Review Article

Occlusal stress is involved in the formation of non-carious cervical lesions. A systematic review of abfraction

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Abstract: Purpose: This systematic review on abfraction studied whether stress is a mechanism in the formation of non-carious cervical lesions (NCCLs). **Methods:** A literature search was performed on three electronic databases (PubMed, ISI Web of Science, and EMBASE) using the keyword "abfraction" in publications published in English. The inclusion critera were clinical and laboratory studies that investigated the role of abfraction in NCCLs. The title and abstract of the identified publications were screened by two investigators independently. Reviews, case reports, and irrelevant papers were excluded. Full text of the remaining publications were retrieved. A manual search was performed on the bibliographies of the selected publications to identify additional relevant publications for review. **Results:** A total of 372 publications were identified, and 165 duplicated publications and 166 irrelevant publications were excluded. From the bibliographies of the remaining 41 publications, 28 relevant publications were found. Therefore, 69 publications (31 clinical studies and 38 laboratory studies) were included in this review and the majority (56/69, 81%) found an association between occlusal stress and NCCLs. Although no clinical study demonstrated that NCCL was caused by stress alone, 23 studies reported that stress or occlusal factors were associated with NCCLs. Of the 38 laboratory studies, 24 that used finite element analysis found that stress was concentrated at the cervical region of the tooth. Nine laboratory studies suggested that stress was a mechanism for NCCLs, whereas five studies reported the opposite. In conclusion, current literature supported an association between occlusal stress and NCCLs. (*Am J Dent* 2017;30:212-220).

Clinical significance: This systematic review of abfraction found the majority of studies reported an association between occlusal stress and non-carious cervical lesions.

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Introduction

"Tooth wear" or "tooth surface loss" has been proposed to be the result of two major mechanisms, namely mechanical wear (abrasion and attrition) and chemical wear (erosion).[1,2] A literature review found that the prevalence of severe tooth wear increased with age.[3] The prevalence of cervical lesions ranged between 39% to 77% in middle-aged populations and 57% to 81% in elderly populations.[4,5] The term "non-carious cervical lesion" (NCCL) has been used to describe a cervical tooth wear lesion created through various processes that are not associated with dental caries. These lesions are commonly attributed to either abrasion from brushing teeth or erosion by acid. However, the mechanism of erosion or abrasion cannot always explain the development of NCCLs.[6] The term "abfraction" was coined by Grippo[7] in 1991. He reported that the mechanism in the formation of NCCLs is stress and abfraction is the manifestation of the results from excessive non-axial loading forces resulting in stress.[4,5,7] The theory of abfraction is primarily based on biomechanics or engineering analysis. It is thought that when a tooth is overloaded in a non-axial direction, the stress will concentrate on the vulnerable cervical area of the tooth. As a result, the bonds between hydroxyapatite crystals of the enamel near the gingival margin will break down, thereby leading to microfractures, chipped enamel, and tooth structure loss. The abfraction theory was supported by a number of finite element analysis (FEA) studies.[8,9] Some clinical studies demonstrated an association between NCCL and occlusal force.[10,11] Previous studies[12,13] showed that subjects with bruxism had significantly more NCCLs than non-bruxers.

Although studies showing a relationship between NCCL and stress concentration have been published in the last two decades, some clinical and laboratory studies reported contradictory or inconclusive results.[14,15] For instance, NCCLs are commonly found on buccal surfaces, whereas lingual lesions are atypical. This phenomenon appears to contradict the results of FEA studies which suggested that both lingual and buccal surfaces should be equally affected. In addition, a prospective study[16] indicated that occlusal adjustment by removal of lateral excursive contacts did not slow down the progression of abfraction lesions.

Narrative reviews[17,18] did not find conclusive evidence to support the abfraction theory. Since dental practitioners need to understand the etiology and risk factors of cervical tooth wear for proper management of NCCLs in their patients, it is important to conduct a thorough review on this topic to see if there is good evidence to guide their practice.

The current systematic review of the literature included both clinical and laboratory studies, to examine whether stress is a mechanism for causing NCCL.

Materials and Methods

This systematic review followed the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement.

Search strategy - A literature search was performed on three electronic databases (PubMed, ISI Web of Science, and EMBASE) using the keyword "abfraction". The search was restricted to reports written in English. No publication-year limit was used, and the last search was made on 31 January 2016.

