A NOVEL CLASSIFICATION FOR CORONAL REMAINING DENTINE THICKNESS IN CARIOUS TEETH

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A NOVEL CLASSIFICATION FOR CORONAL REMAINING DENTINE THICKNESS IN CARIOUS TEETH

by

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TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS

%	Percentage
s	Seconds
mm	Millimetre
µSv	Microsievert
δ	Difference of means
σ	Standard deviation
α	Type I error probability
cd/m^2	Candela per square metre
mA	Milliampere
kV	Kilovolt

LIST OF ABBREVIATIONS

IPS	Institut Pengajian Siswazah
USM	Universiti Sains Malaysia
RDT	Remaining dentine thickness
CBCT	Cone beam computed tomography
Micro-CT/XMT	Micro computed tomography/X-ray micromotorgraphy
OCT	Optical coherence tomography
CLSM	Fluorescent lasers and confocal laser scanning microscopy
VPT	Vital pulp treatment
OPG	Orthopantomogram
DMF	Decayed-Missing-Filled
ADA CSS	American Dental Association Caries Classification System
PA	Periapical
ICDAS	International Caries Detection and Assessment System
MID	Minimally invasive dentistry
IPC	Indirect pulp cap
DPC	Direct pulp capping
MTA	Mineral trioxide aggregate
pH	Power of hydrogen
CT	Computed tomography
e.g.	“exempli gratia” meaning “for example”
RRDT	Radiographic RDT
ARDT	Actual RDT
RDT/TDT	Remaining dentin thickness/total dentin thickness
CI	Confidence interval
3D	Three-dimensional
HDM	Hirox digital microscope
ACS	Auto calibration select
RAM	RAND/UCLA appropriateness method
UCLA	University of California, Los Angeles
JEPeM	Jawatankuasa Etika Penyelidikan Manusia
PS	PS-Power and Sample Size software

SR/SR(s)	Systematic review/systematic reviews
PROSPERO	Prospective Register of Systematic Reviews
NIHR	National Institute for Health Research
PICOS	Participants Intervention Comparison Outcome and Study
MeSH	medical subject heading
JBI	Joanna Briggs Institute
ICC	Intra-class correlation coefficient
DPI	Dots per image
CVI	Content validity index
R1	Round 1
R2	Round 2
R3	Round 3
SD	Standard deviation
ANOVA	Analysis of variance
I-CVI	Item-level content validity index
S-CVI/Ave	Scale-level content validity index based on the average method
PR	Proportional relevance
EA	Experts in agreement
PRISMA	Preferred Reported Items for Systematic Review and Meta-analysis

LIST OF APPENDICES

KLASIFIKASI NOVEL UNTUK KETEBALAN DENTIN KORONAL YANG TINGGAL PADA GIGI YANG MENGALAMI KARIES

ABSTRAK

Karies gigi adalah isu lazim yang memberi kesan kepada sebahagian besar populasi. Bahagian dentin koronal yang kekal selepas serangan karies dirujuk sebagai ketebalan dentin yang tinggal (RDT). Jumlah RDT yang tinggal selepas karies, sangat mempengaruhi diagnosis dan perancangan rawatan. Kajian ini bertujuan untuk memperkenalkan klasifikasi novel yang mengkategorikan RDT koronal berdasarkan ketebalannya yang berkurangan dan maklumat mengenai faktor-faktor yang berkaitan dengannya. Reka bentuk kajian komprehensif yang menggabungkan kajian sistematik (SR), eksperimen *in vitro*, dan teknik Delphi yang diubah suai, telah digunakan. Artikel yang mengukur RDT koronal telah disaring untuk SR. Untuk eksperimen in vitro, geraham besar dan geraham kecil berkaries yang dicabut daripada manusia digunakan, di mana RDT diukur menggunakan radiograf digital periapikal, imbasan tomografi berkomputer sinaran kon (CBCT) dan stereomikroskopi Hirox (bahagian histologi). Rangka kerja klasifikasi telah dibina menggunakan faktor yang dikenal pasti, dan disahkan menggunakan teknik Delphi yang diubah suai dengan bantuan pakar antarabangsa dalam bidang pengurusan karies. Analisis kandungan telah dijalankan ke atas artikel yang disertakan untuk kajian sistematik, ANOVA sehala digunakan untuk membandingkan pengukuran RDT yang diperoleh semasa eksperimen in vitro, dan indeks kesahan kandungan (CVI) digunakan untuk menilai persetujuan konsensus dalam kalangan pakar antarabangsa yang mengambil bahagian dalam proses Delphi yang diubah suai. Sebanyak 17 artikel telah dimasukkan ke dalam SR selepas saringan teks penuh, di mana analisis kandungan dilakukan. Hanya 63 gigi digunakan dalam eksperimen *in vitro*, yang memenuhi kriteria kemasukan dan pengecualian. Tiada perbezaan ketara diperhatikan dalam nilai RDT yang diperoleh menggunakan CBCT dan Hirox. Namun begitu, perbezaan ketara ($p<0.05$) telah diperhatikan di antara radiograf digital dan CBCT, serta di antara radiograf digital dan Hirox. Sebanyak 10 komponen telah dikenal pasti daripada analisis SR/kandungan dan eksperimen in vitro, yang membantu dalam membina rangka kerja Triage Pergigian. Seterusnya, rangka kerja ini menjalani pengesahan menggunakan tiga pusingan Delphi yang diubah suai dengan 22 pakar antarabangsa, menghasilkan skor item-CVI masing-masing 0.89 (89%), 0.97 (97%) dan 0.98 (98%); menunjukkan persetujuan konsensus yang kukuh dalam kalangan panel pakar antarabangsa berkenaan dengan keseluruhan Triage Pergigian, menjelang akhir pusingan ketiga. Kesimpulannya, diperhatikan bahawa radiografi digital memberikan bacaan RDT yang lebih tinggi berbanding CBCT dan Hirox. Namun begitu, ia masih berfungsi sebagai alat bantuan dalam klinik yang paling praktikal untuk menilai RDT koronal. Klasifikasi RDT koronal novel, Dentinal Triage, telah dibangunkan dan berjaya disahkan dengan persetujuan konsensus 98% dalam kalangan pakar pergigian antarabangsa dalam pengurusan karies.

