. https://doi.org/10.1111/j.1365-2842.1989.tb01372.x.

[23] J.L. Drummond, T.J. King, M.S. Bapna, R.D. Koperski, Mechanical property evaluation of pressable restorative ceramics., Dent. Mater. 16 (2000) 226–233. https://doi.org/10.1016/s0109-5641(00)00013-0.

[24] S. Fraga, M. Amaral, M.A. Bottino, L.F. Valandro, C.J. Kleverlaan, L.G. May, Impact of machining on the flexural fatigue strength of glass and polycrystalline CAD/CAM ceramics., Dent. Mater. 33 (2017) 1286–1297. https://doi.org/10.1016/j.dental.2017.07.019.

[25] S. Fraga, G.K.R. Pereira, M. Freitas, C.J. Kleverlaan, L.F. Valandro, L.G. May, Loading frequencies up to 20Hz as an alternative to accelerate fatigue strength tests in a Y-TZP ceramic., J. Mech. Behav. Biomed. Mater. 61 (2016) 79–86. https://doi.org/10.1016/j.jmbbm.2016.01.008.

[26] S. Fraga, C. da S. Rodrigues, C.P. Zucuni, G.K.R. Pereira, M.N. Barbosa, L.F. Valandro, L.G. May, High load frequency at 20Hz: Its effects on the fatigue behavior of a leucite-reinforced glass-ceramic, J. Mech. Behav. Biomed. Mater. 107 (2020) 103769. https://doi.org/10.1016/j.jmbbm.2020.103769.

[27] S. Garoushi, L.V.J. Lassila, A. Tezvergil, P.K. Vallittu, Static and fatigue compression test for particulate filler composite resin with fiber-reinforced composite substructure., Dent. Mater. 23 (2007) 17–23. https://doi.org/10.1016/j.dental.2005.11.041.

[28] S. Gladys, M. Braem, B. Van Meerbeek, P. Lambrechts, G. Vanherle, Immediate versus one-month wet storage fatigue of restorative materials., Biomaterials. 19 (1998) 541–544. https://doi.org/10.1016/s0142-9612(97)00134-8.

[29] P.C. Guess, Y. Zhang, J.-W. Kim, E.D. Rekow, V.P. Thompson, Damage and Reliability of Y-TZP after Cementation Surface Treatment, J. Dent. Res. 89 (2010) 592–596. https://doi.org/10.1177/0022034510363253.

[30] P.C. Guess, Y. Zhang, V.P. Thompson, Effect of veneering techniques on damage and reliability of Y-TZP trilayers., Eur. J. Esthet. Dent. Off. J. Eur. Acad. Esthet. Dent. 4 (2009) 262–276.

[31] L.F. Guilardi, G. Pereira, A.S. Vallau, I.A. Silva, J.C. Giordani, L.F. Valandro, M.P. Rippe, Fatigue Failure Load of a Bonded Simplified Monolithic Feldspathic Ceramic: Influence of Hydrofluoric Acid Etching and Thermocycling., Oper. Dent. 45 (2020) E21–E31. https://doi.org/10.2341/19-069-L.

[32] L.F. Guilardi, G.K.R. Pereira, J.C. Giordani, C.J. Kleverlaan, L.F. Valandro, M.P. Rippe, Effect of zirconia surface treatment, resin cement and aging on the load-bearing capacity under fatigue of thin simplified full-contour Y-TZP restorations., J. Mech. Behav. Biomed. Mater. 97 (2019) 21–29. https://doi.org/10.1016/j.jmbbm.2019.04.050.

[33] Y. He, Q. Yan, Y. Jian, M. V. Swain, K. Zhao, X. Wang, Fatigue degradation of bilayered ceramic structures under different biaxial loading schemes, J. Mech. Behav. Biomed. Mater. 104 (2020) 103651. https://doi.org/10.1016/j.jmbbm.2020.103651.

[34] E. Homaei, K. Farhangdoost, J.K.H. Tsoi, J.P. Matinlinna, E.H.N. Pow, Static and fatigue mechanical behavior of three dental CAD/CAM ceramics., J. Mech. Behav. Biomed. Mater. 59 (2016) 304–313. https://doi.org/10.1016/j.jmbbm.2016.01.023.

[35] R.K. Hurley, J.L. Drummond, G.C. Viana, M.T. Galang, The effects of environment and cyclic fatigue on the mechanical properties of an indirect composite., J. Dent. 40 (2012) 787–792. https://doi.org/10.1016/j.jdent.2012.05.012.

[36] G. V Joshi, Y. Duan, A. Della Bona, T.J. Hill, K. St John, J.A. Griggs, Fatigue loading and R-curve behavior of a dental glass-ceramic with multiple flaw distributions., Dent. Mater. 29 (2013) 1123–1131. https://doi.org/10.1016/j.dental.2013.08.208.

[37] G. V. Joshi, Y. Duan, A. Della Bona, T.J. Hill, K. St. John, J.A. Griggs, Contributions of stress corrosion and cyclic fatigue to subcritical crack growth in a dental glass-ceramic, Dent. Mater. 30 (2014) 884–890. https://doi.org/10.1016/j.dental.2014.05.026.

[38] Y. Kawakami, F. Takeshige, M. Hayashi, S. Ebisu, Fatigue of tooth-colored restoratives in aqueous environment., Dent. Mater. J. 26 (2007) 1–6. https://doi.org/10.4012/dmj.26.1.

[39] J.R. Kelly, P. Rungruanganunt, B. Hunter, F. Vailati, Development of a clinically validated bulk failure test for ceramic crowns, J. Prosthet. Dent. 104 (2010) 228–238. https://doi.org/10.1016/S0022-3913(10)60129-1.

[40] F. Keulemans, P. Palav, M.M.N. Aboushelib, A. van Dalen, C.J. Kleverlaan, A.J. Feilzer, Fracture strength and fatigue resistance of dental resin-based composites, Dent. Mater. 25 (2009) 1433–1441. https://doi.org/10.1016/j.dental.2009.06.013.

[41] B. Kim, Y. Zhang, M. Pines, V.P. Thompson, Fracture of Porcelain-veneered Structures in Fatigue, J. Dent. Res. 86 (2007) 142–146. https://doi.org/10.1177/154405910708600207.

[42] J.-W. Kim, J.-H. Kim, M.N. Janal, Y. Zhang, Damage Maps of Veneered Zirconia under Simulated Mastication, J. Dent. Res. 87 (2008) 1127–1132. https://doi.org/10.1177/154405910808701210.

[43] E. Klauer, R. Belli, A. Petschelt, U. Lohbauer, Mechanical and hydrolytic degradation of an Ormocer®-based Bis-GMA-free resin composite., Clin. Oral Investig. 23 (2019) 2113–2121. https://doi.org/10.1007/s00784-018-2651-3.

[44] S. Kuroda, A. Shinya, P.K. Vallittu, Y. Nakasone, A. Shinya, Effect of water temperature on cyclic fatigue properties of glass-fiber-reinforced hybrid composite resin and its fracture pattern after flexural testing., J. Adhes. Dent. 15 (2013) 19–26. https://doi.org/10.3290/j.jad.a28884.

[45] E. Lodi, K.R. Weber, P. Benetti, P.H. Corazza, Á. Della Bona, M. Borba, How oral environment simulation affects ceramic failure behavior, J. Prosthet. Dent. 119 (2018) 812–818. https://doi.org/10.1016/j.prosdent.2017.05.013.

[46] U. Lohbauer, R. Belli, The Mechanical Performance of a Novel Self-Adhesive Restorative Material., J. Adhes. Dent. 22 (2020) 47–58. https://doi.org/10.3290/j.jad.a43997.

[47] U. Lohbauer, R. Frankenberger, N. Krämer, A. Petschelt, Time-dependent strength and fatigue resistance of dental direct restorative materials., J. Mater. Sci. Mater. Med. 14 (2003) 1047–1053. https://doi.org/10.1023/b:jmsm.0000004001.73640.4c.

[48] U. Lohbauer, R. Frankenberger, N. Krämer, A. Petschelt, Strength and fatigue performance versus filler fraction of different types of direct dental restoratives., J. Biomed. Mater. Res. B. Appl. Biomater. 76 (2006) 114–120. https://doi.org/10.1002/jbm.b.30338.

[49] U. Lohbauer, T. von der Horst, R. Frankenberger, N. Krämer, A. Petschelt, Flexural fatigue behavior of resin composite dental restoratives., Dent. Mater. 19 (2003) 435–440. https://doi.org/10.1016/s0109-5641(02)00088-x.

[50] U. Lohbauer, C. Rahiotis, N. Krämer, A. Petschelt, G. Eliades, The effect of different light-curing units on fatigue behavior and degree of conversion of a resin composite., Dent. Mater. 21 (2005) 608–615. https://doi.org/10.1016/j.dental.2004.07.020.

[51] G.M. Loughran, A. Versluis, W.H. Douglas, Evaluation of sub-critical fatigue crack propagation in a restorative composite, Dent. Mater. 21 (2005) 252–261. https://doi.org/10.1016/j.dental.2004.04.005.

[52] S.Ms. Marocho, A.R. Studart, M.A. Bottino, A. Della Bona, Mechanical strength and subcritical crack growth under wet cyclic loading of glass-infiltrated dental ceramics, Dent. Mater. 26 (2010) 483–490. https://doi.org/10.1016/j.dental.2010.01.007.

[53] L. Gressler May, J.R. Kelly, M.A. Bottino, T. Hill, Influence of the resin cement thickness on the fatigue failure loads of CAD/CAM feldspathic crowns., Dent. Mater. 31 (2015) 895–900. https://doi.org/10.1016/j.dental.2015.04.019.

[54] J.S. Miranda, A.S. de P. Barcellos, T.M.B. Campos, P.F. Cesar, M. Amaral, E.T. Kimpara, Effect of repeated firings and staining on the mechanical behavior and composition of lithium disilicate., Dent. Mater. (2020). https://doi.org/10.1016/j.dental.2020.02.003.

[55] H. Mirmohammadi, C.J. Kleverlaan, A.J. Feilzer, Rotating fatigue and flexural strength of direct and indirect resin-composite restorative materials., Am. J. Dent. 22 (2009) 219–222.

[56] T. Nakazato, H. Takahashi, M. Yamamoto, F. Nishimura, N. Kurosaki, Effect of Polishing oh Cyclic Fatigue Strength of CAD/CAM Ceramics., Dent. Mater. J. 18 (1999) 395–402. https://doi.org/10.4012/dmj.18.395.

[57] G. Nishioka, C. Prochnow, A. Firmino, M. Amaral, M.A. Bottino, L.F. Valandro, M. Renata Marques de, Fatigue strength of several dental ceramics indicated for CAD-CAM monolithic restorations., Braz. Oral Res. 32 (2018) e53. https://doi.org/10.1590/1807-3107bor-2018.vol32.0053.

[58] R. Ottoni, J.A. Griggs, P.H. Corazza, Á. Della Bona, M. Borba, Precision of different fatigue methods for predicting glass-ceramic failure., J. Mech. Behav. Biomed. Mater. 88 (2018) 497–503. https://doi.org/10.1016/j.jmbbm.2018.09.004.

[59] C.H. Pameijer, F. Garcia-Godoy, B.R. Morrow, S.R. Jefferies, Flexural strength and flexural fatigue properties of resin-modified glass ionomers., J. Clin. Dent. 26 (2015) 23–27.

[60] G.K.R. Pereira, T. Silvestri, M. Amaral, M.P. Rippe, C.J. Kleverlaan, L.F. Valandro, Fatigue limit of polycrystalline zirconium oxide ceramics: Effect of grinding and low-temperature aging., J. Mech. Behav. Biomed. Mater. 61 (2016) 45–54. https://doi.org/10.1016/j.jmbbm.2016.01.006.

[61] P. Pittayachawan, A. McDonald, A. Petrie, J.C. Knowles, The biaxial flexural strength and fatigue property of Lava Y-TZP dental ceramic., Dent. Mater. 23 (2007) 1018–1029. https://doi.org/10.1016/j.dental.2006.09.003.

[62] P. Pittayachawan, A. McDonald, A. Young, J.C. Knowles, Flexural strength, fatigue life, and stress-induced phase transformation study of Y-TZP dental ceramic., J. Biomed. Mater. Res. B. Appl. Biomater. 88 (2009) 366–377. https://doi.org/10.1002/jbm.b.31064.

[63] C. Prochnow, G.K.R. Pereira, A.B. Venturini, M.M. Scherer, M.P. Rippe, M.C. Bottino, C.J. Kleverlaan, L.F. Valandro, How does hydrofluoric acid etching affect the cyclic load-to-failure of lithium disilicate restorations?, J. Mech. Behav. Biomed. Mater. 87 (2018) 306–311. https://doi.org/10.1016/j.jmbbm.2018.07.040.

[64] C. Prochnow, A.B. Venturini, L.F. Guilardi, G.K.R. Pereira, T.A.L. Burgo, M.C. Bottino, C.J. Kleverlaan, L.F. Valandro, Hydrofluoric acid concentrations: Effect on the cyclic load-to-failure of machined lithium disilicate restorations., Dent. Mater. 34 (2018) e255–e263. https://doi.org/10.1016/j.dental.2018.06.028.

[65] C. da S. Rodrigues, L.F. Guilardi, A.C. Follak, C. Prochnow, L.G. May, L.F. Valandro, Internal adjustments decrease the fatigue failure load of bonded simplified lithium disilicate restorations., Dent. Mater. 34 (2018) e225–e235. https://doi.org/10.1016/j.dental.2018.05.015.

[66] M. Rosentritt, S. Krifka, V. Preis, T. Strasser, Dynamic fatigue of composite CAD/CAM materials, J. Mech. Behav. Biomed. Mater. 98 (2019) 311–316. https://doi.org/10.1016/j.jmbbm.2019.07.002.

[67] T. Santana, Y. Zhang, P. Guess, V.P. Thompson, E.D. Rekow, N.R.F.A. Silva, Off-axis sliding contact reliability and failure modes of veneered alumina and zirconia., Dent. Mater. 25 (2009) 892–898. https://doi.org/10.1016/j.dental.2009.01.093.

[68] M.M. Scherer, C. Prochnow, A.B. Venturini, G.K.R. Pereira, T.A. de L. Burgo, M.P. Rippe, L.F. Valandro, Fatigue failure load of an adhesively-cemented lithium disilicate glass-ceramic: Conventional ceramic etching vs etch & prime one-step primer., Dent. Mater. 34 (2018) 1134–1143. https://doi.org/10.1016/j.dental.2018.04.012.

[69] S.S. Scherrer, A.H.W. Wiskott, V. Coto-Hunziker, U.C. Belser, Monotonic flexure and fatigue strength of composites for provisional and definitive restorations., J. Prosthet. Dent. 89 (2003) 579–588. https://doi.org/10.1016/s0022-3913(03)00174-4.

[70] R. Schestatsky, C.P. Zucuni, A.B. Venturini, T.A. de Lima Burgo, A. Bacchi, L.F. Valandro, G.K. Rocha Pereira, CAD-CAM milled versus pressed lithium-disilicate monolithic crowns adhesively cemented after distinct surface treatments: Fatigue performance and ceramic surface characteristics., J. Mech. Behav. Biomed. Mater. 94 (2019) 144–154. https://doi.org/10.1016/j.jmbbm.2019.03.005.

[71] G. Schmitt de Andrade, V. Diniz, C.E. Datte, G.K.R. Pereira, A.B. Venturini, T.M.B. Campos, M. Amaral, M.A. Bottino, L.F. Valandro, R. Marques de Melo, Newer vs. older CAD/CAM burs: Influence of bur experience on the fatigue behavior of adhesively cemented simplified lithium-disilicate glass-ceramic restorations, J. Mech. Behav. Biomed. Mater. 95 (2019) 172–179. https://doi.org/10.1016/j.jmbbm.2019.04.002.

[72] N.R.F.A. Silva, G.M. de Souza, P.G. Coelho, C.F.J. Stappert, E.A. Clark, E.D. Rekow, V.P. Thompson, Effect of water storage time and composite cement thickness on fatigue of a glass-ceramic trilayer system, J. Biomed. Mater. Res. Part B Appl. Biomater. 84B (2008) 117–123. https://doi.org/10.1002/jbm.b.30851.

[73] T. Silvestri, G.K.R. Pereira, L.F. Guilardi, M.P. Rippe, L.F. Valandro, Effect of Grinding and Multi-Stimuli Aging on the Fatigue Strength of a Y-TZP Ceramic., Braz. Dent. J. 29 (2018) 60–67. https://doi.org/10.1590/0103-6440201801735.

[74] C.F.J. Stappert, M. Baldassarri, Y. Zhang, D. Stappert, V.P. Thompson, Contact fatigue response of porcelain-veneered alumina model systems., J. Biomed. Mater. Res. B. Appl. Biomater. 100 (2012) 508–515. https://doi.org/10.1002/jbm.b.31977.

[75] T. Stijacic, K.-H. Chung, B.D. Flinn, A.J. Raigrodski, Effect of Tooth-Colored Restorative Materials on Reliability of Heat-Pressed Lithium Disilicate, J. Prosthodont. 24 (2015) 475–483. https://doi.org/10.1111/jopr.12243.

[76] A.R. Studart, F. Filser, P. Kocher, L.J. Gauckler, In vitro lifetime of dental ceramics under cyclic loading in water, Biomaterials. 28 (2007) 2695–2705. https://doi.org/10.1016/j.biomaterials.2006.12.033.

[77] F. Takeshige, Y. Kawakami, M. Hayashi, S. Ebisu, Fatigue behavior of resin composites in aqueous environments, Dent. Mater. 23 (2007) 893–899. https://doi.org/10.1016/j.dental.2006.06.031.

[78] J.P.M. Tribst, J.B. Monteiro, A.B. Venturini, G.K.R. Pereira, M.A. Bottino, R.M. de Melo, L.F. Valandro, Fatigue Failure Load of Resin-bonded Simplified Lithium Disilicate Glass-Ceramic Restorations: Effect of Ceramic Conditioning Methods., J. Adhes. Dent. 21 (2019) 373–381. https://doi.org/10.3290/j.jad.a43000.

[79] A.B. Venturini, C. Prochnow, L.G. May, C.J. Kleverlaan, L.F. Valandro, Fatigue failure load of feldspathic ceramic crowns after hydrofluoric acid etching at different concentrations, J. Prosthet. Dent. 119 (2018) 278–285. https://doi.org/10.1016/j.prosdent.2017.03.021.