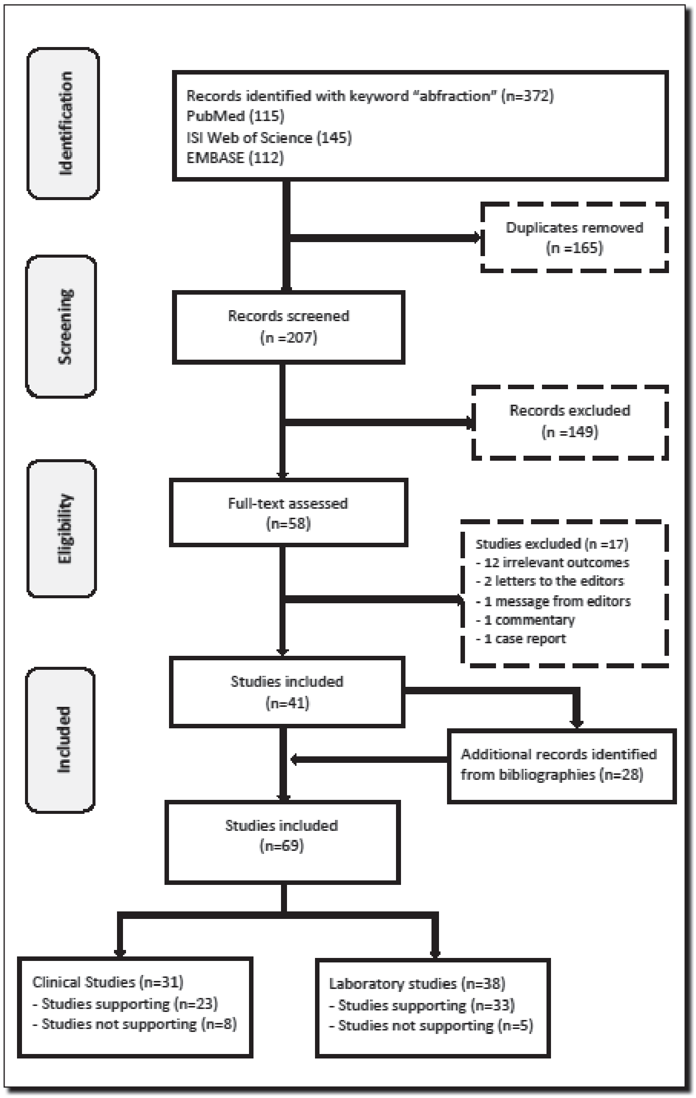

Figure. Flow diagram of identification, screening, eligibility and study selection.

Study selection - A manual search was performed, and the bibliographies of the identified publications were screened. Duplicated publications were removed. Titles and abstracts of the identified studies were independently reviewed by two investigators (PPH and MA) to determine their eligibility. Reviews, case reports and abstracts without full papers and product reports were excluded. Studies were selected in accordance with the inclusion criterion: clinical or laboratory studies that investigated whether stress was a mechanism for causing NCCL. For clinical studies, the inclusion criteria were cross-sectional, case-control, cohort studies or randomized clinical trials. For laboratory studies, all types of studies on extracted teeth, skulls, computer models or animals that used laboratory research equipment, such as FEA and scanning electron microscopy (SEM), were included if their results concerned the effect of stress on the development or progression of NCCL. Irrelevant papers such as reviews related to abfraction and restorative materials for abfraction lesions were excluded. If the information was not available in the title and abstract, full texts of the remaining articles were retrieved and analyzed. Furthermore, the reviewers conducted an additional manual search of the bibliographies of the papers and review articles that were included.

Data collection and analysis - Two investigators (PPH and MA) performed data extraction independently. The required information about the eligible articles was extracted from full-text papers. They discussed the papers with two other investigators (DD and CCH) to reach an agreement when there was a disagreement between the two investigators. The studies that were included could be clinical or laboratory studies. Depending on the findings and conclusions, the studies were classified as either having or lacking evidence to support that an association or causal relationship between stress or occlusal factors (wear facet, bruxism, parafunction, occlusal guidance and grinding pattern, etc.) and NCCLs.

Results

The initial systematic literature search found 372 potentially eligible publications. There were 115, 145 and 112 publications in PubMed, ISI Web of Science and EMBASE, respectively. Next, 165 duplicated publications were removed. The 207 de-duplicated publications were manually checked on the basis of title, keywords, and abstract. After screening the titles and abstracts, 149 publications were excluded because their findings were irrelevant. Then the full-text papers of the remaining 58 publications were retrieved. After that, the investigators excluded 17 papers which reported on irrelevant findings (12 papers) or were letters to the editor (2 papers), case report (1 paper), or editorial commentary (1 paper). As a result, 41 papers from the three databases were included in this review. In addition, manual searches of the references of the selected papers and abfraction reviews identified 28 additional publications that met the inclusion criteria. A flow chart on the identification and selection of papers is shown in the Figure. In the 69 papers that were included, there were 31 clinical studies (27 cross-sectional studies, two case-control studies,[19,20] one prospective cohort study[21] and one randomized controlled trial[16]) and 38 laboratory studies (24 studies used FEA and 14 studies used other laboratory methods). Among the included studies, 56 studies (81%) reported an association between stress and NCCL, while the remaining 13 studies (19%) had inconclusive or contradictory results.