A NOVEL CLASSIFICATION FOR CORONAL REMAINING DENTINE THICKNESS IN CARIOUS TEETH

ABSTRACT

Dental caries is a prevalent issue impacting a significant portion of the population. The part of coronal dentine that remains following a carious attack is referred to as the remaining dentine thickness (RDT). The amount of RDT left after caries significantly influences diagnosis and treatment planning. This study aimed to introduce a novel classification that categorises coronal RDT based on its decreasing thickness and information on its related factors. A comprehensive study design incorporating a systematic review (SR), an in vitro experiment, and a modified Delphi technique was employed. Articles measuring coronal RDT were screened for the SR. For the *in vitro* experiment, human extracted carious molars and premolars were used, in which the RDT was measured utilising digital periapical radiographs, cone-beam computed tomographic (CBCT) scanning, and Hirox stereomicroscopy (histological sections). The classification framework was constructed using the identified factors, and validated using the modified Delphi technique with the help of international experts in the field of caries management. A content analysis was conducted on the articles included for the SR, one-way ANOVA was applied to compare the RDT measurements obtained during the *in vitro* experiment, and a content validity index (CVI) was utilised to assess the consensus agreement among international experts participating in the modified Delphi process. A total of 17 articles were included in the SR after the full-text screening, upon which the content analysis was performed. Only 63 teeth were used in the *in vitro* experiment, that met the inclusion and exclusion criteria. No significant difference was observed in RDT values acquired using CBCT and Hirox. Nonetheless, a significant difference ($p<0.05$) was observed between digital radiographs and CBCT, as well as between digital radiographs and Hirox. A total of 10 components were identified from the SR/content analysis and *in vitro* experiment, that helped in constructing the Dentinal Triage framework. Next, this framework underwent validation utilising three rounds of modified Delphi with 22 international experts, yielding item-CVI scores of 0.89 (89%), 0.97 (97%), and 0.98 (98%), respectively; indicating a strong consensus agreement among the international expert panel in regards to the entire Dentinal Triage by the end of round three. In conclusion, it was observed that digital radiography overestimated RDT relative to CBCT and Hirox microscopy. Nevertheless, it still served as the most practical chairside tool for assessing coronal RDT. The novel coronal RDT classification, the Dentinal Triage, was developed and successfully validated with a 98% consensus agreement amongst the international dental experts in caries management.

CHAPTER 1

INTRODUCTION

Coronal remaining dentine thickness (RDT) can be defined as the dentine left between the pulp chamber and the cavity's pulpal wall after a carious attack (Al Jhany et al., 2019). This dentine thickness is crucial for forecasting diagnosis, and the results of upcoming treatments. In order to enhance the quality of coronal deep caries management while using minimally invasive dentistry techniques, researchers have been attempting to measure this slim thickness accurately for a great deal of time (Banerjee et al., 2017, Al Jhany et al., 2019).

1.1 Background of the study

One of the most common dental problems a patient visits their dentist with is caries. The degree of caries extension, the amount of tooth structure lost, the underlying cellular pulpal activity, and the patient's signs and symptoms, all influence management of dental caries (Bjørndal L, 2016). The amount of RDT that remains to protect the underlying pulp, is the main consideration in treatment planning when the caries is deep and has reached the inner half of the dentine (Al Jhany et al., 2019).

It is important to note, central dentine in the coronal region is more permeable than the root dentine. The permeability of central coronal dentine escalates, as the tubules converge on the pulp. Root dentine contains a reduced quantity of intertubular dentine in comparison to coronal dentine; therefore, it is less permeable (Pashley and Pashley, 1991, Chu et al., 2010, Ghazali, 2003).

The whole tubular surface adjacent to the dentine-enamel junction constitutes around 1% of the overall surface area of dentine, but closer to the pulp chamber area it may account for nearly 45% (Holliday, 2011). Clinically, it is important to acknowledge that dentine beneath a deep cavity preparation has significantly greater permeability compared to dentine beneath a shallow cavity, particularly when the growth of sclerotic or reparative dentine is minimal (LUUKKO et al., 2011). Moreover, the rate of caries progression is faster in dentine as compared to the enamel of a tooth. This is also due to the fact that dentine is more permeable and has a tubular structure (Lehmann et al., 2012).

Caries is very prevalent around the world, even in high-income countries, and it disproportionately affects older and socially disadvantaged people (Whelton et al., 2007, Sengupta et al., 2017, Organization, 2017). In a consensus document, Innes *et al.* defined deep caries as radiographic evidence of caries that reaches the inner third or inner quarter of dentine, and poses a pulp exposure risk (Innes et al., 2016).

More than a century ago, the first caries classification pioneered by G. V. Black was introduced in the year 1896 (Mount et al., 2006). From the time of its' publication, many advancements had been made in management and restorative materials, and this classification appears to be outdated (Mount et al., 2006). This classification wasn't made to recognise the incipient enamel lesions prior to cavitation or the restoration's growing complexity. Therefore, another caries classification was introduced by Mount and Hume, based on the size and site of the caries, commonly known as the Mount-Hume classification system (Mount and BDS, 1998).