[80] A.B. Venturini, C. Prochnow, G.K.R. Pereira, R.D. Segala, C.J. Kleverlaan, L.F. Valandro, Fatigue performance of adhesively cemented glass-, hybrid- and resin-ceramic materials for CAD/CAM monolithic restorations., Dent. Mater. 35 (2019) 534–542. https://doi.org/10.1016/j.dental.2019.01.013.

[81] A.B. Venturini, C. Prochnow, G.K.R. Pereira, A. Werner, C.J. Kleverlaan, L.F. Valandro, The effect of hydrofluoric acid concentration on the fatigue failure load of adhesively cemented feldspathic ceramic discs., Dent. Mater. 34 (2018) 667–675. https://doi.org/10.1016/j.dental.2018.01.010.

[82] C.B. Vicari, B. de O. Magalhães, J.A. Griggs, M. Borba, Fatigue Behavior of Crystalline-Reinforced Glass-Ceramics, J. Prosthodont. 28 (2018) e297–e303. https://doi.org/10.1111/jopr.12739.

[83] I.S.S.L. Weitzel, J.H.R. Rangel, M.P. Perim, R.M. Melo, A.L.S. Borges, L.R. Silva-Concílio, M. Amaral, Mechanical performance of monolithic materials cemented to a dentin-like substrate., J. Prosthet. Dent. (2020). https://doi.org/10.1016/j.prosdent.2019.12.021.

[84] M. Wendler, R. Belli, D. Valladares, A. Petschelt, U. Lohbauer, Chairside CAD/CAM materials. Part 3: Cyclic fatigue parameters and lifetime predictions., Dent. Mater. 34 (2018) 910–921. https://doi.org/10.1016/j.dental.2018.03.024.

[85] K. Yoshida, J.R. Condon, M. Atsuta, J.L. Ferracane, Flexural fatigue strength of CAD/CAM composite material and dual-cured resin luting cements., Am. J. Dent. 16 (2003) 177–180.

[86] K. Yoshida, N. Morimoto, Y. Tsuo, M. Atsuta, Flexural fatigue behavior of machinable and light-activated hybrid composites for esthetic restorations, J. Biomed. Mater. Res. 70B (2004) 218–222. https://doi.org/10.1002/jbm.b.30035.

[87] C.P. Zucuni, L.F. Guilardi, S. Fraga, L.G. May, G.K.R. Pereira, L.F. Valandro, CAD/CAM machining Vs pre-sintering in-lab fabrication techniques of Y-TZP ceramic specimens: Effects on their mechanical fatigue behavior., J. Mech. Behav. Biomed. Mater. 71 (2017) 201–208. https://doi.org/10.1016/j.jmbbm.2017.03.013.

[88] C.P. Zucuni, K.S. Dapieve, M.P. Rippe, G.K.R. Pereira, M.C. Bottino, L.F. Valandro, Influence of finishing/polishing on the fatigue strength, surface topography, and roughness of an yttrium-stabilized tetragonal zirconia polycrystals subjected to grinding, J. Mech. Behav. Biomed. Mater. 93 (2019) 222–229. https://doi.org/10.1016/j.jmbbm.2019.02.013.

[89] C.P. Zucuni, L.F. Guilardi, M.P. Rippe, G.K.R. Pereira, L.F. Valandro, Fatigue strength of yttria-stabilized zirconia polycrystals: Effects of grinding, polishing, glazing, and heat treatment., J. Mech. Behav. Biomed. Mater. 75 (2017) 512–520. https://doi.org/10.1016/j.jmbbm.2017.06.016.

[90] C.P. Zucuni, B.D. Ilha, M.M. May, L.G. May, L.F. Valandro, Grinding the intaglio surface of yttria partially- and fully-stabilized zirconia polycrystals restorations: Effect on their fatigue behavior, J. Mech. Behav. Biomed. Mater. 109 (2020) 103800. https://doi.org/10.1016/j.jmbbm.2020.103800.

[91] C.P. Zucuni, G.K.R. Pereira, L.F. Valandro, Grinding, polishing and glazing of the occlusal surface do not affect the load-bearing capacity under fatigue and survival rates of bonded monolithic fully-stabilized zirconia simplified restorations., J. Mech. Behav. Biomed. Mater. 103 (2020) 103528. https://doi.org/10.1016/j.jmbbm.2019.103528.

[92] C.P. Zucuni, A.B. Venturini, C. Prochnow, G.K. Rocha Pereira, L.F. Valandro, Load-bearing capacity under fatigue and survival rates of adhesively cemented yttrium-stabilized zirconia polycrystal monolithic simplified restorations., J. Mech. Behav. Biomed. Mater. 90 (2019) 673–680. https://doi.org/10.1016/j.jmbbm.2018.11.009.

3 ARTIGO 2: ACCELERATED LOADING FREQUENCY DOES NOT INFLUENCE THE FATIGUE BEHAVIOR OF POLYMER INFILTRATED CERAMIC NETWORK OR LITHIUM DISILICATE GLASS-CERAMIC RESTORATIONS

Este artigo está publicado no periódico *Journal of the Mechanical Behavior of Biomedical Materials, Elsevier*, ISSN: 1751-6161. Fator de impacto: 3,372, Qualis CAPES A2. As normas para publicação estão descritas no Anexo B.

Accelerated loading frequency does not influence the fatigue behavior of polymer infiltrated ceramic network or lithium disilicate glass-ceramic restorations

Helder Callegaro Velho[a], Kiara Serafini Dapieve[a], Gabriel Kalil Rocha Pereira[a], Sara Fraga[b], Luiz Felipe Valandro[a], Andressa Borin Venturini[a]

[a]MSciD and PhD Post-Graduate Program in Oral Science, Faculty of Dentistry, Federal University of Santa Maria (UFSM), Santa Maria, Rio Grande do Sul State, Brazil
[b]Department of Conservative Dentistry, Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Rio Grande do Sul State, Brazil

Authors' e-mail addresses

Helder Callegaro Velho (heldercvelho@hotmail.com)
Kiara Serafini Dapieve (kiara_s_d@hotmail.com)
Gabriel Kalil Rocha Pereira (gabrielkrpereira@hotmail.com)
Sara Fraga (sara.odonto@yahoo.com.br)
Luiz Felipe Valandro (valandrolf@gmail.com)
Andressa Borin Venturini (andressa.venturini@hotmail.com)

Corresponding author:
Luiz Felipe Valandro, D.D.S., M.Sci.D., Ph.D., Associate Professor, Federal University of Santa Maria, Faculty of Odontology, MSciD-PhD Graduate Programs in Oral Science, Prosthodontics Unit, 1000 Roraima Av, T Street, Building 26F, Room 2360, UFSM Campus, 97105-900, Santa Maria, Brazil. E-mail: lfvalandro@hotmail.com (Dr LF Valandro).

Short title: 20 Hz loading frequency as an alternative for fatigue testing

Highlights

- The influence of cyclic loading frequency on fatigue properties was evaluated.
- Loading frequency does not affect the fatigue behavior of lithium disilicate ceramic.
- Loading frequency does not affect the fatigue behavior of polymer infiltrated ceramic.
- Loading frequency does not influence the failure pattern.
- The use of 20Hz frequency is validated to accelerate fatigue tests on such materials.

Abstract

This study aimed to evaluate the influence of loading frequency on the fatigue mechanical behavior of adhesively cemented polymer-infiltrated ceramic-network (PICN) and lithium disilicate (LD) simplified monolithic restorations. Thirty (30) disc-shaped specimens (Ø= 10mm; thickness= 1.0mm) of each ceramic material (PICN – Enamic, Vita Zahnfabrik or LD – IPS e.max CAD, Ivoclar Vivadent) were produced and adhesively cemented onto dentin analogue discs made of fiber and epoxy resin material (Ø= 10mm; thickness= 2.0mm). PICN and LD cemented assemblies were randomly allocated into 2 groups (n= 15) according to the loading frequency used for the fatigue testing (20 Hz or 2 Hz), composing the PICN_20, PICN_2, LD_20 and LD_2 testing groups. Fatigue tests were run using the step-stress approach (initial load= 200 N; step-size= 100 N; 10,000 cycles per step) and the collected data (fatigue failure load – FFL and number of cycles for failure – CFF) were analyzed by survival tests (Kaplan Meier and Mantel-Cox) and Weibull analysis. Fractographic analysis of failed specimens were also performed. No statistically significant differences were detected in relation to FFL and CFF between the groups within the same ceramic material (PICN_20: 1127 N / 102,667 cycles = PICN_2: 1120 N / 102,000 cycles; LD_20: 980 N / 88,000 cycles = LD_2: 900 N / 80,000 cycles). All failures were radial cracks in the cementation surface. Therefore, the use of a 20 Hz loading frequency shows to be a viable alternative to accelerate cyclic fatigue tests without affecting the fatigue mechanical behavior and the failure pattern of simplified restorations made of lithium disilicate glass ceramic or polymer infiltrated ceramic network bonded to the dentin analogue.

Keywords: Glass-ceramics. Hybrid ceramics. Fatigue phenomena. Mechanical cycling. Fatigue testing parameters.

1. Introduction

In order to attend the high aesthetic demand of the patients, new ceramic materials for metal-free restorations have been developed combining esthetics, biocompatibility and better mechanical properties (Bajraktarova-valjakova et al., 2018). In general, dental glass ceramics stand out for its excellent aesthetics, translucency, high strength, biocompatibility, wear resistance and, in certain cases, these materials are bioactive (Kargozar et al., 2019; Montazerian and Zanotto, 2017).

Lithium disilicate (LD) glass-ceramic has been widely used due to an association of factors which enable excellent aesthetic results (glass matrix), high resistance (adding 70% of the volume by elongated and interlocked crystals) (Guess et al., 2011; Kruzic et al., 2018; Zogheib et al., 2011) and thus versatility for clinical indications (Tysowsky, 2009). Another material which has been expanding its use in clinical restorations is the polymer-infiltrated ceramic-network (PICN). PICN allegedly has similar mechanical (elastic modulus and hardness) and aesthetic characteristics to the dental structure, since it combines composite resin characteristics with those of a glass ceramic (He and Swain, 2011). In fact, the development of PICN was tailored to diminish its brittleness and consequently its risk to fracture and antagonist tooth wear (Belli et al., 2017; Wendler et al., 2018, 2017). Despite this, both materials (LD and PICN) are still considered brittle materials, and fracture is one of the commonly reported technical problems (Sailer et al., 2015; Spitznagel et al., 2020).

In vitro tests to evaluate the mechanical behavior of restorative materials should simulate different aspects of the oral environment in order to produce failure modes close to those seen clinically (Kelly, 1999). The mechanical failure of dental restorations occurs after years in function, indicating a failure due to fatigue instead of acute overload through a monotonic test (Zhang and Lawn, 2004). Thus, fatigue tests are essential to predict the long-term mechanical behavior of restorative materials, as they simulate a mechanical scenario closer to what occurs clinically (Wiskott et al., 1995). The load in fatigue tests is cyclically applied with a previously defined frequency (number of cycles per second) for a specified number of cycles. Some studies have been conducted with low loading frequencies such as 1-2Hz (Belli et al., 2013; El Zhawi et al., 2016; Paula et al., 2015), since it is an approximation of the clinical masticatory frequency (Po et al., 2011). However, low frequency fatigue tests at 2 Hz may become very time consuming. Thus, the use of high loading frequencies to enable faster data acquisition is always a must for the scientific community.

High loading frequencies (such as 20 Hz) make in vitro tests more feasible and drastically reduce the time needed to perform them, which would enable testing a greater number of specimens over a high number of cycles and consequently increase the clinical relevance of the results. However, higher fatigue failure load values were observed with a frequency of 20 Hz compared to 2 Hz in a glass-infiltrated alumina ceramic (Kelly et al., 2010). Furthermore, Fraga et al. (2016) stated that it is possible to accelerate the fatigue tests of a Y-TZP ceramic using frequencies up to 20 Hz without influencing the fatigue strength data. Regarding glass-ceramics, it has been reported that loading frequency does not influence the fatigue strength nor the time necessary to promote failure in lifetime studies (Fraga et al., 2020; Joshi et al., 2014). Thus, this theme is still unanswered in literature and more studies are encouraged to assess if loading frequency can be increased without influencing the acquired data.

Considering the absence of studies supporting the use of higher frequencies in fatigue tests of adhesively cemented PICN or LD ceramic restorations and the relevance of this topic for accelerating fatigue testing, the present study aimed to assess whether it is possible to accelerate fatigue tests by increasing loading frequency without influencing the fatigue mechanical behavior of these restorations. The study assumed a null hypothesis that there would not be a difference in the fatigue behavior between 2 and 20 Hz loading frequencies for both materials.

2. Material and methods

The materials used in this study, their chemical composition and manufacturers are described in Table 1.

2.1 Specimen preparation

The specimens were produced using a prior validated method which uses a simplified tri-layer setup (ceramic, cement and epoxy resin adhesively luted to one another) to simulate a monolithic restoration of a posterior molar tooth (Chen et al., 2014).

CAD/CAM blocks of PICN (Vita Enamic, VITA Zahnfabrik, Bad Säckingen, Germany) and LD ceramics (IPS e.Max CAD, Ivoclar Vivadent; Schaan, Liechtenstein) were shaped into cylinders using a diamond drill (internal diameter= 10 mm; Diamant Boart, Brussels, Belgium) coupled to a bench drill (SBE 1010 Plus, Metabo; Nürtingen, Germany) under refrigeration. Next, the cylinders were sectioned under water-cooling in a cutting machine (Isomet 1000; Buehler, Lake Bluff, USA), resulting in 30 discs of each ceramic with an initial thickness of 1.1 mm and 10 mm in diameter. Both surfaces of all discs were ground (EcoMet/AutoMet 250, Buehler) with grit SiC papers (#400, #600 and #1200, 3M; Sumare, Brazil), obtaining a final thickness of 1.0 ± 0.02 mm. Additionally, the LD ceramic discs were crystallized in a specific oven (Vacumat 6000 MP, VITA Zahnfabrik) according to the manufacturer's guidelines.

The epoxy resin discs were obtained from 2.0 mm thick epoxy resin plates (150 × 350 × 2.0 mm; Carbotec GmbH & Co. KG, Königs Wusterhausen, Germany) with a diamond drill in the same aforementioned way for the CAD/CAM blocks, obtaining 60 epoxy resin discs (Ø = 10 mm; thickness = 2.0 mm).

The ceramic discs were cleaned in an ultrasonic bath with isopropyl alcohol (5 min) prior to the surface treatments, while the epoxy resin discs were cleaned with distilled water (5 min).

2.2 Cementation procedure

The cementation surfaces of ceramic discs were treated as recommended by the respective manufacturer (Table 2), washed with air/water spray for 30 s, and cleaned in an ultrasonic bath with distilled water for 5 min. Afterwards, the coupling agent (Monobond N, Ivoclar Vivadent) was applied for 15 s on the treated surface and left to react for 45 s (for a total of 60 s), as recommended by the manufacturer.

The cementation surface of dentin analogue discs was etched with 10% hydrofluoric acid (Condac Porcelana, FGM, Joinville, Brazil) for 60 s (Kelly et al., 2010), followed by washing with air/water spray (30 s) and ultrasonic cleaning (5 min) with distilled water. After the etching procedure, Multilink A and B Primers (Ivoclar Vivadent) were mixed in a 1:1 ratio, scrubbed onto the treated surfaces (30 s), and air-dried until a thin layer was obtained.

Each ceramic disc was adhesively cemented to an epoxy resin disc with resin cement (Multilink Automix, Ivoclar Vivadent) under a constant load of 2.5N for 10 min. The resin cement excesses were removed and the assemblies were light-cured (1200 mW/cm^2, Radii-Cal, SDI, Bayswater, Australia) for five exposures of 20 s each surface (0°, 90°, 180°, 270° and occlusal surface). All specimens were stored in distilled water (37°C) for at least 24 h up to a maximum period of 7 days before performing the mechanical fatigue tests.

After the cementation procedure, the specimens of each ceramic material were randomly allocated (www.randomizer.org) into 2 groups (n= 15) according to the frequency used for the fatigue test (2 Hz or 20 Hz) (Table 2).

2.3 Step-stress fatigue test

The cemented assemblies (n= 15) were subjected to the step-stress fatigue approach in an electric machine (Instron ElectroPuls E3000, InstronCorp, Norwood, USA). Cyclical intermittent loads were applied with a 40 mm diameter stainless steel hemispheric piston (Kelly et al., 2010) under distilled water at a frequency of 2 Hz or 20 Hz. An adhesive tape (110 µm) was placed on the occlusal surface of the cemented assembly and a thin sheet of a non-rigid material (cellophane, 2.50 µm) was placed between the piston and the ceramic surface to reduce the stress concentration contact (Kelly, 1999). An initial load of 200 N per 10,000 cycles and incremental steps of 100 N per 10,000 cycles were applied until failure, being considered as a radial crack. The specimens were checked for cracks at the end of each step by light oblique transillumination (Dibner and Kelly, 2016). When failure was detected, the fatigue failure load (FFL) and the number of failure cycles (CFF) were recorded for further statistical analysis.

2.4 Fractographic analysis

The specimens were analyzed after the fatigue tests in a stereomicroscope to verify the type of macroscopic fracture. Representative samples (n= 1) were selected from each material. The specimens were longitudinally sectioned into two halves, perpendicularly to the radial crack direction with a diamond blade under water-cooling (Isomet 1000, Buehler). The fragments were subsequently ultrasonically cleaned with distilled water, gold sputtered and analyzed under scanning electron microscopy (SEM - Vega3, Tescan, Czech Republic) at 1,000× magnification (Secondary Electrons detector, 20 Kv acceleration voltage) to determine the fractographic characteristics.

2.5 Data analysis

FFL and the CFF data were subjected to survival analysis by Kaplan Meier and Mantel-Cox Log Rank test using IBM SPSS software (IBM, Armonk, NY, USA), and the survival rates relative to each testing step were also tabulated. Additionally, FFL and CFF data were submitted to Weibull analysis using the Super SMITH Weibull 4.0k-32 software program (Wes Fulton, Torrance, United States) under the maximum likelihood method to describe structural reliability (Weibull modulus) of each tested condition. The representative failure pattern of the evaluated conditions was qualitatively analyzed.