Evidence supporting the role of stress in causing NCCL

Among the 56 studies which supported the abfraction theory, 23 were clinical studies and 33 were laboratory studies. A summary of the clinical studies which reported some evidence of association between occlusal factors and NCCLs is shown in Table 1. Among the 23 included clinical studies, there were 21 cross-sectional studies, one case-control study[22] and one cohort study.[21] No randomized clinical trials were found. The total number of patients (subjects) in studies that supported the abfraction theory was 4,505. The age of these patients ranged from 16 to 80 years old. The number of patients in each study varied considerably, ranging between six subjects[6] and 2,707 subjects.[10] Small sample sizes (less than 100 subjects) were commonly found. Sample size calculation was seldom reported, except in one study.[23] A convenient sample was usually adopted, except in a large cross-sectional epidemiological survey.[10] Regarding the diagnostic criteria of NCCL, only one study[24] used the validated Tooth Wear Index, while

Table 1. Summary of clinical studies supporting the association between stress/occlusal factors and non-carious cervical lesions (NCCLs) (n=23).

Author(s) (year)	Population	Objective(s)	Method(s)	Main findings/Conclusion
Antonelli et al (2013)[65]	20 adults, 35-66 years old,	To evaluate the role of occlusal loading in the formation of NCCLs	Exam, casts	Group function was associated with NCCLs
Aw et al (2002)[66]	57 adults, 29-75 years old	To analyze the characteristics of NCCLs and their related factors	Exam	Group function guidance and wear facets were related to NCCLs
Bader et al (1996)[22]	264 adults	To examine the effects of a variety of risk factors for NCCLs	Exam, QS, cast	Right canine guidance was associated with NCCLs
Bernhardt et al (2006)[10]	2,707 adults , 20-59 years old	To determine risk indicators for the etiology of abfraction	Exam, QS	Occlusal wear, inlay restoration, altering tooth position and tooth brushing behaviors were associated with NCCLs
Bevenius et al (1993)[6]	6 adults, 36-42 years olds	To describe the micromorphology of the manifest cervical lesions and risk factors of NCCLs	Exam, QS, SEM	Irregular lateral excursion was correlated with severity and location of NCCLs
Brandini et al (2012)[23]	132 adults, 19-58 years old	To verify the association between NCCLs and the parafunctional habit known as TMD	Exam, QS	Parafunctional habits and TMD were associated with NCCLs
Brandini et al (2012)[11]	111 adults, mean age 24 years old	To assess the relationship between occlusal forces and NCCLs	Exam, QS	Tooth clenching, nail biting and TMD were associated with NCCLs
Faye et al (2006)[28]	102 adults, 20-77 years old	To investigate the presence of NCCLs among adults with leprosy who did not brush their teeth	Exam, interview	Parafunction was associated with NCCLs in this population
Madani & Ahmadian-Yazdi (2005)[55]	77 adult patients	To evaluate the relationship between NCCLs and premature contacts	Exam	Premature contacts had a positive correlation with the incidence of NCCLs
Mayhew et al (1998)[67]	43 adults, mean age 56 years old	To study the relationships of occlusal, dietary and periodontal factors to NCCLs	Exam, QS	Functional wear facets were associated with the presence of NCCLs
Miller et al (2003)[68]	61 patients, 22-81 years old	To verify the association between abfraction and occlusal disturbance	Exam	Signs of occlusal disturbance were consistent with abfractions
Oginni et al (2003)[69]	106 patients	To study the prevalence of NCCLs and association between occlusal wear and brushing habits	Exam, QS	Occlusal wear facets were associated with abfraction
Ommerborn et al (2007)[12]	91 adults, 20-39 years old	To evaluate the association between bruxism habits and NCCLs	Exam	Adults with bruxism habits demonstrated significantly more NCCLs than those without them
Palomino-Gomez et al (2011)[70]	36 adults, 20-45 years old	To evaluate the lateral excursion movement and NCCLs	Exam	Group function might contribute to NCCLs
Pegoraro et al (2005)[71]	70 adults, 25-45 years old	To evaluate the association between the prevalence of NCCLs and occlusal factors	Exam, QS, cast	Occlusal wear facets were correlated with the prevalence of NCCLs
Piotrowski et al (2001)[46]	32 veterans, 38-80 years old	To investigate the characteristics and prevalence of abfraction-like lesions	Exam, QS	Facial toothbrush abrasion and erosion were mostly related with NCCLs, but some NCCLs were associated with stress
Smith et al (2008)[26]	156 patients, 16-73 years old	To determine the prevalence and severity of NCCLs and their related factors	Exam, QS	Group function, faceting, clicking joint and having occlusal splints were associated with NCCLs
Takehara et al (2008)[24]	159 soldiers, mean 36 years old	To examine the relationship between V-shaped NCCLs and occlusal factors	Exam, interview	Occlusal contact area, age and pressure while brushing teeth were associated with NCCLs
Telles et al (2000)[19]	48 dental students, 16-24 years old	To assess the relationship between NCCLs and occlusal aspects	Exam, QS	Occlusal stress affected the development of NCCLs
Telles et al (2006)[21]	40 dental students, 16-22 years old	To investigate the relationship between the presence of wear facets and NCCLs	Exam, cast	Occlusal wear facets were associated with NCCLs
Tokiwa et al (2008)[27]	50 adults, 23-74 years old	To investigate the relationship between bruxism (grinding pattern during sleep) and oral diseases	Exam, cast	Grinding patterns during sleep were associated with NCCLs
Tsiggos et al (2008)[13]	102 patients, mean age 45 years old	To determine the association between the presence of NCCLs and self-reported bruxism	Exam, QS, cast	The self-reported status of bruxism was associated with the occurrence of abfraction
Wada et al (2015)[25]	35 adults, 27-75 years old	To verify the mechanism of NCCLs	Exam, SOCT	Occlusal attrition was associated with larger NCCLs