Another criteria for classifying caries was developed by Nyvad in 1999, known as Nyvad's classification, which was entirely based on tactile and visual examination (Nyvad et al., 1999). Later, in 2002, the well-renown International Caries Detection and Assessment System (ICDAS I) was introduced and was later modified in 2005 to the ICDAS II (Ismail et al., 2007). This system made it very easy to accurately detect early and non-cavitated carious lesions but requires twice as much time in recording and training dental students and dentists (Melgar et al., 2016, Campus et al., 2019, Dikmen, 2015).

Next, the Decayed-Missing-Filled (DMF) index was introduced for caries but had the disadvantage that active and inactive carious lesions could not be properly differentiated (Campus et al., 2019, Melgar et al., 2016). It had a binary rating system (yes/no) rather than grading. Recently, the American Dental Association Caries Classification System (ADA CCS) was introduced, which intends to improve upon current classification schemes, and develop a useful evidence-based method for application in different clinical contexts. It also intends to be a useful tool for researchers, and to encourage uniformity and comparability between studies (Young et al., 2015).

Once dental caries starts to progress, diagnosis of the tooth and underlying pulp is of primary importance. Over the past century, a number of diagnostic tests have been created to identify the condition early on and enable timely intervention that will ultimately address the caries issue. In order to deliver the most accurate and effective care, dentists integrate different diagnostic tests (Ghodasra and Brizuela, 2021).

Visual-tactile examination permits for an initial diagnosis (even if this method fails to detect caries predictability), which can further be validated by using other caries diagnostic tools such as radiographs, caries detector dyes, fibre optic transillumination, photothermal radiometry and modulated luminescence, laser fluorescence, and light-induced fluorescence (Ghodasra and Brizuela, 2021).

Successful treatment outcomes require an appropriate diagnosis, which can further help in providing the best possible/available treatment options for the patient (Ricucci et al., 2019). For decades, dentists and dental researchers have been working hand in hand to achieve, explore, and invent prospects that will help clinicians, not only in providing their patients with desirable dental care but also with reliable and long-lasting treatment options (Fang et al., 2019, Parisay et al., 2015).

Clinical and radiographic findings conjointly play a robust role in decision-making for providing good treatment plans. Relying only on clinical findings hampers a dentist in providing a sound and effective treatment plan. Nowadays, radiographic assessment to plan conservative dental procedures has become a complete necessity to fulfil the pre-requisites of treatment decision-making (Preeja et al., 2020).

To date, dental periapical (PA) radiographs, bitewings, and orthopantomograms (OPG)/dental panoramic tomography are widely used as the initial diagnostic aid following clinical assessment of caries. It is crucial to remember that radiography on its own can not differentiate between active and arrested lesions (Schwendicke et al., 2015, Ghodasra and Brizuela, 2021). But it was observed that for cavitated proximal lesions and dentinal caries, radiographic caries detection was very accurate. More sensitive techniques might be taken into consideration for identifying early carious lesions (Schwendicke et al., 2015). Therefore, dental radiography is the key tool for deep caries detection and further investigations can definitely help in finalising treatment plans.

Depending on the extension of dental caries, it can be treated either with nonrestorative techniques in the initial phases or with restorative techniques in the case of deep caries. Nonrestorative techniques include but are not limited to mechanical and chemical plaque control, dental sealants, and fluoride or calcium-based varnishes that help in remineralisation of incipient carious lesions (Cabalén et al., 2022, Yu et al., 2021). Restorative treatment options include selective or nonselective caries excavation, and partial or full pulpotomies (Banerjee et al., 2017, Bjørndal et al., 2010b).

If caries is not treated, it can cause loss of tooth structure (making it unsalvageable), pulpitis, pulp infection, and ultimately pulp necrosis as it spreads through the dentine. However, pulpal recovery is possible even in severely etched carious lesions with conservative treatment (Al Jhany et al., 2019, Bjørndal et al., 2010b). The advancement of minimally invasive dentistry-based treatment approaches have been opted for in order to reduce the risk of pulp exposure and achieve selective (partial) caries removal (Banerjee et al., 2017, Maqbool et al., 2020).

It is difficult to clinically assess the depth of caries and the thickness of residual dentine (Stanley et al., 1975, Whitworth et al., 2005). Recent studies on deep caries management indicate that it may not always be necessary or desirable to remove all soft dentine in order to leave a thin layer of residual dentine behind (Innes et al., 2016, Maqbool et al., 2020). In such a presentation, a radiographic or clinical "end-point" is set as a threshold for less invasive methods in order to avoid a carious pulp exposure (Bjørndal et al., 2019). Deep caries management in the past involved the non-selective (complete) removal of all carious dentine, which was considered very destructive and potentially would result in a pulp exposure (Elderton, 1993, Bjørndal et al., 2006). Therefore, researchers started paying more attention to RDT and how its' presence could be beneficial in protecting the pulp.

One visit indirect pulp treatment or two visits using a step-by-step caries excavation methodology are two possible approaches for selective caries removal (Bjørndal et al., 1997, Bjørndal et al., 2010b, Bjørndal and Thylstrup, 1998, Maltz et al., 2012). With the use of strategies to avoid a pulpectomy or a pulp exposure, the treatment options for managing a cariously exposed pulp are also changing (Aguilar and Linsuwanont, 2011, Maqbool et al., 2021).