3. Results

No statistically significant differences were detected for the load frequencies tested in PICN or LD restorations for FFL and CFF, as shown in Table 3. The Weibull analysis also showed no statistically significant difference between the frequencies in each material (Table 3).

Table 4 summarizes the survival rates of the restorations for FFL and CFF, while Fig. 1 shows the survival curves for the two aforementioned parameters.

Regarding the fractographic analysis, SEM images showed that the failures during the fatigue tests were radial cracks from the cementation interface (cement-ceramic), propagating parallel to the load application direction (Figure 2).

4. Discussion

The findings of the present study show that it is possible to accelerate the fatigue tests by a frequency of 20 Hz without affecting the fatigue mechanical behavior and fractographic features of an adhesively cemented PICN or LD ceramic restorations. Therefore, the assumed null hypothesis was accepted.

As already mentioned, the desire to accelerate fatigue tests is a necessity to make them more feasible and drastically reduce the time needed to perform them. However, this should be done without compromising the validity of the acquired data and the failure pattern observed in restorations submitted to a clinical environment (Nelson, 1980), meaning radial cracks originating on the intaglio ceramic-cement surface (Kelly et al., 2010, 1989; Thompson et al., 1994).

The existing non-consensual data in literature regarding the effect of testing frequencies are clear. Rosentritt et al. (2006) showed that the increase in the loading frequency (1.6 and 3 Hz) did not influence the fracture strength of LD all-ceramic fixed-partial dentures. Likewise, in evaluating the effect of loading frequencies (2 and 10 Hz) in a lifetime prediction of a fluorapatite glass-ceramic, Joshi et al. (2014) showed that the time to failure was not significantly different when applying 2 Hz or 10 Hz, which indicates that the use of a higher frequency did not optimize data collection in the lifetime test for a glass-ceramic. Similar results were reported for a leucite-reinforced glass-ceramic, in which the use of higher loading frequencies (such as 20 Hz) did not save time, since a higher number of cycles was necessary to promote the failure when compared to 2 Hz (Fraga et al., 2020). On the other hand, Kelly et al. (2010) investigated 2, 10 and 20 Hz frequencies in evaluating adhesively cemented glass-infiltrated alumina ceramic discs, finding an increase in the fatigue failure load when 20 Hz was used. Furthermore, Fraga et al. (2016) found similar results in investigating 2, 10, 20 and 40 Hz frequencies on the fatigue strength of a yttrium stabilized zirconia up to 20 Hz, with higher values when the 40 Hz frequency was applied.

The microstructure of the material undergoes important changes during cyclic loading due to friction between crack walls caused by the change in the stress concentrated in the crack tip from tensile to compression (Jian et al., 1993). In addition, it is known that the microstructure of a ceramic material influences their properties and the way that a crack propagates into its core (Chevalier et al., 2007; Kelly et al., 2017; Kruzic et al., 2018). The crack propagation in LD ceramics only occurs within the glass matrix, and the main toughening mechanism during crack growth is crack deflection and branching by the randomly oriented interlocked crystals (Apel et al., 2008). Meanwhile, crack propagation occurs through the continuous reinforced-glass phase, and the interpenetrated resin matrix is responsible to deflect and bridge the growing cracks in PICN material (Coldea et al., 2013a, 2013b). For polycrystalline ceramics (tested by the aforementioned studies - Kelly et al., 2010; Fraga et al., 2016), there is a combination of such mechanisms further allied with a potential transformation toughening by crystal phase transformation when stimuli is applied, which hinders crack propagation even more (Kelly et al., 2017; Kruzic et al., 2018). Thus, it is logical to assume that the testing frequency may trigger different effects depending on the material being evaluated and its respective susceptibility to slow-crack growth mechanisms.

All scenarios explored in the present study exceed the loads found clinically, which according to Kohyama et al. (2004) and Schindler et al. (1998) ranges from 20 to 140 N. It is important to note that the herein presented values were obtained through an accelerated fatigue test, where fatigue is induced in a faster and more reliable way. In these accelerated tests, the samples are subjected to more severe test conditions (stress levels higher than those found clinically) in order to accelerate the failure, while it is important to maintain the failure modes that occur clinically (Nelson, 1980). Fact that can be confirmed by the failure mode found in the fractographic analysis (radial cracks initiating from the cementation surface, underneath the load application point), which is described as the main failure reported in clinically failed ceramic crowns (Kelly et al., 2010, 1989; Thompson et al., 1994).

Finally, the data herein shows that it was possible to drastically reduce the time required (approximately 90%) for the fatigue tests using a frequency of 20 Hz rather than 2 Hz without changing the fatigue behavior of both simplified ceramic restorative materials tested (LD and PICN) and their fracture pattern. For instance, the time consumed to test one specimen of PICN reduced from 13h50min at 2 Hz to 1h20 min at 20 Hz, while for LD the time reduced from 11h at 2 Hz to 1h12min at 20 Hz. Therefore, although there is a decrease in the contact time of the piston with the materials tested using a frequency of 20 Hz, this decrease has no influence on the fatigue mechanical behavior.

It is pertinent to emphasize that the results of the present study were obtained through an accelerated fatigue method (step-stress) and the extrapolation of using higher frequencies for other fatigue testing methodologies requires prior assessment of each context, even though the same findings would probably be obtained. In addition, the results are limited to the evaluation of PICN and LD ceramic restorations, and therefore prior evaluation is required to indicate high loading frequencies for other ceramics.

5. Conclusion

The use of a 20 Hz frequency during fatigue testing shows to be a viable alternative to accelerate the test without interfering with the accessed fatigue mechanical behavior and the resulting failure pattern of lithium disilicate or polymer-infiltrated ceramic restorations.

ACKNOWLEDGEMENTS

This study was partly supported by: the Brazilian Federal Agency for Coordination of Improvement of Higher Education Personnel – CAPES, Brazil (Finance code 001, H.C.V. master scholarship); the Foundation for Research Support of the Rio Grande do Sul State, Brazil – FAPERGS (A.B.V. post-doctorate scholarship; grants # 18/2551-0000520-7). This study is part of the Master Dissertation of (H.C.V.). The authors also give thanks to the Ivoclar Vivadent company for donating some materials. It is emphasized that those institutions had no role in the scientific decisions of this study. The authors declare no conflicts of interest.

References

Apel, E., Deubener, J., Bernard, A., Höland, M., Müller, R., Kappert, H., Rheinberger, V., Höland, W., 2008. Phenomena and mechanisms of crack propagation in glass-ceramics. J. Mech. Behav. Biomed. Mater. 1, 313–325. https://doi.org/10.1016/j.jmbbm.2007.11.005

Bajraktarova-valjakova, E., Korunoska-stevkovska, V., Kapusevska, B., Gigovski, N., Grozdanov, A., 2018. Contemporary Dental Ceramic Materials , A Review : Chemical Composition , Physical and Mechanical Properties , Indications for Use. Open Access Maced. J. Med. Sci. 6, 1742–1755. https://doi.org/https://doi.org/10.3889/oamjms.2018.378

Belli, R., Frankenberger, R., Appelt, A., Schmitt, J., Baratieri, L.N., Greil, P., Lohbauer, U., 2013. Thermal-induced residual stresses affect the lifetime of zirconia–veneer crowns. Dent. Mater. 29, 181–190. https://doi.org/10.1016/j.dental.2012.11.015

Belli, R., Wendler, M., de Ligny, D., Cicconi, M.R., Petschelt, A., Peterlik, H., Lohbauer, U., 2017. Chairside CAD/CAM materials. Part 1: Measurement of elastic constants and microstructural characterization. Dent. Mater. 33, 84–98. https://doi.org/10.1016/j.dental.2016.10.009

Chen, C., Trindade, F.Z., de Jager, N., Kleverlaan, C.J., Feilzer, A.J., 2014. The fracture resistance of a CAD/CAM Resin Nano Ceramic (RNC) and a CAD ceramic at different thicknesses. Dent. Mater. 30, 954–962. https://doi.org/10.1016/j.dental.2014.05.018

Chevalier, J., Gremillard, L., Deville, S., 2007. Low-Temperature Degradation of Zirconia and Implications for Biomedical Implants. Annu. Rev. Mater. Res. 37, 1–32. https://doi.org/10.1146/annurev.matsci.37.052506.084250

Coldea, A., Swain, M. V., Thiel, N., 2013a. In-vitro strength degradation of dental ceramics and novel PICN material by sharp indentation. J. Mech. Behav. Biomed. Mater. 26, 34–42. https://doi.org/10.1016/j.jmbbm.2013.05.004

Coldea, A., Swain, M. V., Thiel, N., 2013b. Mechanical properties of polymer-infiltrated-ceramic-network materials. Dent. Mater. 29, 419–426. https://doi.org/10.1016/j.dental.2013.01.002

Dibner, A.C., Kelly, J.R., 2016. Fatigue strength of bilayered ceramics under cyclic loading as a function of core veneer thickness ratios. J. Prosthet. Dent. 115, 335–340. https://doi.org/10.1016/j.prosdent.2015.09.017

El Zhawi, H., Kaizer, M.R., Chughtai, A., Moraes, R.R., Zhang, Y., 2016. Polymer infiltrated ceramic network structures for resistance to fatigue fracture and wear. Dent. Mater. 32, 1352–1361. https://doi.org/10.1016/j.dental.2016.08.216

Fraga, S., da Silva Rodrigues, C., Zucuni, C.P., Rocha Pereira, G.K., Barbosa, M.N., Valandro, L.F., May, L.G., 2020. High load frequency at 20Hz: Its effects on the fatigue behavior of a leucite-reinforced glass-ceramic. J. Mech. Behav. Biomed. Mater. 103769. https://doi.org/10.1016/j.jmbbm.2020.103769

Fraga, S., Pereira, G.K.R., Freitas, M., Kleverlaan, C.J., Valandro, L.F., May, L.G., 2016. Loading frequencies up to 20 Hz as an alternative to accelerate fatigue strength tests in a Y-TZP ceramic. J. Mech. Behav. Biomed. Mater. 61, 79–86. https://doi.org/10.1016/j.jmbbm.2016.01.008

Guess, P.C., Schultheis, S., Bonfante, E.A., Coelho, P.G., Ferencz, J.L., Silva, N.R.F.A., 2011. All-Ceramic Systems: Laboratory and Clinical Performance. Dent. Clin. North Am. 55, 333–352. https://doi.org/10.1016/j.cden.2011.01.005

He, L.-H., Swain, M., 2011. A novel polymer infiltrated ceramic dental material. Dent. Mater. 27, 527–534. https://doi.org/10.1016/j.dental.2011.02.002

Jian, W., Zhihao, J., Xiaotian, W., 1993. A comparison of failure predictions by dynamic bending and cyclic bending fatigue techniques for Y2O3ZrO2 ceramics. Int. J. Fatigue 15, 37–40. https://doi.org/10.1016/0142-1123(93)90075-2

Joshi, G. V., Duan, Y., Della Bona, A., Hill, T.J., St. John, K., Griggs, J.A., 2014. Contributions of stress corrosion and cyclic fatigue to subcritical crack growth in a dental glass-ceramic. Dent. Mater. 30, 884–890. https://doi.org/10.1016/j.dental.2014.05.026

Kargozar, S., Baino, F., Banijamali, S., Mozafari, M., 2019. Synthesis and physico-chemical characterization of fluoride (F)- and silver (Ag)-substituted sol-gel mesoporous bioactive glasses. Biomed. Glas. 5, 185–192. https://doi.org/10.1515/bglass-2019-0015

Kelly, J.R., 1999. Clinically relevant approach to failure testing of all-ceramic restorations. J. Prosthet. Dent. 81, 652–661. https://doi.org/10.1016/S0022-3913(99)70103-4

Kelly, J.R., Campbell, S.D., Bowen, H.K., 1989. Fracture-surface analysis of dental ceramics. J. Prosthet. Dent. 62, 536–541. https://doi.org/10.1016/0022-3913(89)90075-9

Kelly, J.R., Cesar, P.F., Scherrer, S.S., Della Bona, A., van Noort, R., Tholey, M., Vichi, A., Lohbauer, U., 2017. ADM guidance-ceramics: Fatigue principles and testing. Dent. Mater. 33, 1192–1204. https://doi.org/10.1016/j.dental.2017.09.006

Kelly, J.R., Rungruanganunt, P., Hunter, B., Vailati, F., 2010. Development of a clinically validated bulk failure test for ceramic crowns. J. Prosthet. Dent. 104, 228–238. https://doi.org/10.1016/S0022-3913(10)60129-1

Kohyama, K., Hatakeyama, E., Sasaki, T., Azuma, T., Karita, K., 2004. Effect of sample thickness on bite force studied with a multiple-point sheet sensor. J. Oral Rehabil. 31, 327–334. https://doi.org/10.1046/j.1365-2842.2003.01248.x

Kruzic, J.J., Arsecularatne, J.A., Tanaka, C.B., Hoffman, M.J., Cesar, P.F., 2018. Recent advances in understanding the fatigue and wear behavior of dental composites and ceramics. J. Mech. Behav. Biomed. Mater. 88, 504–533. https://doi.org/10.1016/j.jmbbm.2018.08.008

Montazerian, M., Zanotto, E.D., 2017. Bioactive and inert dental glass-ceramics. J. Biomed. Mater. Res. Part A 105, 619–639. https://doi.org/10.1002/jbm.a.35923

Nelson, W., 1980. Accelerated Life Testing - Step-Stress Models and Data Analyses. IEEE Trans. Reliab. R-29, 103–108. https://doi.org/10.1109/TR.1980.5220742

Paula, V.G., Lorenzoni, F.C., Bonfante, E.A., Silva, N.R.F.A., Thompson, V.P., Bonfante, G., 2015. Slow cooling protocol improves fatigue life of zirconia crowns. Dent. Mater. 31, 77–87. https://doi.org/10.1016/j.dental.2014.10.005

Po, J.M.C., Kieser, J.A., Gallo, L.M., Tésenyi, A.J., Herbison, P., Farella, M., 2011. Time-Frequency Analysis of Chewing Activity in the Natural Environment. J. Dent. Res. 90, 1206–1210. https://doi.org/10.1177/0022034511416669

Rosentritt, M., Behr, M., Gebhard, R., Handel, G., 2006. Influence of stress simulation parameters on the fracture strength of all-ceramic fixed-partial dentures. Dent. Mater. 22, 176–182. https://doi.org/10.1016/j.dental.2005.04.024

Sailer, I., Makarov, N.A., Thoma, D.S., Zwahlen, M., Pjetursson, B.E., 2015. All-ceramic or metal-ceramic tooth-supported fixed dental prostheses (FDPs)? A systematic review of the survival and complication rates. Part I: Single crowns (SCs). Dent. Mater. 31, 603–623. https://doi.org/10.1016/j.dental.2015.02.011

Schindler, H.J., Stengel, E., Spiess, W.E.L., 1998. Feedback control during mastication of solid food textures—a clinical-experimental study. J. Prosthet. Dent. 80, 330–336. https://doi.org/10.1016/S0022-3913(98)70134-9

Spitznagel, F., Scholz, K., Vach, K., Gierthmuehlen, P., 2020. Monolithic Polymer-Infiltrated Ceramic Network CAD/CAM Single Crowns: Three-Year Mid-Term Results of a Prospective Clinical Study. Int. J. Prosthodont. 33, 160–168. https://doi.org/10.11607/ijp.6548

Thompson, J.Y., Anusavice, K.J., Naman, A., Morris, H.E., 1994. Fracture Surface Characterization of Clinically Failed All-ceramic Crowns. J. Dent. Res. 73, 1824–1832. https://doi.org/10.1177/00220345940730120601

Tysowsky, G.W., 2009. The science behind lithium disilicate: A metal-free alternative. Dent. Today 28, 112–113.

Wendler, M., Belli, R., Petschelt, A., Mevec, D., Harrer, W., Lube, T., Danzer, R., Lohbauer, U., 2017. Chairside CAD/CAM materials. Part 2: Flexural strength testing. Dent. Mater. 33, 99–109. https://doi.org/10.1016/j.dental.2016.10.008

Wendler, M., Belli, R., Valladares, D., Petschelt, A., Lohbauer, U., 2018. Chairside CAD/CAM materials. Part 3: Cyclic fatigue parameters and lifetime predictions. Dent. Mater. 34, 910–921. https://doi.org/10.1016/j.dental.2018.03.024

Wiskott, H.W., Nicholls, J.I., Belser, U.C., 1995. Stress fatigue: basic principles and prosthodontic implications. Int. J. Prosthodont. 8, 105–16.

Zhang, Y., Lawn, B., 2004. Long-term strength of ceramics for biomedical applications. J. Biomed. Mater. Res. 69B, 166–172. https://doi.org/10.1002/jbm.b.20039

Zogheib, L.V., Bona, A. Della, Kimpara, E.T., Mccabe, J.F., 2011. Effect of hydrofluoric acid etching duration on the roughness and flexural strength of a lithium disilicate-based glass ceramic. Braz. Dent. J. 22, 45–50. https://doi.org/10.1590/S0103-64402011000100008

TABLES

Table 1. Description of materials, commercial name, manufacturer, composition and batch number.

Material	**Commercial name/manufacturer**	**Composition**	**Batch number**
Lithium disilicate glass ceramic	IPS e.Max CAD, Ivoclar Vivadent, Schaan, Liechtenstein	SiO_2 57-80%, Li_2O 11-19%, K_2O 0-13%, P_2O_5 0-11%, ZrO_2 0-8%, ZnO 0-8%, other and colouring oxides 0-12%.	W93126
Polymer infiltrated ceramic network	Vita Enamic, VITA Zahnfabrik	SiO_2 58-63%, Al_2O_3 20-23%, Na_2O 6-11%, K_2O 4-6%, B_2O_3 0,5-2%, other and/or colouring oxides 0-1%.	51880
Ceramic primer coupling agent	Monobond N, Ivoclar Vivadent	Alcohol solution of silane methacrylate, phosphoric acid methacrylate and sulphide methacrylate.	Y19262
5% hydrofluoric acid	IPS Ceramic Etching Gel, Ivoclar Vivadent	< 5% hydrofluoric acid.	W14921
10% hydrofluoric acid	Condac Porcelana, FGM, Joinville, Brazil	< 10% hydrofluoric acid.	010819
Dual cure resin cement	Multilink N, Ivoclar Vivadent	Silicate glass, ytterbium trifluoride, highly dispersed silica, catalysts and stabilizer, pigments.	W44613
Primer	Multilink Primer (A and B), Ivoclar Vivadent	Primer A: water, initiators; primer B: phosphonic acid acrylate, hydroxyethyl methacrylate, methacrylate mod. polyacrylic acid, stabilizer.	Primer A: W88902 Primer B: W44494
Epoxy resin	Carbotec GmbH & Co. KG, Königs Wusterhausen, Germany	Continuous filament woven fiberglass bonded with epoxy resin.	-
*The chemical composition is described according to the manufacturers' information.			

