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ORIGINAL ARTICLE

A prospective clinical study investigating the effectiveness of partial pulpotomy after relating preoperative symptoms to a new and established classification of pulpitis

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Abstract

Aim: To prospectively investigate the outcome of partial pulpotomy after 1 year, using a hydraulic calcium silicate cement (HCSC) on symptomatic cariously exposed pulps in adult teeth. To compare the traditional American Association of Endodontists (AAE) pulpitis classification with the recently proposed Wolters classification system in predicting the likelihood of treatment failure.

Methodology: Sixty-two symptomatic adult teeth with deep and extremely deep carious lesions were classified according to the Wolters (mild/moderate/severe pulpitis) and the traditional pulpitis classification (reversible/irreversible pulpitis). Eleven teeth were excluded intraoperatively as there was no pulp exposure after non-selective caries removal. The remaining 51 teeth, regardless of diagnosis, were treated by partial pulpotomy, pulpal lavage with 2.5% sodium hypochlorite solution, haemostasis and HCSC application (Biodentine™) as a pulp capping material. A permanent restoration was placed during a second appointment 1–2 weeks later. Preoperative tenderness to percussion (TTP), bleeding time and material setting time were recorded as was preoperative and postoperative tooth colour under standardized conditions. Clinical review occurred at regular intervals with clinical/radiographic analysis at 12 months. Chi-square analysis and Fisher's exact test assessed different outcomes amongst the diagnostic categories; the Kruskal–Wallis and Wilcoxon rank-sum test assessed influence of pulp bleeding time, TTP or variation in setting time ($p < .05$).

Results: Ten cases were lost to review, and a total of 41 teeth were reviewed at 1 year and classified as either "success," "successful but unresponsive to sensibility testing" or "failed." This included five severe, 17 moderate and 19 mild pulpitis according to Wolters classification or 23 reversible pulpitis and 18 irreversible pulpitis cases by the AAE classification. The majority of the 62 enrolled cases were "extremely deep" ($n = 50$), rather than "deep" ($n = 12$) caries with all failures occurring in the extremely deep group. Partial pulpotomy was 90% successful (100% reversible, 78% irreversible or 100% mild, 88% moderate, 60% severe pulpitis) with a significant difference in outcome between mild and severe pulpitis groups ($p = .04$). Only one, severe pulpitis/irreversible pulpitis, case failed painfully prior to the 1-year review

appointment. Bleeding time ($p = .26$) and TTP ($p = .61$) did not influence treatment outcome, whilst Biodentine™ setting time was significantly longer than manufacturers' claim ($p < .05$). No teeth discoloured.

Conclusions: Partial pulpotomy using Biodentine™ was successful for treating symptomatic carious pulpal exposures after 1 year, but included cases where pulp vitality could not be confirmed. Within the limitations of this study, cases with signs and symptoms indicative of irreversible pulpitis were not less successful; however, Wolters classification highlighted severe pulpitis to be less successful than mild pulpitis, thereby providing a potential prognostic benefit in diagnostically subdividing pulpitis. Caries depth was an indicator of failure, whilst bleeding time and preoperative tenderness to percussion were not.

KEYWORDS

deep caries, exposed pulp, hydraulic calcium silicate cement, partial pulpotomy, pulpitis, vital pulp treatment

INTRODUCTION

The dental pulp can be irritated by a range of chemical, thermal and traumatic stimuli; however, microbial challenge represents the principal threat to pulp vitality (Möller et al., 1981). In response to this threat, the dentine–pulp complex mounts a complex immune response triggered initially via biosensing by odontoblast cells and thereafter by an orchestrated inflammatory process by dental pulp cells and circulating immune cells recruited locally to the injury site (Duncan & Cooper, 2020; Duncan et al., 2019; Farges et al., 2015). The early stages of pulpal inflammation are generally limited to the coronal pulp tissue with other areas of the pulp relatively healthy (Ricucci et al., 2014); however, current ways to categorize pulpitis are absolute considering the pulp to be either salvageable or not (American Association of Endodontists [AAE], 2013).