Deep caries management strategies are also evolving as pulpectomy is avoided and vital pulp treatment (VPT) procedures, such as partial and complete pulpotomies are trending. These changes are the outcome of our growing comprehension of the pulp-dentine complex's defensive and reparative mechanisms in response to irritation (Aguilar and Linsuwanont, 2011).

It is believed that the release of bioactive dentine matrix components and cautious handling of the carious dentine are crucial. The introduction of bioactive pulp capping materials such as mineral trioxide aggregate (MTA) has notably led to more consistent treatments from a histological and clinical standpoint (Bjørndal L, 2016, Bogen et al., 2008, Brizuela et al., 2017, Hegde et al., 2017). Hence, it can be postulated that the use of such materials not only aids in minimal intervention during treatment but also improves treatment outcomes by promoting the formation of new dentine.

One radiographic finding that has proven to be very informative in decision-making is the RDT measurement (Murray et al., 2003, Al Jhany et al., 2019, Berbari et al., 2017). A sufficient amount of RDT protects the underlying dental pulp from multiple insults, whereas when the RDT becomes slim, it loses its ability to protect the pulp from injurious insults, resulting in the provision of more invasive treatment options like pulpotomies and root canal treatments (Murray et al., 2003).

In an effort to precisely estimate the RDT in carious teeth, researchers have been employing a variety of modalities and methodologies for nearly fifty years (Al Jhany et al., 2019, Ayer, 2018, Bandlish et al., 2006, Berbari et al., 2017, Berbari et al., 2018, Fujita et al., 2014, Lancaster et al., 2011). Since the 1980s, attempts are being made to determine the most appropriate methods for determining or estimating the measurement of RDT (Weber et al., 1980). So far researchers have found conventional radiographs, digital radiographs, vernier callipers , rulers, macro-photographs, digital cameras, histological sections, electrical resistance, cone beam computed tomography (CBCT), micro-computed tomography (micro-CT), optical coherence tomography (OCT), fluorescent lasers, and confocal laser scanning microscopy (CLSM) as some of the valuable and effective ways of measuring RDT (Jhany et al., 2019; Krause et al., 2007; Krause et al., 2019; Lancaster et al., 2011; Majkut et al., 2015; Sarhan et al., 2022; Yoshida et al., 1989). All of the discovered methods have their advantages and disadvantages. Some methods overestimate RDT, while others that might accurately measure RDT are very costly or expose the patient to a high radiation dose (Al Jhany et al., 2019, Berbari et al., 2017, Berbari et al., 2018, Fujita et al., 2014, Lancaster et al., 2011).

As mentioned before, one of the most basic diagnostic tools commonly used in dental practice is a PA radiograph. Due to its' ease of availability, cost-effectiveness, and patient-friendly use, it is almost always used in every setting before finalising treatment options (Al Jhany et al., 2019, Schwendicke et al., 2015).

It is evident that the knowledge of RDT is imperative while performing restorative dentistry techniques. In addition, the availability of a proper coronal RDT categorisation could aid in the future development of accurate evidence-based treatment plans, patient education, and dental student training on the management of deep dentinal caries.

Moreover, while developing classifications or diagnostic tools to enhance clinical practice, looking for the experts' opinions is a likely approach. Scientists working to reach a position of consensus can evaluate new findings on areas not yet researched by using a specific question (or set of questions) based entirely on the knowledge and experience of experts in their field (Barrett and Heale, 2020).

One such approach that aids in providing a sound method for collecting expert opinions on an already available or newly constructed framework is known as the modified Delphi technique (Custer et al., 1999). This process is important for determining whether the novelty being introduced is required by professionals practicing in that field or not (Barrett and Heale, 2020).

To be more precise, the modified Delphi technique is a structured process in which a panel of experts arrive at a group opinion or decision with the help of surveying (Niederberger and Spranger, 2020). These specialists have to respond to a few questionnaires in iterative rounds related to whatever new ideas are in the pipeline. Once the responses are compiled, they are fed back to this group again in the form of a questionnaire or a rating list, based on results from the first round (Barrett and Heale, 2020, Niederberger and Spranger, 2020).

This study focused on developing a framework for properly classifying the different ranges of RDT and validating it. This would not only help in learning and educating about the importance of RDT but would also serve as a diagnostic tool in clinical practice while managing deep dentinal caries in permanent teeth of adults and children.

1.2 Problem Statement

All the previously mentioned methods used to measure RDT have had their benefits and limitations, but none has proven to be the best or most appropriate for measuring RDT (Al Jhany et al., 2019). In a study conducted in 2015, micro-CT and dental OCT had shown excellent results for measuring RDT (Majkut et al., 2015), which were very close to the actual RDT measurements. But these techniques were not convenient for a chairside RDT measurement. Also, it is not appropriate to expose a patient to excess radiation for treating only one decaying tooth (Signorelli et al., 2016).

Not knowing the appropriate RDT while managing deep caries can mislead a dental practitioner, as well as cause premature pulpal exposure and unnecessary complications to the patient. Knowledge of coronal RDT guides in making the most reliable treatment plan for the patient (Berbari et al., 2017) that is why it is necessary to know the safe ranges of RDT measurements while treating coronal deep dentinal caries.

Safe/unsafe ranges of RDT have been provided in previous literature but appear to be scattered under different topics related to restorative, operative, endodontic, paediatric, and conservative dentistry (Lancaster et al., 2011, Murray et al., 2003, Al Jhany et al., 2019, Smith et al., 2012, Tomer et al., 2017, Yoshida et al., 1989, Berbari et al., 2017). To the best of our knowledge, there is no reported or published evidence of a definitive classification or categorisation of coronal RDT and its' related factors after a carious attack has taken place.