Table 2. Experimental design.

Group	**Material**	**Loading Frequency**	**Surface treatment***
PICN_20	Polymer-infiltrated ceramic-network (PICN)	20 Hz	Hydrofluoric acid 5% for 60 s
PICN_2		2 Hz	
LD_20	Lithium disilicate ceramic (LD)	20 Hz	Hydrofluoric acid 5% for 20 s
LD_2		2 Hz	
*Recommended by the manufacturer.			

Table 3. Mean fatigue failure loads (FFL) in Newtons, number of cycles for failure (CFF), and Weibull modulus of each evaluated condition, with their respective 95% confidence interval (CI).

Groups	FFL		CFF	
	Mean (CI)*	**Weibull modulus (CI)****	**Mean (CI)***	**Weibull modulus (CI)****
PICN_20	1127 (1078 – 1175) ^{A}	12.33 (8.12 – 17.35) ^{A}	102,667 (97,803 – 107,531) ^{A}	11.27 (7.42 – 15.87) ^{A}
PICN_2	1120 (1034 – 1206) ^{AB}	8.86 (5.57 – 13.12) ^{AB}	102,000 (93,403 – 110,597) ^{AB}	8.05 (5.05 – 11.92) ^{AB}
LD_20	980 (884 – 1076) ^{BC}	5.68 (3.74 – 7.91) ^{B}	88,000 (78,398 – 97,602) ^{BC}	5.13 (3.38 – 7,17) ^{BC}
LD_2	900 (817 – 983) ^{C}	6.23 (4.04 – 8.91) ^{AB}	80,000 (71,663 – 88,338) ^{C}	5.56 (3.60 – 7.96) ^{C}

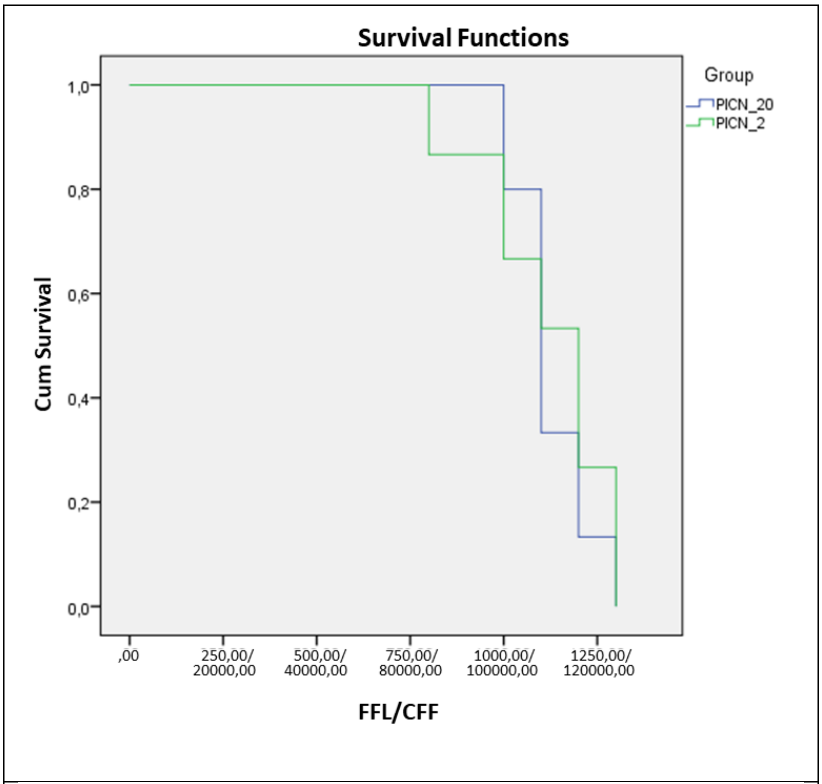
Different letters indicate statistical differences on each column for each considered outcome.
* Kaplan-Meier and Mantel-Cox (log-rank) tests for FFL and CFF.
** Maximum -likelihood estimations for Weibull analysis, based on the absence of CI overlapping.

Table 4. Survival rates – probability of specimens to exceed the respective fatigue failure load (FFL) and number of cycles for failure (CFF) step without crack propagation, and its respective standard error values.

Groups	FFL (N) / CFF													
	200 / 10,000	**300 / 20,000**	**400 / 30,000**	**500 / 40,000**	**600 / 50,000**	**700 / 60,000**	**800 / 70,000**	**900 / 80,000**	**1000 / 90,000**	**1100 / 100,000**	**1200 / 110,000**	**1300 / 120,000**	**1400 / 130,000**	**1500 / 140,000**
PICN_20	1	1	1	1	1	1	1	1	0.80 (0.10)	0.33 (0.12)	0.13 (0.09)	0.00 (0.00)	-	-
PICN_2	1	1	1	1	1	1	0,87 (0,09)	0.87 (0.09)	0.67 (0.12)	0.53 (0.13)	0.27 (0.11)	0.00 (0.00)	-	-
LD_20	1	1	1	1	0.93 (0.06)	0.87 (0.09)	0.87 (0.09)	0.60 (0.13)	0.27 (0.11)	0.13 (0.09)	0.07 (0.07)	0.07 (0.07)	0.00 (0.00)	-
LD_2	1	1	1	1	1	0.73 (0.11)	0.60 (0.13)	0.40 (0.13)	0.20 (0.10)	0.07 (0.06)	0.00 (0.00)	-	-	-

* The symbol '-' indicates absence of specimens being submitted to the respective category.

FIGURES



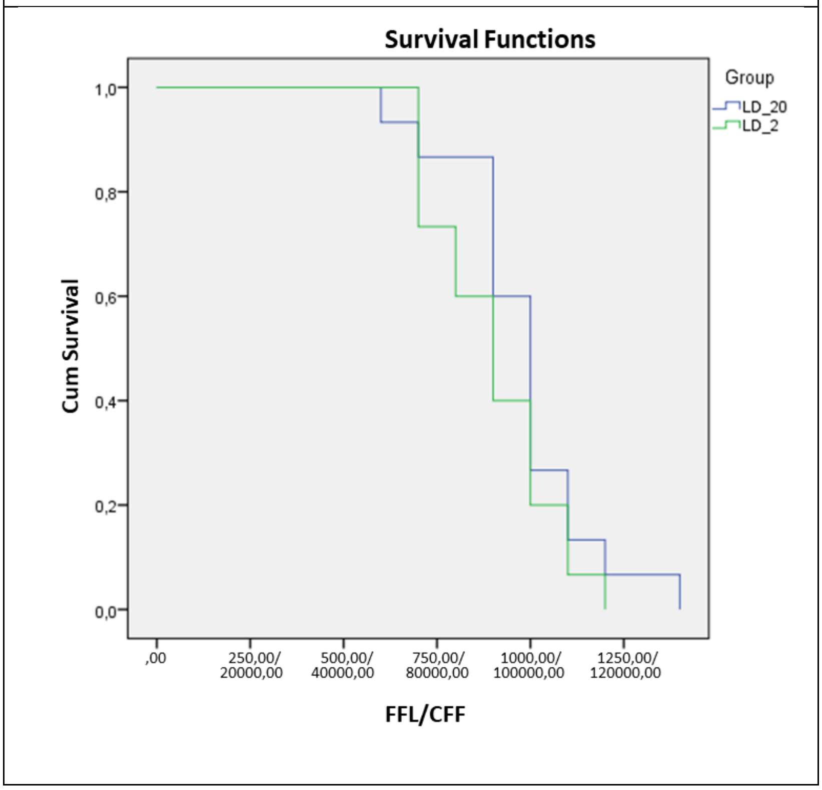


Figure 1. Survival curves according to the steps of fatigue failure loads (FFL) in Newtons, number of cycles for failure (CFF) in which each disc failed, obtained by Kaplan–Meier and Log-rank tests.

PICN	LD

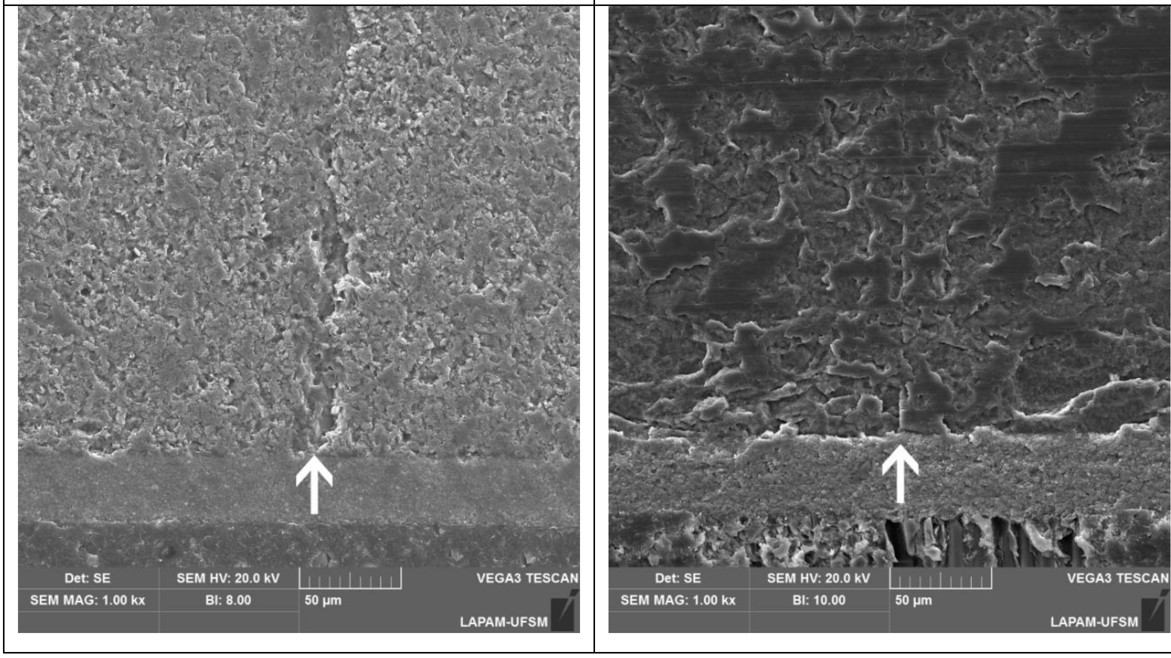


Figure 2. Micrographs obtained by SEM at 1000× magnification illustrating that all failures originated at cementation interface, region pointed by white arrows, which then propagated in a direction parallel to the load application into the opposite side surface.

4 DISCUSSÃO GERAL

Os estudos *in vitro* de materiais restauradores conferem ao pesquisador a possibilidade de isolar fatores e abordar parâmetros específicos que podem influenciar no desfecho estudado. Por outro lado, também podem permitir a adoção de cenários de testes mais complexos, que tentam simular muitos dos fatores a que uma restauração pode ser exposta no ambiente clínico (BONFANTE; COELHO, 2016). Assim, é importante que o pesquisador considere qual desenho experimental e método de teste são mais adequados para que os resultados consigam responder ao objetivo do estudo, seja isolando ou associando os fatores de estudo. Neste sentido, esta dissertação se propôs a investigar os parâmetros de testes adotados nos ensaios de fadiga cíclica de materiais restauradores.

Em um primeiro momento, uma revisão de escopo foi realizada com o propósito de identificar os parâmetros de teste, métodos e características usadas para induzir fadiga cíclica em espécimes não anatômicos de materiais restauradores dentários. Por meio dessa revisão foi possível observar que há uma grande heterogeneidade nos parâmetros de teste e metodologias que têm sido adotados para conduzir ensaios de fadiga cíclica em materiais restauradores dentários. Portanto, é importante discutir as implicações metodológicas e a aproximação com a realidade clínica.

A maioria dos estudos incluídos na presente revisão avaliaram os materiais restauradores através de geometrias de teste de flexão (resistência flexural 3-pontos, 4-pontos ou biaxial), empregadas para caracterização, avaliação da confiabilidade dos materiais ou avaliação de fatores específicos (métodos de processamento ou tratamento de superfície) e influência nas propriedades do material (KELLY et al., 2017). Já as geometrias de teste utilizando materiais restauradores cimentados a um substrato visam a simulação de um cenário mais próximo ao cenário clínico e diferentes distribuições de tensão podem ser esperadas, dependendo do módulo de elasticidade dos materiais restauradores e do substrato (DAL PIVA et al., 2018; FACENDA et al., 2019; OTTONI et al., 2018). Além disso, pode ser avaliado o papel da cimentação adesiva no comportamento mecânico à fadiga das restaurações quando submetidas a diferentes métodos de processamento ou tratamentos de superfície, por exemplo.

Quanto aos métodos de fadiga, métodos acelerados como *Staircase, Stepstress ou Boundary* foram os mais adotados pelos estudos, visto que são uma alternativa para obtenção dos dados de uma forma mais rápida e confiável (KELLY et al., 2017). No entanto, é importante conhecer suas características e limitações. O método *Staircase* determina o valor médio do limite de fadiga do material para uma determinada vida útil (número de ciclos). No entanto, o número pré-definido de ciclos a que o espécime é exposto limita previsões em diferentes números de ciclos e este teste não é conduzido em uma ampla faixa de carga ou valores de estresse extremos, o que poderia mascarar o desempenho nos piores cenários (BONFANTE; COELHO, 2016). Por outro lado, cada corpo de prova no método S*tepstress* é submetido a níveis crescentes de carga, o que significa que após um certo período (número de ciclos) a carga é aumentada passo a passo até sua falha ou término dos perfis de teste. Este método considera o efeito cumulativo das tensões aplicadas, estimando a probabilidade de sobrevivência ao longo do tempo e prevendo a confiabilidade para um período específico (METTAS; VASSILIOU, 2002; NELSON, 1980). Já no método *Boundary*, dois grupos de corpos de prova são avaliados para cada número de ciclos determinados, usando dois níveis de tensão, um correspondendo a uma baixa probabilidade de falha e outro com uma amplitude de tensão correspondendo a uma alta probabilidade de falha. Uma vantagem desta metodologia é que os dados obtidos podem ser usados para prever tensões correspondentes a baixas probabilidades de falha, fornecendo mais precisão na estimativa da faixa de tensões de interesse clínico (HUYSMANS et al., 1992; MAENNIG, 1975; ZHANG; GRIGGS, 2003).

Após a definição da geometria de teste e do método de fadiga, o delineamento dos estudos ainda engloba a definição dos parâmetros de teste a serem empregados. Para isso, deve ser levado em consideração a microestrutura do material, o mecanismo de propagação de trincas e como cada um desses parâmetros influenciará na indução à fadiga cíclica.

O material utilizado para a confecção do aplicador de carga (pistão), formato e dimensões da ponta ativa são fatores que podem influenciar o modo de falha e distribuição de tensões durante o carregamento (KELLY, 1999). No entanto, este parâmetro não foi relatado pela maioria dos estudos. É importante observar que, materiais com alto módulo de elasticidade tendem a induzir maior pressão de contato e, consequentemente, maior concentração de tensões, podendo causar danos de contato na superfície do material, que não são observadas com frequência nas falhas clínicas (KELLY et al., 2010). Neste sentido, uma análise fractográfica criteriosa é fundamental para determinar o padrão de falha gerado.

Por outro lado, parâmetros como ambiente de teste úmido e análise fractográfica foram adotados pela maioria dos estudos, demonstrando o cuidado dos autores da aproximação com o cenário clínico. Sabe-se que a presença de umidade pode influenciar os fenômenos de fadiga por meio de um processo de degradação química (KELLY et al., 2017), o que reforça a necessidade de um ambiente úmido durante o teste. Adicionalmente, a realização de uma análise fractográfica é essencial para caracterizar as falhas observadas, servindo para elucidar a origem e causas da falha, as condições de carregamento e a direção de propagação da trinca (SCHERRER et al., 2017). Dependendo da geometria de teste, diferentes padrões fractográficos podem ser encontrados. Neste sentido, espera-se que as trincas em corpos de prova testados em configurações de ensaio de flexão comecem de defeitos na superfície de tração (parte inferior) em direção à superfície de compressão (parte superior), onde uma curvatura de compressão é encontrada (SCHERRER et al., 2017). Já nas geometrias de teste cimentadas que simulam um cenário mais próximo ao das restaurações clínicas, modos de falha devem mimetizar aqueles que são relatados clinicamente. Dentre eles, trincas iniciando na superfície da interface de cimentação oposta à aplicação de carga (KELLY et al., 2010) e na região da margem da coroa, justaposta ao término do preparo da restauração (ØILO et al., 2014). Defeitos introduzidos pelo processamento em ambos os cenários seriam responsáveis por desencadear concentrações de tensões durante o carregamento mecânico que induziriam a coalescência desses defeitos e subsequentemente propagação catastrófica de trincas (ZHANG; SAILER; LAWN, 2013). Outra região responsável pela origem das falhas é a superfície oclusal (SAILER et al., 2009). Nesta região, as falhas partiriam de defeitos introduzidos por procedimentos de usinagem CAD/CAM e/ou ajuste oclusal, que fazem parte dos processos de fabricação e adaptação/ajuste das restaurações (DELLA BONA; KELLY, 2008; TAUFER; DELLA BONA, 2019).