Inflammation of the dental pulp is classically categorized as being either reversible and irreversible pulpitis based on the relationship of signs and symptoms to management (AAE, 2013). Irreversible pulpitis indicates that the pulp tissue is so damaged that it is impossible to maintain vitality; thus, root canal treatment (RCT) is necessary. On the contrary, reversible pulpitis is a condition in which the pulp, even if damaged, is capable of recovery if the irritant stimulus is removed and the tooth adequately restored (Tronstad & Mjör, 1972). Unfortunately, this classification simplifies the complex and often unpredictable nature of pulpitis and fails to reflect the recently reported success of partial and full pulpotomy in cases with signs and symptoms indicative of irreversible pulpitis (Özyürek & Demiryürek, 2016; Taha & Khazali, 2017; Uesrichai et al., 2019). As a result, there has recently been a call for new classifications of pulpal status to be proposed in an attempt to link the signs and symptoms of pulpitis to vital pulp management strategies (Wolters et al., 2017) and to reflect the localized nature of pulp damage (Rechenberg & Zehnder, 2020; Ricucci et al., 2014). Recently, Wolters et al. (2017) proposed a system based on symptoms with four different categories of pulpitis, initial, mild, moderate and severe, with pulpal exposure and pulpotomy only indicated in selected categories. Notably, the word "irreversible" has been removed from all diagnoses in this proposed classification (Wolters et al., 2017). Although this represents a potentially more relevant diagnostic system, at present, there are no studies investigating its usefulness in determining the predictability of the vital pulp treatment (VPT) procedures.

Hydraulic calcium silicate cements (HCSCs) are recommended as the "gold standard" material for conservative treatment of the exposed pulp (ESE, 2019). HCSCs are characterized by high biocompatibility and hydrophilic nature, which assists their use in VPT procedures; however, mineral trioxide materials (MTA) have been shown to be associated with extended setting and tooth discolouration (Careddu & Duncan, 2018). HCSCs, such as ProRoot® MTA (Dentsply Sirona), modulate the pulp response reducing pulpal inflammation and increasing the quality of hard tissue bridge formation over the exposed pulp, compared with hard setting calcium hydroxide materials (Nair et al., 2008). A recently introduced HCSC, Biodentine™ (Septodont) is specifically marketed for VPT with manufacturer claims that it sets in 12 min, do not cause tooth discolouration with clinical research indicating good success in pulp capping over 2–3 years (Harms et al., 2019) and also pulpotomy (Taha & Abdelkhader, 2018).

The overarching aim of this study was to prospectively investigate the predictability of partial pulpotomy using the

HCSC, Biodentine™, in adult teeth presenting with symptomatic deep and extremely carious lesions and classified according to the AAE and Wolters diagnostic systems (AAE, 2013; Wolters et al., 2017). The following objectives were studied: (1) primary objective—the outcome clinically and radiographically of symptomatic cariously exposed pulps treated using a partial pulpotomy technique and capped with Biodentine™; (2) primary—the practicality and relevance of Wolters (Wolters et al., 2017) and the AAE (AAE, 2013) classification for diagnosis of pulpitis, management and prediction of VPT outcomes; (3) secondary—the association of bleeding time and tenderness to percussion (TTP) with reversible, irreversible pulpits and mild/moderate and severe pulpitis; (4) secondary—practical aspects of Biodentine™ use, including discolouration, setting time and postoperative symptoms.

MATERIALS AND METHODS

Experimental observational study

The proposed study was a longitudinal prospective single-arm clinical study investigating the reliability of Biodentine™ in the treatment of adult teeth presenting with deep/extremely caries and symptoms of pulpitis that related the outcome to an established and new classification of pulpitis. The study was carried out according to the STROBE checklist for observational studies. For the purposes of this study, "deep caries" was defined as reaching the inner quarter of dentine, but with a zone of hard or firm dentine between the caries and the pulp, which was radiographically detectable when located on an interproximal or occlusal surface, whilst "extremely deep caries" was defined as caries penetrating the entire thickness of the dentine, radiographically detectable when located on an interproximal or occlusal surface in which pulp exposure was unavoidable during operative treatment (ESE, 2019). The clinical component was carried out by one operator in dental practice in Dublin (RCD) linked to one senior principal investigator (HD) in the Division of Restorative Dentistry, Dublin Dental University Hospital (DDUH), Ireland.