1.3 Justification of the study

Dental researchers have been working for a long time to comprehend, investigate, and inform the dental community about the significance of coronal RDT. More focus has been placed in the past on coronal RDT after a carious attack has already taken place. This is so because the RDT left behind after a carious attack not only helps dental students, dentists, researchers, and educators in predicting the underlying dental pulp response and its' diagnosis, but also aids in meticulous treatment planning and educating today's well-informed patients about what is the status of their carious tooth.

Nowadays, patients are more knowledgeable and dentists are prone to lawsuits. Therefore, it would be very helpful for dental educators, dental students, researchers, young dental clinicians, as well as patients, if knowledge of RDT and its' related factors were all presented in a uniform framework, so the management and risk assessment related to the decreasing coronal RDT measurements could be properly evaluated, explained and understood.

Since RDT plays a key role in diagnostics, treatment planning, and patient education of deep caries management, it is very important to appropriately measure this thickness prior to starting treatment. Knowledge of RDT measurement can aid the practitioner in saving the carious tooth from a pulp exposure, as well as the patient from needless untoward events.

A validated classification of coronal RDT would help in guiding future dental students and young practitioners in improving their diagnostic skills, as well as in providing evidence-based treatment planning options to their patients chairside.

1.4 Objectives

1.4.1 General Objective

To design a novel classification of coronal RDT for carious permanent teeth by conducting a systematic review, performing an *in vitro* experiment, and validating the classification using a modified Delphi technique.

1.4.2 Specific Objectives

1. To identify factors related to coronal RDT by performing a systematic review on methods used for measuring coronal RDT followed by a content analysis.

2. To compare coronal RDT measured using digital radiography, CBCT scanning, and Hirox microscopy in an *in vitro* experiment on extracted carious permanent teeth, for identifying factors related to this thickness.
3. To synthesise a framework of the novel coronal RDT classification using the identified factors.
4. To synthesise specific questions and definitions for the identified factors of the novel coronal RDT classification framework for the modified Delphi technique.
5. To validate the novel coronal RDT classification framework by a panel of international experts using the modified Delphi technique.

1.5 Research Questions

1. Can factors related to coronal RDT be identified from a systematic review and a content analysis of previous studies?
2. Can factors related to coronal RDT be identified from an *in vitro* experiment conducted on extracted carious permanent teeth by comparing RDT measured utilising digital radiography, CBCT scanning, and Hirox microscopy?
3. Can a framework of the novel coronal RDT classification be synthesised using the identified factors?
4. Can specific questions and definitions be synthesised for the identified factors of the novel coronal RDT classification framework for the modified Delphi technique?
5. Can the novel coronal RDT classification framework be validated by a panel of international experts using the modified Delphi technique?

1.6 Null Hypotheses

1. Factors related to coronal RDT can not be identified from a systematic review and a content analysis of previous studies.
2. Factors related to coronal RDT can not be identified from an *in vitro* experiment conducted on extracted carious permanent teeth by comparing RDT measurements utilising digital radiography, CBCT scanning, and Hirox microscopy.
3. A framework of the novel coronal RDT classification can not be synthesised using the identified factors.
4. Specific questions and definitions for identified factors of the novel coronal RDT classification framework can not be synthesised for the modified Delphi technique.
5. The novel coronal RDT classification framework can not be validated by a panel of international experts using the modified Delphi technique.

1.7 Operational Definitions

a. Factors

Factors or items identified from the SR, content analysis, and *in vitro* experiment for building the novel coronal RDT classification framework.

b. Experts

Dental specialists in cariology or caries management.

c. Rounds

An iterative cycle of questionnaire-feedback process. Whereby, the designed questionnaire on the identified factors will be sent to the experts and their feedback will be analysed, and another questionnaire will be designed and resent for feedback, back and forth.

d. Consensus

Expert agreement of greater than 85% on either the proposed factors, their definitions, or the Dentinal Triage.

CHAPTER 2

LITERATURE REVIEW

This chapter begins by providing an overview of factors highlighting the importance of RDT, such as caries, deep caries, and caries management. Further, it also describes in depth about RDT, techniques used in the past for determining this thickness, as well as a detailed account of machines used in this study for measuring this thickness. Lastly, this chapter also reviews the different expert consensus techniques available and gives a deep overview of the technique used in the present study. Wherever possible, critical appraisal of previous literature can also be appreciated in this chapter.

2.1 Caries

Dental caries is a common yet preventable disease (Petersen et al., 2005). The detrimental health impacts of dental caries are progressive and persistently begin to intensify from childhood to adulthood (Broadbent et al., 2008). Dental caries results from the interplay between tooth structure, the microbial biofilm on the tooth's surface, sugars, and various factors like saliva and genetics, as can be seen in Figure 2.1 (Caries, 2017). The caries process involves cycles of demineralisation and remineralisation of the tooth. When demineralisation outweighs remineralisation over time, carious lesions form at specific anatomical sites on the teeth (Pitts and Zero, 2016).