Em relação a frequência de carregamento, frequências próximas a 2 Hz foram as mais adotadas pelos estudos, o que influencia diretamente no tempo necessário para realização dos ensaios de fadiga cíclica. Neste contexto, alguns estudos têm avaliado o uso que frequências de carregamento mais altas (10, 20 e 40 Hz) como alternativa para acelerar os ensaios de fadiga em materiais cerâmicos como zircônia, leucita, alumina infiltrada por vidro e fluorapatita (FRAGA et al., 2016, 2020; JOSHI et al., 2014; KELLY et al., 2010). No entanto, a degradação mecânica ocasionada pelo atrito entre as paredes da trinca durante o carregamento cíclico, devido à mudança na tensão concentrada na ponta da trinca de tração para compressão (JIAN; ZHIHAO; XIAOTIAN, 1993), pode ser influenciada pela frequência de carregamento adotada pelo ensaio de fadiga cíclica, visto que o tempo disponível para abertura e fechamento da trinca pode variar de acordo com a frequência adotada. Além disso, as diferentes microestruturas dos materiais cerâmicos irão influenciar em suas propriedades e nos mecanismos de propagação de trincas (CHEVALIER; GREMILLARD; DEVILLE, 2007; KELLY et al., 2017; KRUZIC et al., 2018).

Assim, o segundo estudo da presente dissertação teve como proposta avaliar se é possível acelerar os ensaios de fadiga aumentando a frequência de carregamento sem influenciar o comportamento mecânico à fadiga de restaurações de cerâmica infiltrada por polímeros (PICN) e de dissilicato de lítio (LD). Os resultados demonstraram que uma frequência de carregamento de 20 Hz é uma alternativa viável para acelerar os ensaios de fadiga sem afetar o comportamento mecânico e as características fractográficas em ambas as cerâmicas estudadas. Assim, foi possível reduzir o tempo necessário (aproximadamente 90%) para os testes de fadiga usando uma frequência de 20 Hz em vez de 2 Hz. Por exemplo, o tempo consumido para testar um corpo de prova de PICN foi reduzido de 13h50min a 2 Hz para 1h20min a 20 Hz, enquanto para o LD o tempo foi reduzido de 11h a 2 Hz para 1h12min a 20 Hz. Portanto, embora seja observado uma diminuição no tempo de contato do pistão com os materiais ensaiados na frequência de 20 Hz, essa diminuição não teve influência no comportamento mecânico à fadiga dos materiais testados.

As limitações dos estudos da presente dissertação incluem principalmente a grande heterogeneidade entre os estudos incluídos em relação aos materiais considerados, os formatos dos espécimes, características de teste, parâmetros e métodos adotados. No entanto, embora permita uma discussão e orientação para estudos futuros, a ausência de estudos primários comparando a influência de tais fatores na aquisição de dados de fadiga dificulta a indicação de um ou outro parâmetro. Além disso, os resultados do estudo *in vitro* são limitados à avaliação de restaurações de cerâmica PICN e LD e, portanto, uma avaliação prévia é necessária para indicar altas frequências de carregamento para outros materiais restauradores.

5 CONSIDERAÇÕES FINAIS

Com base nas investigações científicas apresentadas nos artigos, pode-se concluir que:

- Configurações de teste de flexão, carregamento axial e ensaios de fadiga acelerada são os mais empregados para induzir fadiga cíclica em espécimes não anatômicos de materiais restauradores dentários. No entanto, a definição da geometria de teste, direção de carregamento e do método de fadiga deve estar relacionada ao objetivo do estudo.

- Frequências de carregamento abaixo de 2 Hz são as mais utilizadas. Apesar disso, frequências de carregamento mais elevadas (ou seja, 20 Hz) são uma alternativa para acelerar os ensaios de fadiga cíclica de materiais como a cerâmica Y-TZP, cerâmica infiltrada por polímeros e cerâmica de dissilicato de lítio.

- Pistões confeccionados com diferentes materiais e formatos/dimensões da ponta ativa são descritos na literatura. Porém, seu uso não deve alterar o modo de falha descrito para a geometria de teste adotada após execução de uma cuidadosa análise fractográfica.

- Um ambiente de teste úmido foi descrito na maioria dos estudos, visto que é uma ferramenta importante para simular a degradação hidrolítica dos materiais observada em cenários clínicos.

REFERÊNCIAS

BARAN, G.; BOBERICK, K.; MCCOOL, J. Fatigue of restorative materials. **Critical reviews in oral biology and medicine : an official publication of the American Association of Oral Biologists**, v. 12, n. 4, p. 350–360, 2001.

BAYNE, S. C. et al. The Evolution of Dental Materials over the Past Century: Silver and Gold to Tooth Color and Beyond. **Journal of Dental Research**, v. 98, n. 3, p. 257–265, 20 mar. 2019.

BONFANTE, E. A.; COELHO, P. G. A Critical Perspective on Mechanical Testing of Implants and Prostheses. **Advances in dental research**, v. 28, n. 1, p. 18–27, mar. 2016.

CHARLES, R. Static fatigue of glass. **Journal of Applied Physics**, p. 1549–60, 1958.

CHEVALIER, J.; GREMILLARD, L.; DEVILLE, S. Low-Temperature Degradation of Zirconia and Implications for Biomedical Implants. **Annual Review of Materials Research**, v. 37, n. 1, p. 1–32, ago. 2007.

DAL PIVA, A. M. DE O. et al. CAD-FEA modeling and analysis of different full crown monolithic restorations. **Dental Materials**, v. 34, n. 9, p. 1342–1350, set. 2018.

DELLA BONA, A.; KELLY, J. R. The Clinical Success Of All-Ceramic Restorations. **The Journal of the American Dental Association**, v. 139, p. S8–S13, set. 2008.

DENRY, I.; HOLLOWAY, J. Ceramics for Dental Applications: A Review. **Materials**, v. 3, n. 1, p. 351–368, 11 jan. 2010.

FACENDA, J. C. et al. Effect of supporting substrate on the failure behavior of a polymer-infiltrated ceramic network material. **The Journal of prosthetic dentistry**, v. 121, n. 6, p. 929–934, jun. 2019.

FRAGA, S. et al. Loading frequencies up to 20Hz as an alternative to accelerate fatigue strength tests in a Y-TZP ceramic. **Journal of the mechanical behavior of biomedical materials**, v. 61, p. 79–86, ago. 2016.

FRAGA, S. et al. High load frequency at 20Hz: Its effects on the fatigue behavior of a leucite-reinforced glass-ceramic. **Journal of the Mechanical Behavior of Biomedical Materials**, v. 107, p. 103769, jul. 2020.

FREIMAN, S. W.; WIEDERHORN, S. M.; MECHOLSKY, JR., J. J. Environmentally Enhanced Fracture of Glass: A Historical Perspective. **Journal of the American Ceramic Society**, v. 92, n. 7, p. 1371–1382, jul. 2009.

HUYSMANS, M. C. D. N. J. M. et al. Fatigue Behavior of Direct Post-and-core-restored Premolars. **Journal of Dental Research**, v. 71, n. 5, p. 1145–1150, 8 maio 1992.

JIAN, W.; ZHIHAO, J.; XIAOTIAN, W. A comparison of failure predictions by dynamic bending and cyclic bending fatigue techniques for Y2O3ZrO2 ceramics. **International Journal of Fatigue**, v. 15, n. 1, p. 37–40, jan. 1993.

JOSHI, G. V. et al. Contributions of stress corrosion and cyclic fatigue to subcritical crack growth in a dental glass-ceramic. **Dental Materials**, v. 30, n. 8, p. 884–890, ago. 2014.

KELLY, J. R. Clinically relevant approach to failure testing of all-ceramic restorations. **The Journal of Prosthetic Dentistry**, v. 81, n. 6, p. 652–661, jun. 1999.

KELLY, J. R. et al. Development of a clinically validated bulk failure test for ceramic crowns. **The Journal of Prosthetic Dentistry**, v. 104, n. 4, p. 228–238, out. 2010.

KELLY, J. R. et al. ADM guidance-ceramics: Fatigue principles and testing. **Dental Materials**, v. 33, n. 11, p. 1192–1204, nov. 2017.

KRUZIC, J. J. et al. Recent advances in understanding the fatigue and wear behavior of dental composites and ceramics. **Journal of the Mechanical Behavior of Biomedical Materials**, v. 88, p. 504–533, dez. 2018.

MAENNIG, W. Statistical planning and evaluation of fatigue tests. A survey of recent results. **Int J Fract**, v. 11, p. 123–129, 1975.

METTAS, A.; VASSILIOU, P. **Modeling and analysis of time-dependent stress accelerated life data**. Annual Reliability and Maintainability Symposium. 2002 Proceedings (Cat. No.02CH37318). **Anais**...IEEE, 2002Disponível em: <http://ieeexplore.ieee.org/document/981665/>

MICHALSKE, T. A.; FREIMAN, S. W. A Molecular Mechanism for Stress-Corrosion in Vitreous Silica. **Journal of the American Ceramic Society**, v. 66, n. 4, p. 284–288, 1993.

NELSON, W. Accelerated Life Testing - Step-Stress Models and Data Analyses. **IEEE Transactions on Reliability**, v. R-29, n. 2, p. 103–108, jun. 1980.

NELSON, W. B. **Accelerated Testing: Statistical Models, Test Plans, and Data Analysis**. New Jersey: Hoboken, 2004.

ØILO, M. et al. Fractographic features of glass-ceramic and zirconia-based dental restorations fractured during clinical function. **European Journal of Oral Sciences**, v. 122, n. 3, p. 238–244, jun. 2014.

OTTONI, R. et al. Precision of different fatigue methods for predicting glass-ceramic failure. **Journal of the mechanical behavior of biomedical materials**, v. 88, p. 497–503, dez. 2018.

PO, J. M. C. et al. Time-Frequency Analysis of Chewing Activity in the Natural Environment. **Journal of Dental Research**, v. 90, n. 10, p. 1206–1210, out. 2011.

ROSENTRITT, M.; BEHR, M.; PREIS, V. A Critical Evaluation of Fatigue Studies for Restorative Materials in Dentistry. **Current Oral Health Reports**, v. 3, n. 3, p. 221–228, 16 set. 2016.

SAILER, I. et al. Randomized controlled clinical trial of zirconia-ceramic and metal-ceramic posterior fixed dental prostheses: a 3-year follow-up. **The International journal of prosthodontics**, v. 22, n. 6, p. 553–60, 2009.

SCHERRER, S. S. et al. ADM guidance-Ceramics: guidance to the use of fractography in failure analysis of brittle materials. **Dental materials : official publication of the Academy**

of Dental Materials, v. 33, n. 6, p. 599–620, jun. 2017.

TAKESHIGE, F. et al. Fatigue behavior of resin composites in aqueous environments. **Dental Materials**, v. 23, n. 7, p. 893–899, jul. 2007.

TASKONAK, B. et al. Analysis of subcritical crack growth in dental ceramics using fracture mechanics and fractography. **Dental materials : official publication of the Academy of Dental Materials**, v. 24, n. 5, p. 700–707, maio 2008.

TAUFER, C.; DELLA BONA, A. Edge chipping resistance of ceramics bonded to a dentine analogue. **Journal of the Mechanical Behavior of Biomedical Materials**, v. 90, p. 587–590, fev. 2019.

WIEDERHORN, S. M. Influence of Water Vapor on Crack Propagation in Soda-Lime Glass. **Journal of the American Ceramic Society**, v. 50, n. 8, p. 407–414, ago. 1967.

WIEDERHORN, S. M.; BOLZ, L. H. Stress Corrosion and Static Fatigue of Glass. **Journal of the American Ceramic Society**, v. 53, n. 10, p. 543–548, out. 1970.

WISKOTT, H. W.; NICHOLLS, J. I.; BELSER, U. C. Stress fatigue: basic principles and prosthodontic implications. **The International journal of prosthodontics**, v. 8, n. 2, p. 105–16, 1995.

ZHANG, Y.; GRIGGS, J. A. Evaluation of failure probability estimators for cyclic fatigue using boundary technique. **Journal of Materials Science Letters**, v. 22, n. 24, p. 1775–1777, dez. 2003.

ZHANG, Y.; KELLY, J. R. Dental Ceramics for Restoration and Metal Veneering. **Dental Clinics of North America**, v. 61, n. 4, p. 797–819, out. 2017.

ZHANG, Y.; SAILER, I.; LAWN, B. R. Fatigue of dental ceramics. **Journal of dentistry**, v. 41, n. 12, p. 1135–1147, dez. 2013.

ANEXO A – NORMAS PARA PUBLICAÇÃO NO PERIÓDICO *MATERIALS SCIENCE AND ENGINEERING C: MATERIALS FOR BIOLOGICAL APPLICATIONS*

GUIDE FOR AUTHORS

Your Paper Your Way

We now differentiate between the requirements for new and revised submissions. You may choose to submit your manuscript as a single Word or PDF file to be used in the refereeing process. Only when your paper is at the revision stage, will you be requested to put your paper in to a 'correct format' for acceptance and provide the items required for the publication of your article.

To find out more, please visit the Preparation section below.

INTRODUCTION

Materials Science and Engineering C: Materials for Biological Applications includes topics at the interface of the biomedical sciences and materials engineering. These topics include: Bioinspired and biomimetic materials for medical applications Materials of biological origin for medical applications Materials for "active" medical applications Self-assembling and self-healing materials for medical applications "Smart" (i.e., stimulus-response) materials for medical applications Ceramic, metallic, polymeric, and composite materials for medical applications Materials for in vivo sensing Materials for in vivo imaging Materials for delivery of pharmacologic agents and vaccines Novel approaches for characterizing and modeling materials for medical applications Manuscripts on biological topics without a materials science component, or manuscripts on materials science without biological applications, will not be considered for publication in Materials Science and Engineering C. New submissions are first assessed for language, scope and originality (plagiarism check) and can be desk rejected before review if they need English language improvements, are out of scope or present excessive duplication with published sources.

Types of paper

°Original research work not already published

°Plenary lectures and/or individual papers given at conferences

°Invited reviews of specialized topics within the scope of the journal*

°Letters intended for rapid publications *The Journal publishes invited reviews presenting a detailed, critical summary of current research findings on a particular topic or area of research. If you are interested in writing a review article for the journal, please get in touch with the Journal (msc@elsevier.com) outlining the proposed focus of your review article.

Revised submission

When submitting the revised manuscript, please make sure that you upload the final version of the paper. Please remove the old version(s) of the manuscript before submitting the revised version.

Submission checklist

You can use this list to carry out a final check of your submission before you send it to the journal for review. Please check the relevant section in this Guide for Authors for more details.

Ensure that the following items are present:

One author has been designated as the corresponding author with contact details:

• E-mail address
• Full postal address

All necessary files have been uploaded:

Manuscript:

• Include keywords
• All figures (include relevant captions)
• All tables (including titles, description, footnotes)
• Ensure all figure and table citations in the text match the files provided
• Indicate clearly if color should be used for any figures in print

Graphical Abstracts / Highlights files (where applicable)

Supplemental files (where applicable)

Further considerations

• Manuscript has been 'spell checked' and 'grammar checked'
• All references mentioned in the Reference List are cited in the text, and vice versa
• Permission has been obtained for use of copyrighted material from other sources (including the Internet)
• A competing interests statement is provided, even if the authors have no competing interests to declare
• Journal policies detailed in this guide have been reviewed
• Referee suggestions and contact details provided, based on journal requirements
For further information, visit our Support Center.

BEFORE YOU BEGIN

Ethics in publishing

Please see our information pages on Ethics in publishing and Ethical guidelines for journal publication.

"Public trust in the peer review process and the credibility of published articles depend in part on how well conflict of interest is handled during writing, peer review, and editorial decision making. Conflict of interest exists when an author (or the author's institution), reviewer, or editor has financial or personal relationships that inappropriately influence (bias) his or her actions (such relationships are also known as dual commitments, competing interests, or competing loyalties). These relationships vary from those with negligible potential to those with great potential to influence judgment, and not all relationships represent true conflict of interest. The potential for conflict of interest can exist whether or not an individual believes that the relationship affects his or her scientific judgment. Financial relationships (such as employment, consultancies, stock ownership, honoraria, paid expert testimony) are the most easily identifiable conflicts of interest and the most likely to undermine the credibility of the journal, the authors, and of science itself. However, conflicts can occur for other reasons, such as personal relationships, academic competition, and intellectual passion." *

"Patients have a right to privacy that should not be infringed without informed consent. Identifying information, including patients' names, initials, or hospital numbers, should not be published in written descriptions, photographs, and pedigrees unless the information is essential for scientific purposes and the patient (or parent or guardian) gives written informed consent for publication. Informed consent for this purpose requires that a patient who is identifiable be shown the manuscript to be published. Authors should identify Individuals who provide writing assistance and disclose the funding source for this assistance."*

Identifying details should be omitted if they are not essential. Complete anonymity is difficult to achieve, however, and informed consent should be obtained if there is any doubt. For example, masking the eye region in photographs of patients is inadequate protection of anonymity. If identifying characteristics are altered to protect anonymity, such as in genetic pedigrees, authors should provide assurance that alterations do not distort scientific meaning and editors should so note. The requirement for informed consent should be included in the journal's instructions for authors." **

"When informed consent has been obtained it should be indicated in the published article." ***

"When reporting experiments on human subjects, authors should indicate whether the procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000 (5). If doubt exists whether the research was conducted in accordance with the Helsinki Declaration, the authors must explain the rationale for their approach, and demonstrate that the institutional review body explicitly approved the doubtful aspects of the study. When reporting experiments on animals, authors should be asked to indicate whether the institutional and national guide for the care and use of laboratory animals was followed." *

* International Committee of Medical Journal Editors ("Uniform Requirements for Manuscripts Submitted to Biomedical Journals") -- February 2006

** International Committee of Medical Journal Editors ("Uniform Requirements for Manuscripts Submitted to Biomedical Journals") -- February 2006

*** Daniel D. Federman, Kathi E. Hanna, and Laura Lyman Rodriguez, Editors, Committee on Assessing the System for Protecting Human Research Participants, in: Responsible Research: A Systems Approach to Protecting Research Participants, The National Academies Press, 2002

Declaration of competing interest

All authors must disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work. Examples of potential conflicts of interest include employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/ registrations, and grants or other funding. Authors should complete the declaration of competing interest statement using this template and upload to the submission system at the Attach/Upload Files step. Note: Please do not convert the .docx template to another file type. Author signatures are not required. If there are no interests to declare, please choose the first option in the template. This statement will be published within the article if accepted. More information.

Submission declaration and verification

Submission of an article implies that the work described has not been published previously (except in the form of an abstract, a published lecture or academic thesis, see 'Multiple, redundant or concurrent publication' for more information), that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright holder. To verify originality, your article may be checked by the originality detection service Crossref Similarity Check.