Ethical approval

As the nature of this study is a clinical intervention on human subjects, an ethical approval was necessary. An application was submitted to the Research Ethics Committee at St James's Hospital (JREC), Dublin, and Ethical Approval (REC ref: 2017/04/01) was obtained on 25 April 2017.

Size of patient cohort

It was not possible to design this study as a randomized clinical trial comparing two diagnoses, but rather as a practicality-based prospective clinical study investigating the usefulness of a new classification system in general dental practice and relating it to outcome. Although the sample size was based on the numbers included in several studies investigating both the outcome of partial and full pulpotomy in teeth exhibiting reversible and irreversible pulpitis (Taha & Abdelkhader, 2018, Taha & Abdulkhader, 2018 [reviewed in] Cushley et al., 2019), as well as outcome studies demonstrating the success rate of partial pulpotomy in teeth with reversible pulpitis to be 98% (Chailertvanitkul et al., 2014) and approximately 68% with irreversible pulpitis (Elmsmari et al., 2019; Taha & Khazali, 2017) after 1 year. As the aim of this study was exploratory to investigate the usefulness of two pulp diagnosis systems a convenience sample size was used.

Patient sample

The sample group consisted of patients with a deep or extremely deep carious lesion and associated symptoms (ESE, 2019). Symptomatology was recorded and used to categorize the clinical features into mild, moderate or severe pulpitis (Wolters et al., 2017). In order to compare the results with a more established classification, the teeth were also categorized as either reversible or symptomatic irreversible pulpitis (AAE, 2013). Although "Wolters" classification (Wolters et al., 2017) was used to categorize pulpal condition, the proposed management strategies also advocated by Wolters were not rigidly followed and all cases were treated by non-selective caries removal and partial pulpotomy if the pulp was exposed after non-selective removal. This was carried out in order to standardize treatment and to assess the validity of Wolters' diagnosis as well as evaluating the efficacy of partial pulpotomy after non-selective caries removal in deep and extremely deep carious lesions with associated symptoms. The material chosen as pulp capping agent was Biodentine™ a HCSC marketed for VPT procedures.

Inclusion and exclusion criteria

The sample group consisted of patients between 14 and 60 years old, presence of deep/extremely carious lesion (evident from periapical ± bitewing radiographs), pulpal symptoms ranging from mild-to-severe pain, positive response to cold pulp sensibility test, and pulpal exposure during non-selective caries removal.

Pregnant women, teeth that were giving mild-to-severe pain and the patient preferred RCT, teeth not responsive to pulp sensibility testing (cold) and teeth that were not exposed after non-selective removal of caries were excluded (Table 1). In addition, teeth in which the pulpal haemorrhage could not be arrested intraoperatively were also excluded.

Patients were recruited by the operator (RCD). After taking a detailed pain history, and clinical/radiographic (periapical) examination, if a case was considered suitable for the study, he/she was informed about the possibility of being involved in this research project and a full explanation about the procedure, its risks and benefits were discussed. A clinical information leaflet was also provided for the patient.