Note: Exam = clinical examination, QS = questionnaire survey, SOCT = swept-source optical coherence tomography, TMD = temporomandibular joint disorder.

Table 2. Summary of laboratory studies supporting that stress is a possible mechanism of non-carious cervical lesions (NCCLs) (n=33).

Author(s) (year)	Samples	Objective(s)	Method(s)	Main findings/Conclusion
Andreaus & Colloca (2010)[61]	Upper first premolars	To compare stress profile in buccal and palatal cervical regions	3D-FEA	Occlusal forces played a role in NCCLs
Benazzi et al (2014)[72]	Lower second premolars	To compare patterns of stress distribution under occlusal loadings	3D-FEA	High tensile stress in the buccal aspect of the crown after occlusal loading
Benazzi et al (2013)[73]	Lower premolars	To compare stress in slightly and heavily worn premolars during maximum intercuspation contact	3D-FEA	Tooth wear changed the stress distribution independent of the morphology of the tooth
Beresescu & Brezeanu (2011)[30]	Lower canines	To investigate behavior of an intact and restored tooth undergoing different loads	2D-FEA	The maximum strain appeared in cervical area above cervical line, irrespective of load direction
Borcic et al (2005)[8]	Upper first premolars	To investigate stress distribution under two different occlusal force vectors	3D-FEA	Tensile stresses on cervical areas of teeth were higher in malocclusion than normal occlusion
Borcic et al (2007)[74]	Upper first premolars	To investigate stress distribution under two different occlusal force vectors	3D-FEA	Cervical and occlusal areas were the parts that bore the highest stress
Chun & Lee (2006)[75]	Lower first premolars	To investigate stress distribution	3D-FEA	Stress was concentrated on the cervical lines
de las Casas et al (2003)[63]	Upper premolars	To study effect of enamel anisotropy on stress concentration of the cement-enamel junction	2D-FEA	Enamel anisotropy affected stress distribution. Occlusion played major role in stress distribution
Dejak et al (2005)[32]	Lower first molars	To calculate stresses and strength ratio in the cervical area during grinding and clenching	2D-FEA	Overloading by computer simulation resulted in enamel damage and subsequent enamel chipping at the CEJ

Table 2. (continued).