Preprints

Please note that preprints can be shared anywhere at any time, in line with Elsevier's sharing policy. Sharing your preprints e.g. on a preprint server will not count as prior publication (see 'Multiple, redundant or concurrent publication' for more information).

Use of inclusive language

Inclusive language acknowledges diversity, conveys respect to all people, is sensitive to differences, and promotes equal opportunities. Content should make no assumptions about the beliefs or commitments of any reader; contain nothing which might imply that one individual is superior to another on the grounds of age, gender, race, ethnicity, culture, sexual orientation, disability or health condition; and use inclusive language throughout. Authors should ensure that writing is free from bias, stereotypes, slang, reference to dominant culture and/or cultural assumptions. We advise to seek gender neutrality by using plural nouns ("clinicians, patients/clients") as default/wherever possible to avoid using "he, she," or "he/she." We recommend avoiding the use of descriptors that refer to personal attributes such as age, gender, race, ethnicity, culture, sexual orientation, disability or health condition unless they are relevant and valid. These guidelines are meant as a point of reference to help identify appropriate language but are by no means exhaustive or definitive.

Author contributions

For transparency, we encourage authors to submit an author statement file outlining their individual contributions to the paper using the relevant CRediT roles: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing. Authorship statements should be formatted with the names of authors first and CRediT role(s) following. More details and an example

Changes to authorship

Authors are expected to consider carefully the list and order of authors before submitting their manuscript and provide the definitive list of authors at the time of the original submission. Any addition, deletion or rearrangement of author names in the authorship list should be made only before the manuscript has been accepted and only if approved by the journal Editor. To request such a change, the Editor must receive the following from the corresponding author: (a) the reason for the change in author list and (b) written confirmation (e-mail, letter) from all authors that they agree with the addition, removal or rearrangement. In the case of addition or removal of authors, this includes confirmation from the author being added or removed. Only in exceptional circumstances will the Editor consider the addition, deletion or rearrangement of authors after the manuscript has been accepted. While the Editor considers the request, publication of the manuscript will be suspended. If the manuscript has already been published in an online issue, any requests approved by the Editor will result in a corrigendum.

Article transfer service

This journal is part of our Article Transfer Service. This means that if the Editor feels your article is more suitable in one of our other participating journals, then you may be asked to consider transferring the article to one of those. If you agree, your article will be transferred automatically on your behalf with no need to reformat. Please note that your article will be reviewed again by the new journal. More information.

Copyright

Upon acceptance of an article, authors will be asked to complete a 'Journal Publishing Agreement' (see more information on this). An e-mail will be sent to the corresponding author confirming receipt of the manuscript together with a 'Journal Publishing Agreement' form or a link to the online version of this agreement.

Subscribers may reproduce tables of contents or prepare lists of articles including abstracts for internal circulation within their institutions. Permission of the Publisher is required for resale or distribution outside the institution and for all other derivative works, including compilations and translations. If excerpts from other copyrighted works are included, the author(s) must obtain written permission from the copyright owners and credit the source(s) in the article. Elsevier has preprinted forms for use by authors in these cases.

For gold open access articles: Upon acceptance of an article, authors will be asked to complete an 'Exclusive License Agreement' (more information). Permitted third party reuse of gold open access articles is determined by the author's choice of user license.

Author rights

As an author you (or your employer or institution) have certain rights to reuse your work. More information.

Elsevier supports responsible sharing

Find out how you can share your research published in Elsevier journals.

Role of the funding source

You are requested to identify who provided financial support for the conduct of the research and/or preparation of the article and to briefly describe the role of the sponsor(s), if any, in study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication. If the funding source(s) had no such involvement then this should be stated.

Open access

Please visit our Open Access page for more information.

Elsevier Researcher Academy

Researcher Academy is a free e-learning platform designed to support early and mid-career researchers throughout their research journey. The "Learn" environment at Researcher Academy offers several interactive modules, webinars, downloadable guides and resources to guide you through the process of writing for research and going through peer review. Feel free to use these free resources to improve your submission and navigate the publication process with ease.

Language (usage and editing services)

Please write your text in good English (American or British usage is accepted, but not a mixture of these). Authors who feel their English language manuscript may require editing to eliminate possible grammatical or spelling errors and to conform to correct scientific English may wish to use the English Language Editing service available from Elsevier's Author Services.

Submission

Our online submission system guides you stepwise through the process of entering your article details and uploading your files. The system converts your article files to a single PDF file used in the peer-review process. Editable files (e.g., Word, LaTeX) are required to typeset your article for final publication. All correspondence, including notification of the Editor's decision and requests for revision, is sent by e-mail.

Submit your article

Please submit your article via https://www.editorialmanager.com/msec/default.aspx

Referees

Please submit the names and institutional e-mail addresses of several potential referees. For more details, visit our Support site. Note that the editor retains the sole right to decide whether or not the suggested reviewers are used.

PREPARATION

NEW SUBMISSIONS

Submission to this journal proceeds totally online and you will be guided stepwise through the creation and uploading of your files. The system automatically converts your files to a single PDF file, which is used in the peer-review process.

As part of the Your Paper Your Way service, you may choose to submit your manuscript as a single file to be used in the refereeing process. This can be a PDF file or a Word document, in any format or layout that can be used by referees to evaluate your manuscript. It should contain high enough quality figures for refereeing. If you prefer to do so, you may still provide all or some of the source files at the initial submission. Please note that individual figure files larger than 10 MB must be uploaded separately.

References

There are no strict requirements on reference formatting at submission. References can be in any style or format as long as the style is consistent. Where applicable, author(s) name(s), journal title/ book title, chapter title/article title, year of publication, volume number/book chapter and the article number or pagination must be present. Use of DOI is highly encouraged. The reference style used by the journal will be applied to the accepted article by Elsevier at the proof stage. Note that missing data will be highlighted at proof stage for the author to correct.

Formatting requirements

There are no strict formatting requirements but all manuscripts must contain the essential elements needed to convey your manuscript, for example Abstract, Keywords, Introduction, Materials and Methods, Results, Conclusions, Artwork and Tables with Captions. If your article includes any Videos and/or other Supplementary material, this should be included in your initial submission for peer review purposes.

Divide the article into clearly defined sections.

Figures and tables embedded in text

Please ensure the figures and the tables included in the single file are placed next to the relevant text in the manuscript, rather than at the bottom or the top of the file. The corresponding caption should be placed directly below the figure or table.

Editor; 2 reviewers, single blind

This journal operates a single blind review process. All contributions will be initially assessed by the editor for suitability for the journal. Papers deemed suitable are then typically sent to a minimum of two independent expert reviewers to assess the scientific quality of the paper. The Editor is responsible for the final decision regarding acceptance or rejection of articles. The Editor's decision is final. More information on types of peer review.

You will be asked to suggest potential reviewers for their manuscript and provide reason for suggesting them in the online submission system. The Editors kindly request that authors suggest referees who are not in the same local geographic area. Please provide verifiable institutional email address for the suggested referees. The editorial office may not use your suggestions, but they are greatly appreciated.

REVISED SUBMISSIONS

Use of word processing software

Regardless of the file format of the original submission, at revision you must provide us with an editable file of the entire article. Keep the layout of the text as simple as possible. Most formatting codes will be removed and replaced on processing the article. The electronic text should be prepared in a way very similar to that of conventional manuscripts (see also the Guide to Publishing with Elsevier). See also the section on Electronic artwork.

To avoid unnecessary errors you are strongly advised to use the 'spell-check' and 'grammar-check'functions of your word processor.

Article structure

Subdivision - numbered sections

Divide your article into clearly defined and numbered sections. Subsections should be numbered 1.1 (then 1.1.1, 1.1.2, ...), 1.2, etc. (the abstract is not included in section numbering). Use this numbering also for internal cross-referencing: do not just refer to 'the text'. Any subsection may be given a brief heading. Each heading should appear on its own separate line.

Introduction

State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

Material and methods

Provide sufficient details to allow the work to be reproduced by an independent researcher. Methods that are already published should be summarized, and indicated by a reference. If quoting directly from a previously published method, use quotation marks and also cite the source. Any modifications to existing methods should also be described.

Experimental

Provide sufficient details to allow the work to be reproduced by an independent researcher. Methods that are already published should be summarized, and indicated by a reference. If quoting directly from a previously published method, use quotation marks and also cite the source. Any modifications to existing methods should also be described.

Theory/calculation

A Theory section should extend, not repeat, the background to the article already dealt with in the Introduction and lay the foundation for further work. In contrast, a Calculation section represents a practical development from a theoretical basis.

Results

Results should be clear and concise.

Discussion

This should explore the significance of the results of the work, not repeat them. A combined Results and Discussion section is often appropriate. Avoid extensive citations and discussion of published literature.

Conclusions

The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results and Discussion section.

Appendices

If there is more than one appendix, they should be identified as A, B, etc. Formula and equations in appendices should be given separate numbering: Eq. (A.1), Eq. (A.2), etc.; in a subsequent appendix, Eq. (B.1) and so on. Similarly for tables and figures: Table A.1; Fig. A.1, etc.

Vitae

Submit a short (maximum 100 words) biography of each author, along with a passport-type photograph accompanying the other figures. Please provide the biography in an editable format (e.g.Word), not in PDF format.

Essential title page information

• Title. Concise and informative. Titles are often used in information-retrieval systems. Avoid abbreviations and formulae where possible.

• Author names and affiliations. Please clearly indicate the given name(s) and family name(s) of each author and check that all names are accurately spelled. You can add your name between parentheses in your own script behind the English transliteration. Present the authors' affiliation addresses (where the actual work was done) below the names. Indicate all affiliations with a lowercase superscript letter immediately after the author's name and in front of the appropriate address.

Provide the full postal address of each affiliation, including the country name and, if available, the e-mail address of each author.

• Corresponding author. Clearly indicate who will handle correspondence at all stages of refereeing and publication, also post-publication. This responsibility includes answering any future queries about Methodology and Materials. Ensure that the e-mail address is given and that contact details are kept up to date by the corresponding author.

• Present/permanent address. If an author has moved since the work described in the article was done, or was visiting at the time, a 'Present address' (or 'Permanent address') may be indicated as a footnote to that author's name. The address at which the author actually did the work must be retained as the main, affiliation address. Superscript Arabic numerals are used for such footnotes.

Highlights

Highlights are mandatory for this journal as they help increase the discoverability of your article via search engines. They consist of a short collection of bullet points that capture the novel results of your research as well as new methods that were used during the study (if any). Please have a look at the examples here: example Highlights.

Highlights should be submitted in a separate editable file in the online submission system. Please use 'Highlights' in the file name and include 3 to 5 bullet points (maximum 85 characters, including spaces, per bullet point).

Abstract

A concise and factual abstract is required. The abstract should state briefly the purpose of the research, the principal results and major conclusions. An abstract is often presented separately from the article, so it must be able to stand alone. For this reason, References should be avoided, but if essential, then cite the author(s) and year(s). Also, non-standard or uncommon abbreviations should be avoided, but if essential they must be defined at their first mention in the abstract itself.

Graphical abstract

Although a graphical abstract is optional, its use is encouraged as it draws more attention to the online article. The graphical abstract should summarize the contents of the article in a concise, pictorial form designed to capture the attention of a wide readership. Graphical abstracts should be submitted as a separate file in the online submission system. Image size: Please provide an image with a minimum of 531 × 1328 pixels (h × w) or proportionally more. The image should be readable at a size of 5 × 13 cm using a regular screen resolution of 96 dpi. Preferred file types: TIFF, EPS, PDF or MS Office files. You can view Example Graphical Abstracts on our information site.

Authors can make use of Elsevier's Illustration Services to ensure the best presentation of their images and in accordance with all technical requirements.

Keywords

Immediately after the abstract, provide a maximum of 6 keywords, using British spelling and avoiding general and plural terms and multiple concepts (avoid, for example, 'and', 'of'). Be sparing with abbreviations: only abbreviations firmly established in the field may be eligible. These keywords will be used for indexing purposes.

Abbreviations

Define abbreviations that are not standard in this field in a footnote to be placed on the first page of the article. Such abbreviations that are unavoidable in the abstract must be defined at their first mention there, as well as in the footnote. Ensure consistency of abbreviations throughout the article.

Acknowledgements

Collate acknowledgements in a separate section at the end of the article before the references and do not, therefore, include them on the title page, as a footnote to the title or otherwise. List here those individuals who provided help during the research (e.g., providing language help, writing assistance or proof reading the article, etc.).

Formatting of funding sources

List funding sources in this standard way to facilitate compliance to funder's requirements:

Funding: This work was supported by the National Institutes of Health [grant numbers xxxx, yyyy]; the Bill & Melinda Gates Foundation, Seattle, WA [grant number zzzz]; and the United States Institutes of Peace [grant number aaaa].

It is not necessary to include detailed descriptions on the program or type of grants and awards. When funding is from a block grant or other resources available to a university, college, or other research institution, submit the name of the institute or organization that provided the funding.

If no funding has been provided for the research, please include the following sentence:

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Math formulae

Please submit math equations as editable text and not as images. Present simple formulae in line with normal text where possible and use the solidus (/) instead of a horizontal line for small fractional terms, e.g., X/Y. In principle, variables are to be presented in italics. Powers of e are often more conveniently denoted by exp. Number consecutively any equations that have to be displayed separately from the text (if referred to explicitly in the text).

Footnotes

Footnotes should be used sparingly. Number them consecutively throughout the article. Many word processors build footnotes into the text, and this feature may be used. Should this not be the case, indicate the position of footnotes in the text and present the footnotes themselves separately at the end of the article.

Artwork

Electronic artwork
General points
• Make sure you use uniform lettering and sizing of your original artwork.
• Preferred fonts: Arial (or Helvetica), Times New Roman (or Times), Symbol, Courier.
• Number the illustrations according to their sequence in the text.
• Use a logical naming convention for your artwork files.
• Indicate per figure if it is a single, 1.5 or 2-column fitting image.
• For Word submissions only, you may still provide figures and their captions, and tables within a single file at the revision stage.
• Please note that individual figure files larger than 10 MB must be provided in separate source files.

A detailed guide on electronic artwork is available.

You are urged to visit this site; some excerpts from the detailed information are given here.

Formats

Regardless of the application used, when your electronic artwork is finalized, please 'save as' or convert the images to one of the following formats (note the resolution requirements for line drawings, halftones, and line/halftone combinations given below):

EPS (or PDF): Vector drawings. Embed the font or save the text as 'graphics'.
TIFF (or JPG): Color or grayscale photographs (halftones): always use a minimum of 300 dpi.
TIFF (or JPG): Bitmapped line drawings: use a minimum of 1000 dpi.
TIFF (or JPG): Combinations bitmapped line/half-tone (color or grayscale): a minimum of 500 dpi is required.
Please do not:
• Supply files that are optimized for screen use (e.g., GIF, BMP, PICT, WPG); the resolution is too low.
• Supply files that are too low in resolution.
• Submit graphics that are disproportionately large for the content.

Color artwork

Please make sure that artwork files are in an acceptable format (TIFF (or JPEG), EPS (or PDF), or MS Office files) and with the correct resolution. If, together with your accepted article, you submit usable color figures then Elsevier will ensure, at no additional charge, that these figures will appear in color online (e.g., ScienceDirect and other sites) regardless of whether or not these illustrations are reproduced in color in the printed version. For color reproduction in print, you will receive information regarding the costs from Elsevier after receipt of your accepted article. Please indicate your preference for color: in print or online only. Further information on the preparation of electronic artwork.

Figure captions

Ensure that each illustration has a caption. A caption should comprise a brief title (not on the figure itself) and a description of the illustration. Keep text in the illustrations themselves to a minimum but explain all symbols and abbreviations used.

Text graphics

Text graphics may be embedded in the text at the appropriate position. See further under Electronic artwork.

Tables

Please submit tables as editable text and not as images. Tables can be placed either next to the relevant text in the article, or on separate page(s) at the end. Number tables consecutively in accordance with their appearance in the text and place any table notes below the table body. Be sparing in the use of tables and ensure that the data presented in them do not duplicate results described elsewhere in the article. Please avoid using vertical rules and shading in table cells.

References

Citation in text

Please ensure that every reference cited in the text is also present in the reference list (and vice versa). Any references cited in the abstract must be given in full. Unpublished results and personal communications are not recommended in the reference list, but may be mentioned in the text. If these references are included in the reference list they should follow the standard reference style of the journal and should include a substitution of the publication date with either 'Unpublished results' or 'Personal communication'. Citation of a reference as 'in press' implies that the item has been accepted for publication.

Web references

As a minimum, the full URL should be given and the date when the reference was last accessed. Any further information, if known (DOI, author names, dates, reference to a source publication, etc.), should also be given. Web references can be listed separately (e.g., after the reference list) under a different heading if desired, or can be included in the reference list.

Data references

This journal encourages you to cite underlying or relevant datasets in your manuscript by citing them in your text and including a data reference in your Reference List. Data references should include the following elements: author name(s), dataset title, data repository, version (where available), year, and global persistent identifier. Add [dataset] immediately before the reference so we can properly identify it as a data reference. The [dataset] identifier will not appear in your published article.

References in a special issue

Please ensure that the words 'this issue' are added to any references in the list (and any citations in the text) to other articles in the same Special Issue.

Reference management software

Most Elsevier journals have their reference template available in many of the most popular reference management software products. These include all products that support Citation Style Language styles, such as Mendeley. Using citation plug-ins from these products, authors only need to select the appropriate journal template when preparing their article, after which citations and bibliographies will be automatically formatted in the journal's style. If no template is yet available for this journal, please follow the format of the sample references and citations as shown in this Guide. If you use reference management software, please ensure that you remove all field codes before submitting the electronic manuscript. More information on how to remove field codes from different reference management software. Users of Mendeley Desktop can easily install the reference style for this journal by clicking the following link: http://open.mendeley.com/use-citation-style/materials-science-and-engineering-c When preparing your manuscript, you will then be able to select this style using the Mendeley plugins for Microsoft Word or LibreOffice.