Consent and pseudo-anonymous data storage

After a patient was considered potentially suitable for the study and expressed an interest in participating, an informed consent was obtained. During the consent procedure, it was stressed that the current "gold standard" for the treatment for the cariously exposed pulp in mature adult teeth was RCT. Due to the emergency nature of "toothache," it was not possible in the bulk of cases to allow a "cooling off" period as the patient was in pain and required immediate treatment. For this reason, the operator (RCD) carefully discussed consent with the patient on the day of presentation, clarifying doubts and explaining aspects of the procedure that the patient was unclear about. Afterwards, if the patient remained willing to participate, he/she was asked to sign the form. Within the consent procedure, it was further explained that the patient would only be enrolled into the study if the pulp was exposed after non-selective caries removal. If a pulp was not exposed, an indirect pulp cap would be carried out, and equally if on entry to the pulp, there were clear signs of pulp necrosis a RCT would be performed. The number of these cases was recorded in the experiment flow chart (Figure 1). Three copies of the consent were signed: one for the patient, one for the patient's dental chart and one for the researcher's own study record. Any data collected by RCD collected were stored on an encrypted computer. The key to the code was kept on a separate encrypted computer held by the principal investigator (HD), hence keeping any data in a pseudo-anonymized state. All the images (excluding radiographs) taken before, during and after the procedure were not associated to names (only codes) and did not include the face of the patient and did not have any identifiable features. This material was stored under the same code as described above. All data will be deleted after 5 years.

Patient assessment and operative procedure

Before beginning the procedure, the patient was assessed and the tooth categorized according to the classification of Wolters et al. (2017); "Mild Pulpitis" if the tooth was asymptomatic until triggered by cold stimuli or percussion, "Moderate Pulpitis" if the tooth demonstrated clear symptoms triggered by cold stimuli or percussion that lasted for minutes, but the pain could be stopped using medications; or "Severe Pulpitis" if the tooth displayed severe spontaneous pain and clear strong reaction to thermal stimuli as well as pain to percussion. The tooth was also categorized as having either reversible or symptomatic irreversible pulpitis based on strict definitions (AAE 2013) (Table 2). Further analysis of an intraoral periapical radiograph was carried out by the operator and later by a second evaluator to ascertain the depth of the lesion as being either "deep" or "extremely" deep caries. Although this did not alter the operative procedure, as all cases were treated by non-selective caries removal, this subdivision

TABLE 1 Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
- Patient aged 14–60 years	- Patient aged <14 or >60 years
- One tooth per patient	- Incisors or canines
- Premolar or molar tooth	- Absence of deep carious lesions radiographically
- Presence of a deep and extremely deep carious lesions on radiograph	- Preference: patient has moderate-severe pain and preferred root canal treatment
- Symptoms: range from mild, non-spontaneous pain to spontaneous severe pain	- Pregnant women
- Positive response to pulp sensibility test	- Negative response to vitality test
- Pulp exposure after non-selective caries removal	- Presence of "sound" dentine over pulp
	- Pulp not exposed intraoperatively
	- Pulpal haemorrhage could not be arrested
	- Pulp necrosis evident on exposure