Author(s) (year)	Samples	Objective(s)	Method(s)	Main findings/Conclusion
Dejak et al 2003[33]	Lower first molars	To analyze stress induced during clenching and chewing of morsels with elastic moduli	2D-FEA	Masticating a morsel of low elastic modules created stresses in the cervical lingual wall of molars
Demjan et al (2010)[38]	Premolars	To describe microstructural characteristics of cervical lesions	OCT	Multiple large cracks appeared in the cervical region confirming the biomechanical theory of abfraction
Geramy & Sharafoddin (2003)[34]	Upper central incisors	To evaluate tooth behavior when forces were applied from different directions	3D-FEA	The application of force, except intrusive force, produced increases in von Mises stress and tooth deflections
Goel et al (1991)[59]	Upper first premolars	To investigate stress variations in the enamel and dentin adjacent to the dentino-enamel junction	3D-FEA	Stresses increased at cervical enamel, which showed increased values for shear stress distribution
Grippo et al (2013)[35]	Premolars	To evaluate combined effects of cyclic fatigue stress and bio-corrosion activity on NCCLs	SEM, LM	Cyclic fatigue stress and acid bio-corrosion had a significant effect on the depth of the NCCLs
Jakupovic et al (2014)[62]	Lower first premolars	To describe stress distribution under static occlusal loadings	3D-FEA	Occlusal load led to significant stress in cervical area
Kishen et al (2006)[76]	Lower central incisors	To evaluate biomechanical basis of NCCLs by examining patterns of deformation (strain)	DMII	The strains in enamel increased at buccal cervical edge, whereas strains in dentin increased below CEJ
Kuroe et al (1999)[77]	Upper first premolars	To determine locations of occlusal load-induced stress concentrations	Photo-elastic	Cuspal loading concentrated stress around the cervical area below the loaded cusp
Lee et al (2002)[78]	Upper premolars	To compare changes in stress of different occlusal loads	3D-FEA	Tensile stresses were detected in the cervical region using various loading sites and directions
Marcauteanu et al (2010)[40]	Incisors and canines	To evaluate the importance of occlusal factors in the etiology of NCCLs	OCT	The microstructural parameters of NCCLs allowed for the identification of occlusal overload as an etiology of abfraction
Palamara et al (2000)[58]	Lower second premolars	To investigate variations in strains in enamel under different patterns of occlusal loading	3D-FEA	The magnitude, direction and character of strains in cervical enamel are dependent on loading patterns
Palamara et al (2001)[36]	Lower premolars	To measure dissolution of buccal enamel to acid with or without cyclic occlusal loading	SEM	Teeth undergoing cyclic loading during acid exposure showed greater volumetric loss than teeth not subjected to load
Palamara et al (2006)[57]	Lower premolars, central incisor	To investigate effects of load on the location and magnitude of cervical strains	3D-FEA	Tooth morphology and the location of loading might have an influence on the initial location of NCCLs
Poiate et al (2009)[31]	Upper central incisors	To evaluate stress distribution of the cervical region under two simulated clinical situations	3D-FEA	Stress concentration in ADJ exceeded the enamel's tensile strength under simulated conditions
Rees (2002)[9]	Lower second premolars	To study the effect that varying positions of occlusal load have on the stress contour in the cervical area	2D-FEA	Varying the position of occlusal load produced marked variation in the stresses
Rees & Hammadeh (2004)[79]	Upper incisors, canines and first premolars	To examine the effect undermining buccal cervical enamel has on the stress distribution	2D-FEA	Undermining the buccal ADJ caused significant increases in the cervical stress profile
Rees et al (2003)[60]	Upper incisors, canines and premolars	To provide a biomechanical explanation of abfraction lesion formation	2D-FEA	The buccal stress profile of an upper incisor was greater than an upper canine and premolar
Romeed et al (2012)[29]	Upper canines	To investigate the biomechanics of NCCLs under axial and lateral loading conditions	3D-FEA	Stresses were concentrated at the CEJ. Lateral loading produced greater stresses than axial loading
Soares et al (2014)[80]	Upper premolars	To investigate the effect of root morphology and different loadings on biomechanical behaviors	3D-FEA	Oblique loading promoted high stress and strain levels
Staninec et al (2005)[41]	Molars	To quantify the relative environmental effects of abfraction and erosion on dentin loss	LM	Both mechanical stress and lower pH accelerated the material loss of dentin surfaces
Stoica et al (2010)[39]	Incisors and canines	To investigate the microstructural subsurface of pathological dental wear	OCT	High eccentric occlusal forces produced flexure at the cervical area. Cervical stress concentration produced a fracture line
Tanaka et al (2003)[81]	Upper central incisors, lower first premolars	To investigate stress analysis using the plastic-elastic deformation theory	2D-FEA	Oblique loading stretched the enamel surface at the cervical area and caused plastic deformation
Vasudeva & Bogra (2008)[82]	Lower first premolar	To compare the stress profile of a sound and restored tooth under varied occlusal loads	2D-FEA	High occlusal loading and occlusal amalgam restoration increased the stress at the cervical region
Whitehead et al (1999)[37]	100 extracted premolars	To report the development of artificial notch-shaped lesions by stress corrosion	SEM	Occlusal factors might play a significant role in the initiation and progression of NCCLs

Note: ADJ = amelo-dentinal junction, CEJ = cemento-enamel junction, DMII = digital moiré interferometric investigation, LM = light microscopy, OCT = optical coherence tomography, SEM = scanning electron microscopy, 2D-FEA = two-dimensional finite element analysis, 3D-FEA = three-dimensional finite element analysis.

the others used different diagnostic criteria for NCCL. Few studies used multivariate analysis to investigate the association between stress and NCCLs[10,22,24] whereas a majority of the studies tested their hypotheses using univariate and bivariate analysis. The results of cross-sectional and case-control studies showed that many occlusal factors, such as occlusal wear, parafunctional habits, occlusal guidance and grinding patterns, were associated with the presence or progression of NCCLs. A relationship between occlusal wear or wear facets and NCCLs was found in most studies.[11,24-26] Parafunctional habits[23,27,28] and grinding patterns[11,22,27] were found to be significantly related to the presence of NCCLs. One prospective study[21] showed that the presence of occlusal wear facets was related to NCCLs occurring in 3 years.

Of the 33 laboratory studies, 24 used FEA methods and the other nine employed other methods to investigate occlusal stress and cervical lesions (Table 2). Among the theoretical FEA studies, 15 studies compared stress distribution using three-dimensional finite element analysis (3D-FEA), whereas nine studies used two-dimensional finite element analysis (2D-FEA). Stress analysis in premolar models was found more often than in other tooth type models.[29-34] All FEA studies showed

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Table 3. Summary of clinical studies that do not support the association between stress/occlusal factors and non-carious cervical lesions (NCCLs) (n=8).