Reference formatting

There are no strict requirements on reference formatting at submission. References can be in any style or format as long as the style is consistent. Where applicable, author(s) name(s), journal title/ book title, chapter title/article title, year of publication, volume number/book chapter and the article number or pagination must be present. Use of DOI is highly encouraged. The reference style used by the journal will be applied to the accepted article by Elsevier at the proof stage. Note that missing data will be highlighted at proof stage for the author to correct. If you do wish to format the references yourself they should be arranged according to the following examples:

Reference style

Text: Indicate references by number(s) in square brackets in line with the text. The actual authors can be referred to, but the reference number(s) must always be given.

Example: '..... as demonstrated [3,6]. Barnaby and Jones [8] obtained a different result ....' AUTHOR INFORMATION PACK 30 Dec 2020 www.elsevier.com/locate/msec 13 List: Number the references (numbers in square brackets) in the list in the order in which they appear in the text.

Examples:

Reference to a journal publication:

[1] J. van der Geer, J.A.J. Hanraads, R.A. Lupton, The art of writing a scientific article, J. Sci. Commun. 163 (2010) 51–59. https://doi.org/10.1016/j.Sc.2010.00372.

Reference to a journal publication with an article number:

[2] J. van der Geer, J.A.J. Hanraads, R.A. Lupton, 2018. The art of writing a scientific article. Heliyon. 19, e00205. https://doi.org/10.1016/j.heliyon.2018.e00205.

Reference to a book:

[3] W. Strunk Jr., E.B. White, The Elements of Style, fourth ed., Longman, New York, 2000. Reference to a chapter in an edited book:

[4] G.R. Mettam, L.B. Adams, How to prepare an electronic version of your article, in: B.S. Jones, R.Z. Smith (Eds.), Introduction to the Electronic Age, E-Publishing Inc., New York, 2009, pp. 281–304.

Reference to a website:

[5] Cancer Research UK, Cancer statistics reports for the UK. http://www.cancerresearchuk.org/aboutcancer/statistics/cancerstatsreport/, 2003 (accessed 13 March 2003).

Reference to a dataset:

[dataset] [6] M. Oguro, S. Imahiro, S. Saito, T. Nakashizuka, Mortality data for Japanese oak wilt disease and surrounding forest compositions, Mendeley Data, v1, 2015. https://doi.org/10.17632/xwj98nb39r.1. Journal abbreviations source

Journal names should be abbreviated according to the List of Title Word Abbreviations.

Video

Elsevier accepts video material and animation sequences to support and enhance your scientific research. Authors who have video or animation files that they wish to submit with their article are strongly encouraged to include links to these within the body of the article. This can be done in the same way as a figure or table by referring to the video or animation content and noting in the body text where it should be placed. All submitted files should be properly labeled so that they directly relate to the video file's content. In order to ensure that your video or animation material is directly usable, please provide the file in one of our recommended file formats with a preferred maximum size of 150 MB per file, 1 GB in total. Video and animation files supplied will be published online in the electronic version of your article in Elsevier Web products, including ScienceDirect. Please supply 'stills' with your files: you can choose any frame from the video or animation or make a separate image. These will be used instead of standard icons and will personalize the link to your video data. For more detailed instructions please visit our video instruction pages. Note: since video and animation cannot be embedded in the print version of the journal, please provide text for both the electronic and the print version for the portions of the article that refer to this content.

Data visualization

Include interactive data visualizations in your publication and let your readers interact and engage more closely with your research. Follow the instructions here to find out about available data visualization options and how to include them with your article.

Supplementary material

Supplementary material such as applications, images and sound clips, can be published with your article to enhance it. Submitted supplementary items are published exactly as they are received (Excel or PowerPoint files will appear as such online). Please submit your material together with the article and supply a concise, descriptive caption for each supplementary file. If you wish to make changes to supplementary material during any stage of the process, please make sure to provide an updated file. Do not annotate any corrections on a previous version. Please switch off the 'Track Changes' option in Microsoft Office files as these will appear in the published version.

Research data

This journal encourages and enables you to share data that supports your research publication where appropriate, and enables you to interlink the data with your published articles. Research data refers to the results of observations or experimentation that validate research findings. To facilitate reproducibility and data reuse, this journal also encourages you to share your software, code, models, algorithms, protocols, methods and other useful materials related to the project.

Below are a number of ways in which you can associate data with your article or make a statement about the availability of your data when submitting your manuscript. If you are sharing data in one of these ways, you are encouraged to cite the data in your manuscript and reference list. Please refer to the "References" section for more information about data citation. For more information on depositing, sharing and using research data and other relevant research materials, visit the research data page.

Data linking

If you have made your research data available in a data repository, you can link your article directly to the dataset. Elsevier collaborates with a number of repositories to link articles on ScienceDirect with relevant repositories, giving readers access to underlying data that gives them a better understanding of the research described.

There are different ways to link your datasets to your article. When available, you can directly link your dataset to your article by providing the relevant information in the submission system. For more information, visit the database linking page.

For supported data repositories a repository banner will automatically appear next to your publishedarticle on ScienceDirect.

In addition, you can link to relevant data or entities through identifiers within the text of your manuscript, using the following format: Database: xxxx (e.g., TAIR: AT1G01020; CCDC: 734053; PDB: 1XFN).

Mendeley Data

This journal supports Mendeley Data, enabling you to deposit any research data (including raw and processed data, video, code, software, algorithms, protocols, and methods) associated with your manuscript in a free-to-use, open access repository. During the submission process, after uploading your manuscript, you will have the opportunity to upload your relevant datasets directly to Mendeley Data. The datasets will be listed and directly accessible to readers next to your published article online. For more information, visit the Mendeley Data for journals page.

Data in Brief

You have the option of converting any or all parts of your supplementary or additional raw data into a data article published in Data in Brief. A data article is a new kind of article that ensures that your data are actively reviewed, curated, formatted, indexed, given a DOI and made publicly available to all upon publication (watch this video describing the benefits of publishing your data in Data in Brief). You are encouraged to submit your data article for Data in Brief as an additional item directly alongside the revised version of your manuscript. If your research article is accepted, your data article will automatically be transferred over to Data in Brief where it will be editorially reviewed, published open access and linked to your research article on ScienceDirect. Please note an open access fee is payable for publication in Data in Brief. Full details can be found on the Data in Brief website. Please use this template to write your Data in Brief data article.

MethodsX

You have the option of converting relevant protocols and methods into one or multiple MethodsX articles, a new kind of article that describes the details of customized research methods. Many researchers spend a significant amount of time on developing methods to fit their specific needs or setting, but often without getting credit for this part of their work. MethodsX, an open access journal, now publishes this information in order to make it searchable, peer reviewed, citable and reproducible. Authors are encouraged to submit their MethodsX article as an additional item directly alongside the revised version of their manuscript. If your research article is accepted, your methods article will automatically be transferred over to MethodsX where it will be editorially reviewed. Please note an open access fee is payable for publication in MethodsX. Full details can be found on the MethodsX website. Please use this template to prepare your MethodsX article.

Data statement

To foster transparency, we encourage you to state the availability of your data in your submission. This may be a requirement of your funding body or institution. If your data is unavailable to access or unsuitable to post, you will have the opportunity to indicate why during the submission process, for example by stating that the research data is confidential. The statement will appear with your published article on ScienceDirect. For more information, visit the Data Statement page.

AFTER ACCEPTANCE

Online proof correction

To ensure a fast publication process of the article, we kindly ask authors to provide us with their proof corrections within two days. Corresponding authors will receive an e-mail with a link to our online proofing system, allowing annotation and correction of proofs online. The environment is similar to MS Word: in addition to editing text, you can also comment on figures/tables and answer questions from the Copy Editor. Web-based proofing provides a faster and less error-prone process by allowing you to directly type your corrections, eliminating the potential introduction of errors.

If preferred, you can still choose to annotate and upload your edits on the PDF version. All instructions for proofing will be given in the e-mail we send to authors, including alternative methods to the online version and PDF.

We will do everything possible to get your article published quickly and accurately. Please use this proof only for checking the typesetting, editing, completeness and correctness of the text, tables and figures. Significant changes to the article as accepted for publication will only be considered at this stage with permission from the Editor. It is important to ensure that all corrections are sent back to us in one communication. Please check carefully before replying, as inclusion of any subsequent corrections cannot be guaranteed. Proofreading is solely your responsibility.

Offprints

The corresponding author will, at no cost, receive a customized Share Link providing 50 days free access to the final published version of the article on ScienceDirect. The Share Link can be used for sharing the article via any communication channel, including email and social media. For an extra charge, paper offprints can be ordered via the offprint order form which is sent once the article is accepted for publication. Both corresponding and co-authors may order offprints at any time via Elsevier's Author Services. Corresponding authors who have published their article gold open access do not receive a Share Link as their final published version of the article is available open access on ScienceDirect and can be shared through the article DOI link.

AUTHOR INQUIRIES

Visit the Elsevier Support Center to find the answers you need. Here you will find everything from Frequently Asked Questions to ways to get in touch. You can also check the status of your submitted article or find out when your accepted article will be published.

ANEXO B – NORMAS PARA PUBLICAÇÃO NO PERIÓDICO *JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS*

GUIDE FOR AUTHORS

Your Paper Your Way

We now differentiate between the requirements for new and revised submissions. You may choose to submit your manuscript as a single Word or PDF file to be used in the refereeing process. Only when your paper is at the revision stage, will you be requested to put your paper in to a 'correct format' for acceptance and provide the items required for the publication of your article.

To find out more, please visit the Preparation section below.

INTRODUCTION

Authors are requested to submit a cover letter that clearly states the novelty of the work presented in their manuscript.

Types of Contributions

Research Paper: A full-length article describing original research. There is no limit on the number of words, figures etc but authors should be as succinct as possible.

Review Article: An article which reviews previous work in a given field. Reviews are written by invitation only but the editor would welcome suggestions.

Technical Note: A short article describing a new experimental technique or analytical approach.

Short Communication: An article presenting new work in reduced form, which for some reason is not suitable for a full research paper. For example a case study.

Opinion Piece: A short article presenting the author's opinion on a particular question. Normally shorter and less comprehensive than a review article, making use of published and/or unpublished results.

Tutorial: An article of an educational nature, explaining how to use a particular experimental technique or analytical method. Normally written by invitation only but the editor welcomes suggestions.

Please ensure that you select the appropriate article type from the list of options when making your submission. Authors contributing to special issues should ensure that they select the special issue article type from this list.

The journal also accepts letters, which should be sent directly to the editor in chief for consideration.

Submission checklist

You can use this list to carry out a final check of your submission before you send it to the journal for review. Please check the relevant section in this Guide for Authors for more details.

Ensure that the following items are present:

One author has been designated as the corresponding author with contact details:

• E-mail address

• Full postal address

All necessary files have been uploaded:

Manuscript:

• Include keywords

• All figures (include relevant captions)

• All tables (including titles, description, footnotes)

• Ensure all figure and table citations in the text match the files provided

• Indicate clearly if color should be used for any figures in print

Graphical Abstracts / Highlights files (where applicable)

Supplemental files (where applicable)

Further considerations

• Manuscript has been 'spell checked' and 'grammar checked'

• All references mentioned in the Reference List are cited in the text, and vice versa

• Permission has been obtained for use of copyrighted material from other sources (including the Internet)

• A competing interests statement is provided, even if the authors have no competing interests to declare

• Journal policies detailed in this guide have been reviewed

• Referee suggestions and contact details provided, based on journal requirements

For further information, visit our Support Center.

BEFORE YOU BEGIN

Ethics in publishing

Please see our information pages on Ethics in publishing and Ethical guidelines for journal publication.

Declaration of interest

All authors must disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work. Examples of potential conflicts of interest include employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/ registrations, and grants or other funding. Authors should complete the declaration of interest statement using this template and upload to the submission system at the Attach/Upload Files step.

If there are no interests to declare, please choose: 'Declarations of interest: none' in the template.

This statement will be published within the article if accepted. More information.

Submission declaration and verification

Submission of an article implies that the work described has not been published previously (except in the form of an abstract, a published lecture or academic thesis, see 'Multiple, redundant or concurrent publication' for more information), that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyrightholder. To verify originality, your article may be checked by the originality detection service Crossref

Similarity Check.

Preprints

Please note that preprints can be shared anywhere at any time, in line with Elsevier's sharing policy. Sharing your preprints e.g. on a preprint server will not count as prior publication (see 'Multiple, redundant or concurrent publication' for more information).

Use of inclusive language

Inclusive language acknowledges diversity, conveys respect to all people, is sensitive to differences, and promotes equal opportunities. Articles should make no assumptions about the beliefs or commitments of any reader, should contain nothing which might imply that one individual is superior to another on the grounds of race, sex, culture or any other characteristic, and should use inclusive language throughout. Authors should ensure that writing is free from bias, for instance by using 'he or she', 'his/her' instead of 'he' or 'his', and by making use of job titles that are free of stereotyping (e.g. 'chairperson' instead of 'chairman' and 'flight attendant' instead of 'stewardess').

Author contributions

For transparency, we encourage authors to submit an author statement file outlining their individual contributions to the paper using the relevant CRediT roles: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing. Authorship statements should be formatted with the names of authors first and CRediT role(s) following. More details and an example

Changes to authorship

Authors are expected to consider carefully the list and order of authors before submitting their manuscript and provide the definitive list of authors at the time of the original submission. Any addition, deletion or rearrangement of author names in the authorship list should be made only before the manuscript has been accepted and only if approved by the journal Editor. To request such a change, the Editor must receive the following from the corresponding author: (a) the reason for the change in author list and (b) written confirmation (e-mail, letter) from all authors that they agree with the addition, removal or rearrangement. In the case of addition or removal of authors, this includes confirmation from the author being added or removed. Only in exceptional circumstances will the Editor consider the addition, deletion or rearrangement of authors after the manuscript has been accepted. While the Editor considers the request, publication of the manuscript will be suspended. If the manuscript has already been published in an online issue, any requests approved by the Editor will result in a corrigendum.

Copyright

Upon acceptance of an article, authors will be asked to complete a 'Journal Publishing Agreement' (see more information on this). An e-mail will be sent to the corresponding author confirming receipt of the manuscript together with a 'Journal Publishing Agreement' form or a link to the online version of this agreement.

Subscribers may reproduce tables of contents or prepare lists of articles including abstracts for internal circulation within their institutions. Permission of the Publisher is required for resale or distribution outside the institution and for all other derivative works, including compilations and translations. If excerpts from other copyrighted works are included, the author(s) must obtain written permission from the copyright owners and credit the source(s) in the article. Elsevier has preprinted forms for use by authors in these cases.

For gold open access articles: Upon acceptance of an article, authors will be asked to complete an 'Exclusive License Agreement' (more information). Permitted third party reuse of gold open access articles is determined by the author's choice of user license.

Author rights

As an author you (or your employer or institution) have certain rights to reuse your work. More information.

Elsevier supports responsible sharing

Find out how you can share your research published in Elsevier journals.

Role of the funding source

You are requested to identify who provided financial support for the conduct of the research and/or preparation of the article and to briefly describe the role of the sponsor(s), if any, in study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication. If the funding source(s) had no such involvement then this should be stated.

Open access

Please visit our Open Access page from the Journal Homepage for more information.

Elsevier Researcher Academy

Researcher Academy is a free e-learning platform designed to support early and mid-career researchers throughout their research journey. The "Learn" environment at Researcher Academy offers several interactive modules, webinars, downloadable guides and resources to guide you through the process of writing for research and going through peer review. Feel free to use these free resources to improve your submission and navigate the publication process with ease.

Language (usage and editing services)

Please write your text in good English (American or British usage is accepted, but not a mixture of these). Authors who feel their English language manuscript may require editing to eliminate possible grammatical or spelling errors and to conform to correct scientific English may wish to use the English Language Editing service available from Elsevier's Author Services.

Submission

Our online submission system guides you stepwise through the process of entering your article details and uploading your files. The system converts your article files to a single PDF file used in the peer-review process. Editable files (e.g., Word, LaTeX) are required to typeset your article for final publication. All correspondence, including notification of the Editor's decision and requests for revision, is sent by e-mail.

PREPARATION

NEW SUBMISSIONS

Submission to this journal proceeds totally online and you will be guided stepwise through the creation and uploading of your files. The system automatically converts your files to a single PDF file, which is used in the peer-review process.

As part of the Your Paper Your Way service, you may choose to submit your manuscript as a single file to be used in the refereeing process. This can be a PDF file or a Word document, in any format or layout that can be used by referees to evaluate your manuscript. It should contain high enough quality figures for refereeing. If you prefer to do so, you may still provide all or some of the source files at the initial submission. Please note that individual figure files larger than 10 MB must be uploaded separately.

References

There are no strict requirements on reference formatting at submission. References can be in any style or format as long as the style is consistent. Where applicable, author(s) name(s), journal title/book title, chapter title/article title, year of publication, volume number/book chapter and the article number or pagination must be present. Use of DOI is highly encouraged. The reference style used by the journal will be applied to the accepted article by Elsevier at the proof stage. Note that missing data will be highlighted at proof stage for the author to correct.

Formatting requirements

There are no strict formatting requirements but all manuscripts must contain the essential elements needed to convey your manuscript, for example Abstract, Keywords, Introduction, Materials and Methods, Results, Conclusions, Artwork and Tables with Captions.

If your article includes any Videos and/or other Supplementary material, this should be included in your initial submission for peer review purposes.

Divide the article into clearly defined sections.

Figures and tables embedded in text

Please ensure the figures and the tables included in the single file are placed next to the relevant text in the manuscript, rather than at the bottom or the top of the file. The corresponding caption should be placed directly below the figure or table.

Peer review

This journal operates a single blind review process. All contributions will be initially assessed by the editor for suitability for the journal. Papers deemed suitable are then typically sent to a minimum of two independent expert reviewers to assess the scientific quality of the paper. The Editor is responsible for the final decision regarding acceptance or rejection of articles. The Editor's decision is final. More information on types of peer review.

REVISED SUBMISSIONS

Use of word processing software Regardless of the file format of the original submission, at revision you must provide us with an editable file of the entire article. Keep the layout of the text as simple as possible. Most formatting codes will be removed and replaced on processing the article. The electronic text should be prepared in a way very similar to that of conventional manuscripts (see also the Guide to Publishing with Elsevier). See also the section on Electronic artwork.

To avoid unnecessary errors you are strongly advised to use the 'spell-check' and 'grammar-check' functions of your word processor.

LaTeX

You are recommended to use the Elsevier article class elsarticle.cls to prepare your manuscript and BibTeX to generate your bibliography.