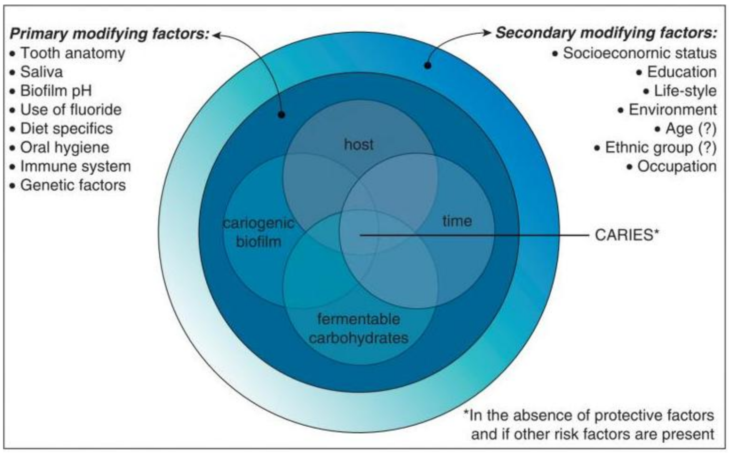

Figure 2. 1 Adapted Keyes-Jordan diagram. Essentially, dental caries occurs when cariogenic oral flora (biofilm) interacts with fermentable food carbohydrates on the tooth surface (host) progressively. Nevertheless, the development and progression of dental caries are notably intricate, since not all individuals with teeth, biofilm, and carbohydrate consumption will develop caries in the long run. Multiple modifying risk factors and protective variables

The widespread daily use of fluoride toothpaste is widely recognised as a key factor in the global decline of caries over recent decades (Marinho et al., 2003). These toothpastes work by promoting a healthier balance within the oral biofilm. Dental caries typically begins beneath the enamel surface, with early demineralisation happening in the subsurface. This is due to organic acids produced by biofilm bacteria that metabolise dietary sugars. Lactic acid, the primary end-product of sugar metabolism, plays a major role in the formation of caries (Pitts et al., 2017).

As these acids accumulate in the biofilm, the power of hydrogen (pH) level decreases, causing undersaturation at the biofilm-enamel interface and partial demineralisation of the tooth surface (Meyer et al., 2021). This loss of minerals enhances porosity, enlarges the spaces between enamel crystals, and softens the surface, enabling acids to penetrate further and cause subsurface demineralisation (Anil et al., 2022).

The release of calcium and phosphate from mineral dissolution of the tooth raises the degree of saturation, providing partial protection to the surface layer against further demineralisation (Hicks et al., 2005). Additionally, fluoride presence can inhibit surface demineralisation. Once sugars are removed from the mouth through swallowing and dilution by saliva, the acids in the biofilm are neutralised by the buffering action of saliva. The pH of the biofilm fluid returns to neutral, becoming adequately saturated with calcium, phosphate, and fluoride ions, which halts demineralisation and promotes the remineralisation process (Pitts et al., 2017).

Given the dynamic nature of caries, early stages of the disease can be reversed or halted, especially with fluoride. However, as demineralisation advances deeper into the enamel and dentine with ongoing acid challenges and pH drops, the subsurface mineral loss rate exceeds that of the surface, resulting in a subsurface lesion. This is a crucial phase, as preventive measures taken at this point can halt the caries progression (Brown et al., 2015).

2.2 Deep Caries

A recent consensus document defines deep caries as radiographic evidence indicating caries extending to the inner third or inner quarter of the dentine, posing a risk of pulp exposure (Innes et al., 2016). To facilitate management, deep caries can be further subdivided into deep and extremely deep carious lesions. Extremely deep caries is defined as radiographic evidence showing caries penetrating the entire thickness of the dentine with certain pulp exposure. In these cases, the demineralisation process extends throughout the dentine, making them unsuitable for selective caries removal and strategies aimed at avoiding pulp exposure (Wolters et al., 2017).

The dental-pulp complex reacts to irritation by a combination of inflammation and the promotion of mineralisation, which are crucial in maintaining vitality of the tooth (Goldberg, 2014). In cases of pulpal inflammation caused by deep caries infection, it can be clinically managed either by an attempt to preserve the tissue or by removing it and root-filling the tooth. Researchers of the field are looking for ways to preserve the pulp vitality in order to facilitate continuous root development and preserve the tooth structure (Ward, 2002).

2.3 Caries management

Management of dental caries has evolved over the years. Traditionally it involved removal of all soft demineralised dentine prior to restorative procedure, and now the doctrine of caries removal has slowly shifted towards the concept of minimally invasive dentistry (MID) via two main techniques, namely, selective caries excavation and stepwise excavation, in treating deep caries (Innes et al., 2016, Warreth, 2023).

2.3.1 Non-selective caries excavation

Conventional management of caries involves the removal of all carious tissue. It has been considered an essential step in the treatment of carious lesions, considering that the success of restorative treatment depends on complete elimination of the bacteria (Weerheijm et al., 1999). This method aimed to eradicate all infected dentin and leave remaining hard and firm tissue. Often this method is tested by means of a tactile approach with a sharp excavator (Barrett and O'Sullivan, 2021).

The rationale for this extensive tissue removal is to get rid of all infected dentine as well as total bacterial removal so that caries could be stopped from progressing further, thus providing a firm base to the lesion so that restorative materials could be placed and retained adequately via the removal of all demineralised dentine.

This procedure carries a significant risk of pulpal exposure during full caries removal and is frequently thought to be extremely damaging to the tooth tissue, going against the MID philosophy. Non-selective removal to hard dentine or complete caries removal is now considered overtreatment, and this approach is no longer recommended (Thompson et al., 2008, Barros et al., 2020).

2.3.2 Selective caries excavation

In view of the high risk of pulpal exposure in cases of deep carious lesions with proximity to the pulp, a more conservative approach has been proposed, which is "*selective caries removal.*" This technique is based on the concept that the carious process is guided by caries activity in the biofilm. Therefore, this process could be halted simply by sealing the cavity (Kidd, 2004, Duncan et al., 2019). The goal of the treatment is to arrest carious lesion activity while simultaneously reducing the risk of pulpal exposure and preserving the odontoblasts; to induce the formation of reactionary dentine instead of reparative dentine (Bjørndal et al., 2019, Banerjee and Watson, 2015). It also reduces the risk of bacterial ingress into the pulp, thereby maintaining pulp vitality. The approach maximises the prognosis of the tooth and should reduce long-term management costs and burden associated with maintaining healthy, caries free teeth (Schwendicke et al., 2016).