Author(s) (year)	Population	Objective(s)	Method(s)	Main findings/Conclusion
Ahmed et al (2009)[42]	95 adults, mean age 50 years old	To determine factors associated with NCCLs	Exam, QS	Angle's classification, exclusive guidance, wear facets and bruxism were not associated with NCCLs
Estafan et al (2005)[47]	299 dental students	To evaluate the relationship between NCCLs, occlusal wear and other occlusal factors	Cast	Occlusal wear, occlusal guidance, restoration, and Angle's classification were not correlated with NCCLs
Khan et al. (1999)45	122 adults, 14-70 years old	To describe the incidence and types of NCCLs and their association with occlusal attrition and erosion	Exam, SEM	Occlusal and cervical lesions were associated, but erosion and salivary protection played central roles in the etiology of NCCLs
Pikdoken et al (2011)[15]	30 adults, 45-80 years old	To investigate whether NCCLs were associated with occlusal wear and clinical periodontal parameters	Exam	Occlusal wear was not associated with cervical wear. The cause of NCCLs was possibly multifactorial
Reyes et al (2009)[43]	46 adults, 23-82 years old	To determine the association between premature contacts, clinical attachment loss and NCCLs	Exam	Premature contact in centric relation was not associated with abfraction lesions or increased attachment loss
Shah et al (2009)[20]	119 adults	To study the prevalence of NCCLs in people with bruxism or combined tooth wear	Exam, QS	The prevalence of NCCLs in people with bruxism or combined tooth wear was similar to that of control group.
Wood et al (2009)[16]	39 patients, 18-75 years old	To investigate whether adjusting the occlusion had any effect on the rate of progression of NCCLs	Exam, cast	Occlusal adjustment did not reduce rate of progression of abfraction lesions in upper teeth
Young & Khan (2002)[44]	174 patients	To investigate the association between occlusal and cervical lesions	Exam, SEM	Occlusal wear was not associated with NCCLs. Cervical wear lesions were seldom found on the lingual aspects

Note: Exam = clinical examination, QS = questionnaire survey, SEM = scanning electron microscopy.

Table 4. Summary of laboratory studies that do not support stress as a mechanism of non-carious cervical lesions (NCCLs) (n=5).

Author(s) (year)	Samples	Objective(s)	Method(s)	Main findings/Conclusion
Daley et al (2009)[50]	Lower incisors and canines	To examine the histologic findings (surface, dentin tubule, tract) of anterior teeth with NCCLs	SEM, LM	No histopathological evidence of abfraction was found
Horning et al (2000)[51]	Modern skulls	To investigate the correlation between occlusion, attrition, periodontal ligaments and bone buttressing	Skulls	No evidence supporting the theory of abfraction was found
Hur et al (2011)[49]	Extracted teeth	To investigate morphological characteristics of NCCLs	Micro-CT	All lesions were located below the CEJ level. No enamel fracture at coronal margin of NCCLs
Litonjua et al (2004)[14]	Matched pair of extracted premolars	To investigate the roles of axial and non-axial loading loading in the development of cervical lesions	SEM, OM	Occlusal load showed no significant role in the progression of NCCLs
Walter et al (2014)[48]	Extracted teeth	To investigate the morphological characteristics of NCCLs	SEM, LM	No micro-fracture could be detected in the wedge-shaped lesions

Note: CEJ = cemento-enamel junction, LM = light microscopy, Micro-CT = micro-computerized tomography, OM = optical microscopy, SEM = scanning electron microscopy.

that occlusal load led to significant stress on the cervical area regardless of the types and direction of loading. Besides FEA, SEM[35-37] and optical coherence tomography[38-40] were other common methods used for imaging the microstructural subsurface of cervical lesions. Four experimental studies that investigated the effect of cyclic mechanical loading on NCCLs gave evidence supporting the combined mechanism between abfraction and acid erosion.[35-37,41] Grippo et al[35] demonstrated the effect of acid erosion (either hydrochloric acid, pH 0.1, or orange juice, pH 4) and cyclic fatigue stress (100 N, 72 cycles/minute, 9,200 cycles) on the depth of the NCCLs of extracted premolars. Teeth that received cyclic loading showed significantly deeper lesions than teeth without fatigue stress. Staninec et al[41] investigated the effects of bio-corrosion (a mildly acidic pH 6 or a neutral pH 7) and mechanical stress (5.5-55 MPa, 2 Hz, 1,000,000 cycles) on dentin loss. Palamara et al[36] demonstrated that acid dissolution (1% lactic acid, pH 4.5, 28 hours) of cervical lesions was affected by cyclic occlusal loadings (100 N, 2 Hz, 200,000 cycles). Another exploratory study by Whitehead et al[37] revealed that both abfraction and erosion-like lesions developed under axial loading (670 N) and acid erosion (10% sulfuric acid, pH 0.3, 5 days).