Our LaTeX site has detailed submission instructions, templates and other information.

Article structure

Subdivision - numbered sections

Divide your article into clearly defined and numbered sections. Subsections should be numbered 1.1 (then 1.1.1, 1.1.2, ...), 1.2, etc. (the abstract is not included in section numbering). Use this numbering also for internal cross-referencing: do not just refer to 'the text'. Any subsection may be given a brief heading. Each heading should appear on its own separate line.

Introduction

State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

Material and methods

Provide sufficient details to allow the work to be reproduced by an independent researcher. Methods that are already published should be summarized, and indicated by a reference. If quoting directly from a previously published method, use quotation marks and also cite the source. Any modifications to existing methods should also be described.

Theory/calculation

A Theory section should extend, not repeat, the background to the article already dealt with in the Introduction and lay the foundation for further work. In contrast, a Calculation section represents a practical development from a theoretical basis.

Results

Results should be clear and concise.

Discussion

This should explore the significance of the results of the work, not repeat them. A combined Results and Discussion section is often appropriate. Avoid extensive citations and discussion of published literature.

Conclusions

The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results and Discussion section.

Appendices

If there is more than one appendix, they should be identified as A, B, etc. Formulae and equations in appendices should be given separate numbering: Eq. (A.1), Eq. (A.2), etc.; in a subsequent appendix, Eq. (B.1) and so on. Similarly for tables and figures: Table A.1; Fig. A.1, etc.

Essential title page information

• Title. Concise and informative. Titles are often used in information-retrieval systems. Avoid abbreviations and formulae where possible.

• Author names and affiliations. Please clearly indicate the given name(s) and family name(s) of each author and check that all names are accurately spelled. You can add your name between parentheses in your own script behind the English transliteration. Present the authors' affiliation addresses (where the actual work was done) below the names. Indicate all affiliations with a lowercase superscript letter immediately after the author's name and in front of the appropriate address. Provide the full postal address of each affiliation, including the country name and, if available, the e-mail address of each author.

• Corresponding author. Clearly indicate who will handle correspondence at all stages of refereeing and publication, also post-publication. This responsibility includes answering any future queries about Methodology and Materials. Ensure that the e-mail address is given and that contact details are kept up to date by the corresponding author.

• Present/permanent address. If an author has moved since the work described in the article was done, or was visiting at the time, a 'Present address' (or 'Permanent address') may be indicated as a footnote to that author's name. The address at which the author actually did the work must be retained as the main, affiliation address. Superscript Arabic numerals are used for such footnotes.

Highlights

Highlights are mandatory for this journal as they help increase the discoverability of your article via search engines. They consist of a short collection of bullet points that capture the novel results of your research as well as new methods that were used during the study (if any). Please have a look at the examples here: example Highlights.

Highlights should be submitted in a separate editable file in the online submission system. Please use 'Highlights' in the file name and include 3 to 5 bullet points (maximum 85 characters, including spaces, per bullet point).

Abstract

A concise and factual abstract is required. The abstract should state briefly the purpose of the research, the principal results and major conclusions. An abstract is often presented separately from the article, so it must be able to stand alone. For this reason, References should be avoided, but if essential, then cite the author(s) and year(s). Also, non-standard or uncommon abbreviations should be avoided, but if essential they must be defined at their first mention in the abstract itself.

Graphical abstract

A graphical abstract is mandatory for this journal. It should summarize the contents of the article in a concise, pictorial form designed to capture the attention of a wide readership online. Authors must provide images that clearly represent the work described in the article. Graphical abstracts should be submitted as a separate file in the online submission system. Image size: please provide an image with a minimum of 531 × 1328 pixels (h × w) or proportionally more. The image should be readable at a size of 5 × 13 cm using a regular screen resolution of 96 dpi. Preferred file types: TIFF, EPS, PDF or MS Office files. You can view Example Graphical Abstracts on our information site. Authors can make use of Elsevier's Illustration Services to ensure the best presentation of their images also in accordance with all technical requirements.

Abbreviations

Define abbreviations that are not standard in this field in a footnote to be placed on the first page of the article. Such abbreviations that are unavoidable in the abstract must be defined at their first mention there, as well as in the footnote. Ensure consistency of abbreviations throughout the article.

Acknowledgements

Collate acknowledgements in a separate section at the end of the article before the references and do not, therefore, include them on the title page, as a footnote to the title or otherwise. List here those individuals who provided help during the research (e.g., providing language help, writing assistance or proof reading the article, etc.).

Formatting of funding sources

List funding sources in this standard way to facilitate compliance to funder's requirements:

Funding: This work was supported by the National Institutes of Health [grant numbers xxxx, yyyy]; the Bill & Melinda Gates Foundation, Seattle, WA [grant number zzzz]; and the United States Institutes of Peace [grant number aaaa].

It is not necessary to include detailed descriptions on the program or type of grants and awards. When funding is from a block grant or other resources available to a university, college, or other research institution, submit the name of the institute or organization that provided the funding.

If no funding has been provided for the research, please include the following sentence:

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Units

Follow internationally accepted rules and conventions: use the international system of units (SI). If other quantities are mentioned, give their equivalent in SI. Authors wishing to present a table of nomenclature should do so on the second page of their manuscript.

Math formulae

Please submit math equations as editable text and not as images. Present simple formulae in line with normal text where possible and use the solidus (/) instead of a horizontal line for small fractional terms, e.g., X/Y. In principle, variables are to be presented in italics. Powers of e are often more conveniently denoted by exp. Number consecutively any equations that have to be displayed separately from the text (if referred to explicitly in the text).

Footnotes

Footnotes should be used sparingly. Number them consecutively throughout the article. Many word processors build footnotes into the text, and this feature may be used. Should this not be the case, indicate the position of footnotes in the text and present the footnotes themselves separately at the end of the article.

Artwork

Electronic artwork

General points

• Make sure you use uniform lettering and sizing of your original artwork.

• Preferred fonts: Arial (or Helvetica), Times New Roman (or Times), Symbol, Courier.

• Number the illustrations according to their sequence in the text.

• Use a logical naming convention for your artwork files.

• Indicate per figure if it is a single, 1.5 or 2-column fitting image.

• For Word submissions only, you may still provide figures and their captions, and tables within a single file at the revision stage.

• Please note that individual figure files larger than 10 MB must be provided in separate source files.

A detailed guide on electronic artwork is available.

You are urged to visit this site; some excerpts from the detailed information are given here.

Formats

Regardless of the application used, when your electronic artwork is finalized, please 'save as' or convert the images to one of the following formats (note the resolution requirements for line drawings, halftones, and line/halftone combinations given below):

EPS (or PDF): Vector drawings. Embed the font or save the text as 'graphics'.

TIFF (or JPG): Color or grayscale photographs (halftones): always use a minimum of 300 dpi.

TIFF (or JPG): Bitmapped line drawings: use a minimum of 1000 dpi.

TIFF (or JPG): Combinations bitmapped line/half-tone (color or grayscale): a minimum of 500 dpi is required.

Please do not:

• Supply files that are optimized for screen use (e.g., GIF, BMP, PICT, WPG); the resolution is too low.

• Supply files that are too low in resolution.

• Submit graphics that are disproportionately large for the content.

Color artwork

Please make sure that artwork files are in an acceptable format (TIFF (or JPEG), EPS (or PDF) or MS Office files) and with the correct resolution. If, together with your accepted article, you submit usable color figures then Elsevier will ensure, at no additional charge, that these figures will appear in color online (e.g., ScienceDirect and other sites) in addition to color reproduction in print. Further information on the preparation of electronic artwork.

Figure captions

Ensure that each illustration has a caption. A caption should comprise a brief title (not on the figure itself) and a description of the illustration. Keep text in the illustrations themselves to a minimum but explain all symbols and abbreviations used.

Tables

Please submit tables as editable text and not as images. Tables can be placed either next to the relevant text in the article, or on separate page(s) at the end. Number tables consecutively in accordance with their appearance in the text and place any table notes below the table body. Be sparing in the use of tables and ensure that the data presented in them do not duplicate results described elsewhere in the article. Please avoid using vertical rules and shading in table cells.

References

Citation in text

Please ensure that every reference cited in the text is also present in the reference list (and vice versa). Any references cited in the abstract must be given in full. Unpublished results and personal communications are not recommended in the reference list, but may be mentioned in the text. If these references are included in the reference list they should follow the standard reference style of the journal and should include a substitution of the publication date with either 'Unpublished results' or 'Personal communication'. Citation of a reference as 'in press' implies that the item has been accepted for publication.

Reference links

Increased discoverability of research and high quality peer review are ensured by online links to the sources cited. In order to allow us to create links to abstracting and indexing services, such as Scopus, CrossRef and PubMed, please ensure that data provided in the references are correct. Please note that incorrect surnames, journal/book titles, publication year and pagination may prevent link creation. When copying references, please be careful as they may already contain errors. Use of the DOI is highly encouraged.

A DOI is guaranteed never to change, so you can use it as a permanent link to any electronic article. An example of a citation using DOI for an article not yet in an issue is: VanDecar J.C., Russo R.M., James D.E., Ambeh W.B., Franke M. (2003). Aseismic continuation of the Lesser Antilles slab beneath northeastern Venezuela. Journal of Geophysical Research, https://doi.org/10.1029/2001JB000884. Please note the format of such citations should be in the same style as all other references in the paper.

Web references

As a minimum, the full URL should be given and the date when the reference was last accessed. Any further information, if known (DOI, author names, dates, reference to a source publication, etc.), should also be given. Web references can be listed separately (e.g., after the reference list) under a different heading if desired, or can be included in the reference list.

Data references

This journal encourages you to cite underlying or relevant datasets in your manuscript by citing them in your text and including a data reference in your Reference List. Data references should include the following elements: author name(s), dataset title, data repository, version (where available), year, and global persistent identifier. Add [dataset] immediately before the reference so we can properly identify it as a data reference. The [dataset] identifier will not appear in your published article.

References in a special issue

Please ensure that the words 'this issue' are added to any references in the list (and any citations in the text) to other articles in the same Special Issue.

Reference management software

Most Elsevier journals have their reference template available in many of the most popular reference management software products. These include all products that support Citation Style Language styles, such as Mendeley. Using citation plug-ins from these products, authors only need to select the appropriate journal template when preparing their article, after which citations and bibliographies will be automatically formatted in the journal's style. If no template is yet available for this journal, please follow the format of the sample references and citations as shown in this Guide. If you use reference management software, please ensure that you remove all field codes before submitting the electronic manuscript. More information on how to remove field codes from different reference management software.

Users of Mendeley Desktop can easily install the reference style for this journal by clicking the following link: http://open.mendeley.com/use-citation-style/journal-of-the-mechanical-behavior-of-biomedical-materials

When preparing your manuscript, you will then be able to select this style using the Mendeley plugins for Microsoft Word or LibreOffice.

Reference formatting

There are no strict requirements on reference formatting at submission. References can be in any style or format as long as the style is consistent. Where applicable, author(s) name(s), journal title/book title, chapter title/article title, year of publication, volume number/book chapter and the article number or pagination must be present. Use of DOI is highly encouraged. The reference style used by the journal will be applied to the accepted article by Elsevier at the proof stage. Note that missing data will be highlighted at proof stage for the author to correct. If you do wish to format the references yourself they should be arranged according to the following examples:

Reference style

Text: All citations in the text should refer to:

1. Single author: the author's name (without initials, unless there is ambiguity) and the year of publication;

2. Two authors: both authors' names and the year of publication;

3. Three or more authors: first author's name followed by 'et al.' and the year of publication. Citations may be made directly (or parenthetically). Groups of references can be listed either first alphabetically, then chronologically, or vice versa.

Examples: 'as demonstrated (Allan, 2000a, 2000b, 1999; Allan and Jones, 1999)…. Or, as demonstrated (Jones, 1999; Allan, 2000)… Kramer et al. (2010) have recently shown …'

List: References should be arranged first alphabetically and then further sorted chronologically if necessary. More than one reference from the same author(s) in the same year must be identified by the letters 'a', 'b', 'c', etc., placed after the year of publication.

Examples:

Reference to a journal publication:

Van der Geer, J., Hanraads, J.A.J., Lupton, R.A., 2010. The art of writing a scientific article. J. Sci. Commun. 163, 51–59. https://doi.org/10.1016/j.Sc.2010.00372.

Reference to a journal publication with an article number: Van der Geer, J., Hanraads, J.A.J., Lupton, R.A., 2018. The art of writing a scientific article. Heliyon. 19, e00205. https://doi.org/10.1016/j.heliyon.2018.e00205.

Reference to a book:

Strunk Jr., W., White, E.B., 2000. The Elements of Style, fourth ed. Longman, New York.

Reference to a chapter in an edited book:

Mettam, G.R., Adams, L.B., 2009. How to prepare an electronic version of your article, in: Jones, B.S., Smith , R.Z. (Eds.), Introduction to the Electronic Age. E-Publishing Inc., New York, pp. 281–304.

Reference to a website:

Cancer Research UK, 1975. Cancer statistics reports for the UK. http://www.cancerresearchuk.org/ aboutcancer/statistics/cancerstatsreport/ (accessed 13 March 2003).

Reference to a dataset:

[dataset] Oguro, M., Imahiro, S., Saito, S., Nakashizuka, T., 2015. Mortality data for Japanese oak wilt disease and surrounding forest compositions. Mendeley Data, v1. https://doi.org/10.17632/ xwj98nb39r.1.

Journal abbreviations source

Journal names should be abbreviated according to the List of Title Word Abbreviations.

Video

Elsevier accepts video material and animation sequences to support and enhance your scientific research. Authors who have video or animation files that they wish to submit with their article are strongly encouraged to include links to these within the body of the article. This can be done in the same way as a figure or table by referring to the video or animation content and noting in the body text where it should be placed. All submitted files should be properly labeled so that they directly relate to the video file's content. In order to ensure that your video or animation material is directly usable, please provide the file in one of our recommended file formats with a preferred maximum size of 150 MB per file, 1 GB in total. Video and animation files supplied will be published online in the electronic version of your article in Elsevier Web products, including ScienceDirect. Please supply 'stills' with your files: you can choose any frame from the video or animation or make a separate image. These will be used instead of standard icons and will personalize the link to your video data. For more detailed instructions please visit our video instruction pages. Note: since video and animation cannot be embedded in the print version of the journal, please provide text for both the electronic and the print version for the portions of the article that refer to this content.

Data visualization

Include interactive data visualizations in your publication and let your readers interact and engage more closely with your research. Follow the instructions here to find out about available data visualization options and how to include them with your article.

Supplementary material

Supplementary material such as applications, images and sound clips, can be published with your article to enhance it. Submitted supplementary items are published exactly as they are received (Excel or PowerPoint files will appear as such online). Please submit your material together with the article and supply a concise, descriptive caption for each supplementary file. If you wish to make changes to supplementary material during any stage of the process, please make sure to provide an updated file. Do not annotate any corrections on a previous version. Please switch off the 'Track Changes' option in Microsoft Office files as these will appear in the published version.

Research data

This journal encourages and enables you to share data that supports your research publication where appropriate, and enables you to interlink the data with your published articles. Research data refers to the results of observations or experimentation that validate research findings. To facilitate reproducibility and data reuse, this journal also encourages you to share your software, code, models, algorithms, protocols, methods and other useful materials related to the project.

Below are a number of ways in which you can associate data with your article or make a statement about the availability of your data when submitting your manuscript. If you are sharing data in one of these ways, you are encouraged to cite the data in your manuscript and reference list. Please refer to the "References" section for more information about data citation. For more information on depositing, sharing and using research data and other relevant research materials, visit the research data page.

Data linking

If you have made your research data available in a data repository, you can link your article directly to the dataset. Elsevier collaborates with a number of repositories to link articles on ScienceDirect with relevant repositories, giving readers access to underlying data that gives them a better understanding of the research described.

There are different ways to link your datasets to your article. When available, you can directly link your dataset to your article by providing the relevant information in the submission system. For more information, visit the database linking page.

For supported data repositories a repository banner will automatically appear next to your published article on ScienceDirect.

In addition, you can link to relevant data or entities through identifiers within the text of your manuscript, using the following format: Database: xxxx (e.g., TAIR: AT1G01020; CCDC: 734053; PDB: 1XFN).

Mendeley Data

This journal supports Mendeley Data, enabling you to deposit any research data (including raw and processed data, video, code, software, algorithms, protocols, and methods) associated with your manuscript in a free-to-use, open access repository. During the submission process, after uploading your manuscript, you will have the opportunity to upload your relevant datasets directly to Mendeley Data. The datasets will be listed and directly accessible to readers next to your published article online.

For more information, visit the Mendeley Data for journals page.

Data in Brief

You have the option of converting any or all parts of your supplementary or additional raw data into one or multiple data articles, a new kind of article that houses and describes your data. Data articles ensure that your data is actively reviewed, curated, formatted, indexed, given a DOI and publicly available to all upon publication. You are encouraged to submit your article for Data in Brief as an additional item directly alongside the revised version of your manuscript. If your research article is accepted, your data article will automatically be transferred over to Data in Brief where it will be editorially reviewed and published in the open access data journal, Data in Brief. Please note an open access fee of 600 USD is payable for publication in Data in Brief. Full details can be found on the Data in Brief website. Please use this template to write your Data in Brief.

MethodsX

You have the option of converting relevant protocols and methods into one or multiple MethodsX articles, a new kind of article that describes the details of customized research methods. Many researchers spend a significant amount of time on developing methods to fit their specific needs or setting, but often without getting credit for this part of their work. MethodsX, an open access journal, now publishes this information in order to make it searchable, peer reviewed, citable and reproducible. Authors are encouraged to submit their MethodsX article as an additional item directly alongside the revised version of their manuscript. If your research article is accepted, your methods article will automatically be transferred over to MethodsX where it will be editorially reviewed. Please note an open access fee is payable for publication in MethodsX. Full details can be found on the MethodsX website. Please use this template to prepare your MethodsX article.

Data statement

To foster transparency, we encourage you to state the availability of your data in your submission. This may be a requirement of your funding body or institution. If your data is unavailable to access or unsuitable to post, you will have the opportunity to indicate why during the submission process, for example by stating that the research data is confidential. The statement will appear with your published article on ScienceDirect. For more information, visit the Data Statement page.