2.3.3 Stepwise excavation

Teeth that are presented with deep carious lesions often possess a risk of pulpal exposure during caries removal via the conventional method. In order to avoid pulp exposure and its consequent complications, conservative techniques of carious dentin removal have been developed for the treatment of asymptomatic teeth with reversible pulp inflammation, which is characterised by a quick, sharp, hypersensitive response that arises upon stimuli and the sensation subsides as soon as the stimulus is removed (Donnermeyer et al., 2023).

Stepwise excavation consists of complete excavation of decayed tissue in a two-step procedure with a six to nine-month gap period between each procedure

(Magnusson and Sundell, 1977). In the first visit, carious dentine is completely removed from the surrounding cavity walls, followed by the removal of the more necrotic and infected dentin at the pulpal wall. After a period of temporary sealing of six to nine months, the cavity is reopened for the final excavation, and the tooth is restored (Bjørndal et al., 2011). The goal of this technique is to reduce the likelihood of pulp exposure by promoting reactions from the pulp-dentin complex, such as dentine sclerosis and tertiary dentin development, and to regulate the advancement of caries by isolating the bacteria from the oral environment (Tziafas et al., 2000).

To be suitable for stepwise excavation, the tooth should not present with spontaneous or provoked pain, and the tooth should respond positively to pulp sensibility tests, and the previous radiographic evaluation should not show any signs of periapical pathology (Mattos et al., 2014).

2.3.4 Indirect pulp cap

An indirect pulp cap (IPC) is described in the Current Dental Terminology 2007 glossary as a "procedure in which the nearly exposed pulp is covered with a protective dressing to protect the pulp from additional injury and to promote healing and repair via formation of secondary dentin (Association, 2005)."

IPC can be done via one-step or two-step approaches. In the one-step approach (partial caries removal), most of the carious dentin is removed, and a biomaterial is placed. In this scenario, the biomaterial should not be in contact with the pulp, and the final restoration will be placed at the same appointment (Islam et al., 2023).

On the other hand, a two-step approach (step-wise caries removal) refers to the removal of caries in a stepwise technique, starting with the removal of soft carious dentin. A firm, discoloured, deep carious dentin should remain on the floor of the cavity in such cases where the possibility of pulp exposure may arise. After that, a biomaterial liner should be placed and overlaid by a temporary restoration. After clinical observation for several months, if there are no clinical symptoms of pain or signs of radicular pathology, the temporary restoration and any remaining caries should be removed, and the final restoration is placed (Islam et al., 2023)

When performing an IPC, most of the caries is removed. However, a thin layer of caries remains approximate to the pulp. In an effort to facilitate pulpal repair via a medication and a temporary filling (Thompson et al., 2008, Carrotte and Waterhouse, 2009). The temporary filling is then removed after a couple of months, and an x-ray is to be taken to observe the pulp repair process. The remaining caries is then removed and replaced with permanent restorations once the tooth shows clinical and radiographical signs of healing (Bjørndal et al., 2010a, Alex, 2018).

2.3.5 Direct pulp cap

The direct pulp capping (DPC) procedure refers to the placement of a biomaterial over an exposed coronal pulp after caries excavation (da Rosa et al., 2018). During DPC, a dental biomaterial is placed directly over the exposed dental pulp. This helps to promote the mineralised tissue formation and is also used to protect the vitality of the dental pulp (Okamoto et al., 2018).

DPC treatment aims at not only the healing of the pulp but also the maintenance of tooth vitality. The mechanisms of most DPC biomaterials cause superficial necrosis after placement directly over the exposed pulp tissue. The DPC biomaterial possesses antimicrobial properties that also induce mineralisation (Hilton, 2009). The release of hydroxyl ions by DPC biomaterials causes a raised pH of the underlying tissue. Therefore, a thin necrotic layer between the vital pulp tissue and the DPC agent will be formed (Téclès et al., 2008). This layer may seal the communication between the pulp and the outer environment as well as act as a barrier. Meanwhile, all of this aids in protecting the pulp complex and consequently, preserving its' vitality (Song et al., 2017).

2.3.6 Vital pulp therapy

VPT is designated to preserve and maintain pulp vitality and health that have been compromised due to trauma, caries, and restorative procedures. This technique sets a goal to initiate the formation of tertiary reparative dentine or a calcified bridge formation. The procedure is crucial in maintaining the involved immature permanent teeth, where the root development is incomplete, and maintaining the arch perimeter during orofacial growth is necessary (Coll et al., 2017). VPT is an umbrella term encompassing IPC, DPC, and pulpotomy (Cohenca et al., 2013).

IPC is used when the pulp is not exposed but there are deep caries that, if fully removed, might expose the pulp. In this procedure, most of the carious dentin is removed, leaving a thin layer of affected dentin to avoid pulp exposure and cover with a biocompatible material (Alex, 2018).

DPC, on the other hand, is indicated when the pulp is exposed due to caries, trauma, or during dental procedures (Islam et al., 2023). This procedure involves covering the exposed pulp directly with a biocompatible material, such as calcium hydroxide, MTA, or a bioceramic material, followed by placing a protective liner or base over the pulp capping material (Komabayashi et al., 2016). The tooth is then restored with a suitable permanent filling material. The objective of DPC is to promote the formation of reparative dentin and maintain the vitality of the pulp. DPC results in a higher success rate in young patients and when there is no infection or inflammation of the pulp (Cushley et al., 2021).