Evidence not supporting the role of stress in causing NCCL

A total of 13 studies, eight clinical studies and five laboratory studies, did not find stress as a mechanism for causing NCCL. Main findings of these clinical studies are summarized in Table 3. Among the eight clinical studies, six were cross-sectional studies, one was a case-control study[20] and one was a clinical trial.[16] The age of the patients (subjects) ranged from 14 to 80 years. The total number of patients was 924. The number of patients in each study varied from 30 to 299. Half of the included studies (4/8) had a sample size of less than 100 patients. None of the included studies described how the sample size was determined. Moreover, all studies except the study by Ahmed et al[42] did not report the sampling method. Around half of the studies (5/8)[15,16,20,42,43] reported the inclusion and exclusion criteria used for patient recruitment. Five studies recruited their patients in clinics,[20,42-45] and one study from a pool of dental students.[47] Two studies[15,16] did not report details of their patient recruitment. Regarding the evaluation of NCCLs, although the diagnostic criteria for NCCL were usually described (except one study[42]), the definition of NCCL varied widely among the studies. The Tooth Wear Index was adopted in two studies.[15,20] Univariate and bivariate analysis were used in most studies, whereas multivariate analysis was only used in one study.[15]

Results of the laboratory studies that investigated the morphological characteristics of NCCLs in extracted human teeth were inconclusive in regards to the abfraction hypothesis. An anthropological study which examined 52 skulls demonstrated no association between severe attrition on occlusal surfaces and NCCLs.[51] Another experimental study found that application of occlusal loadings (45 kg) did not affect the development of cervical lesions in teeth that underwent toothbrush abrasion (1.4 million strokes, 80 hours).[14] Table 4 shows the five laboratory studies[14,48-51] which did not support the abfraction theory.

Discussion

Although several narrative reviews on abfraction have been published,[17,18] few systematic reviews on clinical studies that investigated the association between occlusal stress and NCCL were found in the literature.[52,53] Based on our last search (on 31 January 2016), the present study is the first systematic review that summarized findings on abfraction in both in vitro and in vivo studies. Since the theory of abfraction was derived from biomechanics, the summary of the existing evidence based on relevant laboratory and clinical findings may be a useful overview for clinicians when they make decisions about how to manage cervical tooth wear. According to the number of the included studies (clinical and laboratory), the majority (81%, n= 56/69) showed some evidence supporting the association between stress and NCCLs, whereas some (19%, 13/69) had contradictory results. The results of the present review should be interpreted with caution because most of the studies included in this review were laboratory studies, predominantly FEA studies, and cross-sectional studies with small sample sizes. Surprisingly, only one large population-based survey was found, and it concluded that abfraction was significantly related to occlusal factors such as wear facets and inlay restorations.[10] Unfortunately, confounding factors were seldom taken into account. It was a factor that was correlated (directly or inversely) to the causal factor and also correlated to abfraction. Only a few studies[10,15,22,24] measured the known confounding factors and included them in multivariate analyses. Omitting confounding factors might threaten the internal validity of causal inferences, thus lowering the quality of the studies. One should keep in mind that cross-sectional study is conducted at a single time point and therefore there is no information on the sequence of incidents, i.e. whether the occlusal risk factors happened before or after the development of NCCLs. Consequently, results of these cross-sectional studies cannot be used to infer causality. Regarding the unit of analysis, results were separately analyzed at the tooth level[16,46,55] or subject-level.[12,24,26] Nevertheless, multiple NCCLs can be found within one subject. Multilevel modelling, which can adjust the clustering effect, should be more suitable for handling these grouped data. However, no multilevel model was adopted in the studies included in the present review. Additionally, it seems difficult to compare abfraction findings among the studies included because there was a wide variation in the diagnostic criteria of NCCLs used by the different researchers. Thus, to improve the comparability of research results, development and adoption of a valid and reliable assessment tool for cervical tooth wear is necessary.

Prospective studies are known to provide a higher level of evidence than cross-sectional studies. Unfortunately, only two prospective studies[16,21] were found in the search. A 3-year prospective cohort study[21] observed NCCLs in 40 dental students. The results of the bivariate analysis revealed that there was an association between wear facets and the increased occurrence of NCCLs.[21] Nevertheless, bias could possibly occur since other confounding factors were not taken into consideration. On the contrary, a randomized controlled trial[16] provided some evidence that reducing lateral excursive load using occlusal adjustment did not prevent the progression of abfraction lesions in 30 months. However, it should be noted that these findings may be questionable due to the small sample size (31 patients) as well as the lack of details regarding sample size estimation and allocation concealment. In summary, the internal validity of these clinical studies is jeopardized in many ways, such as lacking reliable procedures and measures, and the use of a low-power design (insufficient sample size). External validity is also unclear because the results included studies that were mostly obtained from small or specific study groups.

A causal factor brings about a disease (i.e. no disease appears without the factor), while a contributory factor shares in or is partly responsible for a disease development. Although plenty of clinical studies supported an association between occlusal factors and NCCL, none of them verified stress as a significant or main causal factor initiating NCCL. Laboratory studies[35-37,41] suggested that NCCLs are the results of stress and other mechanisms. These results are in accordance with the previous review by Grippo et al;[54] the combined mechanism of stress (abfraction), friction (wear) and biocorrosion (chemical degradation) causes the initiation and perpetuation of NCCLs. The review also suggested that biocorrosion was necessary to cause the degradation of dentin which in composition is almost identical to bone. Stress works in concert with a biocorrodent to cause abfraction of both dentin and enamel. Bartlett & Shah[83] also suggested that cervical tooth wear is multifactorial in origin. The possibility of occlusal stress causing NCCLs cannot be eliminated though its effect towards the formation of NCCLs is difficult to evaluate in clinical studies.

In the laboratory studies, FEA was the most commonly employed method to investigate the effect of occlusal loading forces on the development of NCCL. FEA is a computerized method that can anticipate the response or behavior of tooth structures affected by mechanical stress. It can also solve complicated mechanical problems. However, appropriate mathematical equations are needed to predict the actual response of tooth structures. The inputted values of the physical properties of teeth and supporting tissues are critical for the validity of FEA results. The 2D-FEA model has some limitations that may undermine the reliability of capturing the anatomy of tooth structures. Sophisticated models are needed to better understand the tooth behavior after loadings.[56] Nevertheless, several researchers employed 2D-FEA models (9/24) in the studies included in this review. A wide variation in the values of Young's modulus of tooth structures were found. The values of the enamel Young's modulus ranged from

87,500[32,33] to 46,900[57,58] MPa, whereas the values for dentin ranged from 19,800[59] to 15,000[9,60] MPa. In addition, enamel is thought to be an anisotropic material due to its structure, which is basically made of hydroxyapatite with its different prism orientations. However, FEA models that are assumed to have different enamel behaviors (either isotropy[57,61,62] or anisotropy[60,63]) were found. Compared to the enamel that was assumed to have isotropic characteristics, the anisotropic enamel would yield a better wearing protective surface and could better tolerate stresses, thereby resulting in less potential for tooth fracture.[64] Besides the tooth model geology and the stipulation of dental properties, the location, direction and magnitude of applied loadings will also significantly affect the stress distribution. Accordingly, the use of FEA methods under assumptions of different behavior that are mostly set to be static and homogeneous may have some shortcomings due to their inability to simulate the accurate model and thereby predict the response of vital teeth to a stimulus. Nevertheless, these laboratory studies provided a constant condition for evaluation of the effect of the studied variable on the outcome. The design and quality of study are more important than the type of the study. Although laboratory studies often have plenty of assumptions, results of a well-designed laboratory study can provide better evidence than those of clinical studies with risk of bias.

All of the studies included in this review which used FEA argued that abfraction was a possible mechanism for causing NCCL, while the results of other laboratory studies that used different methods had contradictory findings. Among the laboratory studies, observational studies were more common than experimental studies. Four experimental laboratory studies[35-37,41] reported some evidence of abfraction. Based on a small number of experimental studies, there is a possibility that the cervical tooth area is susceptible to abfraction lesions when undergoing stress fatigue and acid exposure in the simulated laboratory conditions. Nevertheless, questions remain about whether the replicated clinical situations that aimed to accelerate the development of NCCL in a short period of time could mimic the slow process of natural tooth wear.

Although a number of abfraction studies were included and analyzed, there are a number of potential limitations of the current review. The first issue is the heterogeneity of study designs (observational vs. experimental studies and clinical vs. laboratory studies) and outcome measurement. Therefore, meta-analysis could not be performed, and methodological quality assessment of the studies that used a single appraisal criterion may be impossible. There may be language bias since the literature search was confined to publications published in English. In addition, due to the original research question's focus on abfraction, the specific keyword "abfraction" was used instead of general words such as "tooth wear" or "cervical lesions," which probably diminished the quantity of studies that could be included. Therefore, the bibliographies of the studies under review were extensively examined. As a result, a number of studies (28/69) that were derived from cross-referencing were added in this review. In summary, this systematic review found inconsistent results from the clinical and laboratory studies on the stress mechanism producing NCCL. Based on the findings of the majority of the studies, there is some evidence supporting an association between stress or occlusal factors and NCCL. Although there is inadequate clinical evidence to support that mechanical stress alone can create NCCL without other causal or contributory factors, results of the FEA studies propose stress as a possible mechanism.

In conclusion, the majority of the studies on abfraction reported an association between occlusal stress and NCCL.

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