Additionally, Pulpotomy is a procedure used when there is more extensive pulp involvement, often due to caries or trauma, but the root pulp remains healthy (Cushley et al., 2019). In a pulpotomy, the coronal portion of the pulp is amputated, leaving the healthy radicular pulp. The remaining pulp tissue is then treated with medicament to promote healing and maintain vitality. The objective of pulpotomy is to preserve the vitality of the remaining pulp tissue and prevent the need for more extensive treatments, such as root canal therapy (Bimstein and Rotstein, 2016).

Outcome of VPT can vary depending on the age of patient, extent of bacterial contamination, and degree of pulpal inflammation, and most importantly, the choice of pulp capping material and quality of permanent restoration (Sabeti et al., 2021). Case selection to undergo the procedure is crucial in determining the success rate of the treatment. According to the American Academy of Paediatric Dentistry, teeth exhibiting stimulated pain of short duration, which was relieved with over-the-counter analgesics, by brushing, or upon the removal of the stimulus; without signs and symptoms of irreversible pulpitis, and having a clinical diagnosis of reversible pulpitis are deemed to be excellent candidates for VPT (Teeth, 2016).

2.3.6(a) Pulpotomy in immature teeth with symptomatic irreversible pulpitis

Pulpotomy is defined as the removal of the coronal portion of the vital pulp as a means of preserving the vitality of the remaining radicular pulpal portion (Duncan et al., 2019). It is often carried out as a part of an urgent procedure for symptom alleviation or as a therapeutic measure (e.g., Cvek pulpotomy) (Dentistry, 2021). A capping material is placed over the pulp floor and the remaining exposed tissue in the canal orifices after complete amputation of coronal pulp.

Teeth with irreversible pulpitis classically will be treated via apexification or pulpectomy, coupled with root canal filling as proposed by the American Association of Endodontists (Marroquín Peñaloza and García Guerrero, 2015, Huang, 2009). However, there is a rising trend of treating irreversible pulpitis by means of a pulpotomy, as there is evidence suggesting that symptoms arising from irreversible pulpitis may be confined only to the coronal portion and not extending to radicular pulp. Hence, it is deemed to be a feasible method (Ricucci et al., 2014).

Common pulpotomy medicaments formerly used include formocresol and ferric sulphate. However, formocresol has numerous drawbacks, particularly with regards to its carcinogenicity and genotoxicity, when used in humans (Ko et al., 2017). MTA with its superior properties, has proven to be an appropriate replacement of formocresol during primary molar pulpotomies. According to a study, MTA is preferred due to its' better biocompatibility and ability to induce the formation of a thicker and more complete dentin bridge, leading to higher success rates (Cervino et al., 2020). Vitapex, a calcium hydroxide and iodoform mixture, also shows positive results but is more commonly used as root canal filling material for deciduous molars (Lu et al., 2022).

2.3.6(b) Pulpotomy in mature teeth with symptomatic irreversible pulpitis

According to American Association of Endodontists, irreversible pulpitis is defined as "a clinical diagnosis based on subjective and objective findings indicating that the vital inflamed pulp is incapable of healing and that root canal treatment is indicated (Glickman, 2009)". As a result, pulp extirpation remains the classical treatment option for teeth diagnosed with irreversible pulpitis. Teeth with symptomatic irreversible pulpitis can be defined as teeth with either spontaneous pain and/or pain exacerbated by cold stimuli with prolonged episodes of pain, even after the thermal stimulus had been removed (Uesrichai et al., 2019). However, it has been discussed that the terminology might not correlate with the histologic condition of the pulp, as the irreversibly inflamed pulp may only depict bacterial involvement on the coronal aspect and no involvement of the radicular portion (Ricucci et al., 2014). Furthermore, once the coronal pulp, which is in direct contact with bacterial insult, is removed, the pulp exhibits excellent regenerative potential (Bjørndal et al., 2019). Hence, pulpotomy of symptomatic mature teeth is emerging as a promising treatment option for teeth with symptomatic irreversible pulpitis.

Clinical data on the success of pulpotomy procedures done in permanent mature teeth ranges from 82 to 100% (Alqaderi et al., 2014, Simon et al., 2013). A recent SR revealed that coronal pulpotomy in mature teeth with irreversible pulpitis achieved success rates exceeding 90% after one year (Cushley et al., 2019). In another SR, the success rate of pulpotomy for irreversible pulpitis in teeth with closed apex versus open apex depicted that the overall success rate of pulpotomy in teeth with irreversible pulpitis with closed apex was 83%, while pulpotomy in teeth with incomplete root development (open apex) demonstrated a cumulative success rate of 95.8% (Ather et al., 2022). Moreover, a meta-analysis reported an 84% success rate for pulpotomy in teeth with symptomatic irreversible pulpitis, which is comparable to the results of teeth with asymptomatic irreversible pulpitis (Taha and Abdelkhader, 2018, Taha and Abdulkhader, 2018, Taha and Khazali, 2017, Uesrichai et al., 2019).

The positive outcomes for symptomatic irreversible pulpitis can be attributed to the pulpotomy's ability to modulate immune responses and reduce pro-inflammatory cytokine levels in the dental pulp (Chang et al., 2014). Additionally, new-generation tricalcium silicate materials have anti-inflammatory properties that help reverse residual inflammation and maintain healthy pulp tissue (Meschi et al., 2020). Therefore, removing the coronally inflamed pulp may be sufficient to maintain pulp viability.