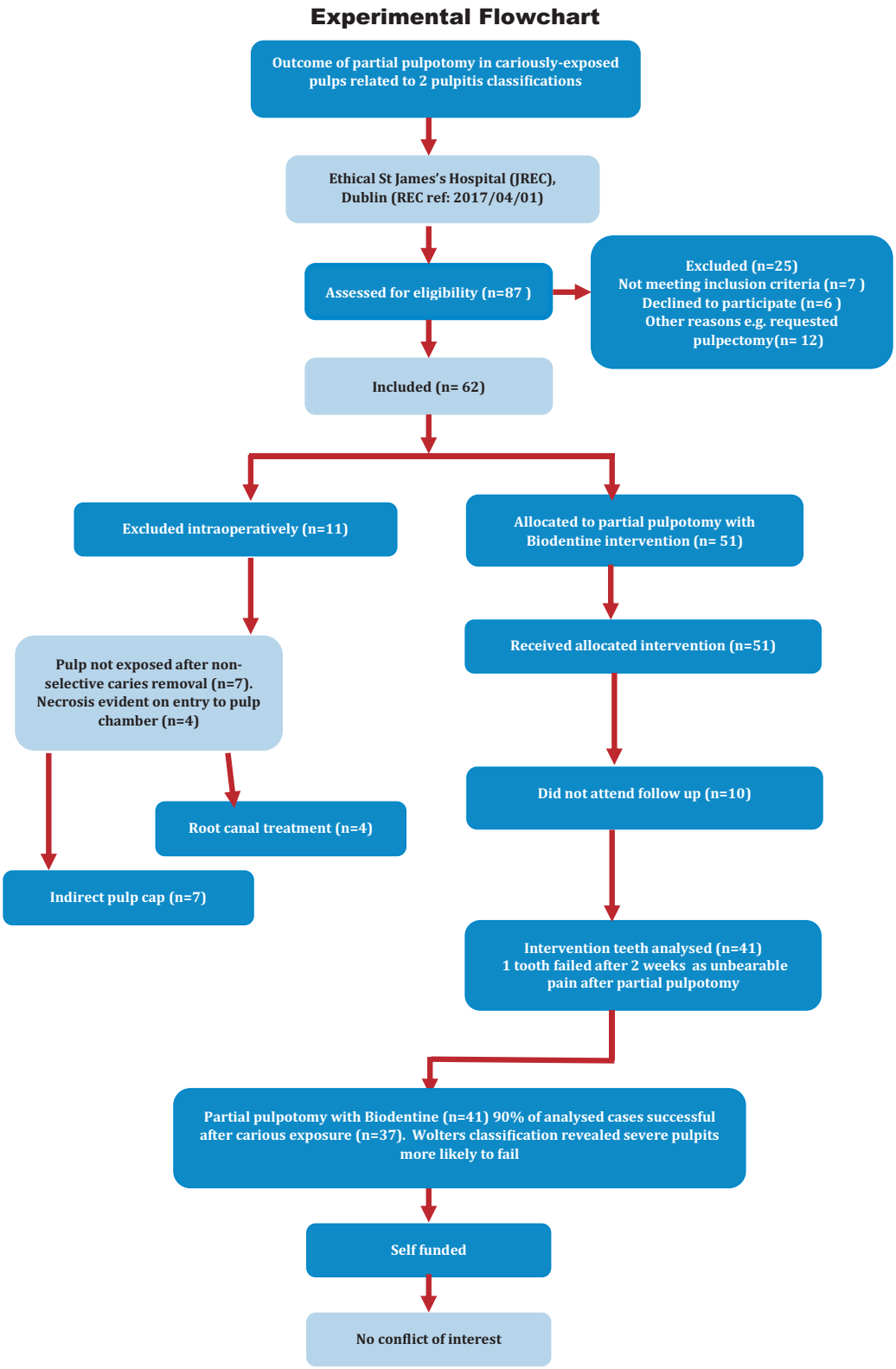

FIGURE 1 Experimental flow chart

facilitated later subanalysis of the results according to caries depth (Tables 3 and 4).

In order to assess preoperative pulp vitality, the teeth were isolated with cotton wool and dried prior to a −50°C thermal test (Endofrost; Roeko) being applied. After administration of the local anaesthetic (2% lignocaine hydrochloride with adrenaline 1:80 000), the tooth was isolated with rubber dam and liquid dam (Ena-dam; Micerium).

TABLE 2 Pulpal disease classification systems used

Wolters classification **Wolters et al. (2017)**	**Standard classification** **AAE Endodontic diagnosis (2013)**
Mild pulpitis: Heightened and lengthened reaction to cold, warm and sweet stimuli that can last up to 20 s, but then subsides. Tooth may be percussion sensitive. **Moderate pulpitis:** Clear symptoms, strong, heightened and prolonged reaction to cold, which can last for minutes, possibly percussion sensitive and spontaneous dull pain that can be suppressed with pain medication. **Severe pulpitis:** Severe spontaneous pain and clear pain reaction to warm and cold stimuli, often, sharp to dull throbbing pain, patients have trouble sleeping because of the pain (worsens when lying down). Tooth is sensitive to touch and percussion.	**Reversible pulpitis:** Discomfort triggered by cold/sweet stimuli, which relieves within seconds after the removal of the stimulus. The pain is non-spontaneous **Symptomatic irreversible pulpitis:** Sharp and lingering pain triggered by thermal stimulus (often 30 s or longer after stimulus removal), spontaneous pain and often referred pain. The pain can be accentuated by postural changes such as lying down or bending over and over-the-counter analgesics are typically ineffective.

Thereafter, the isolated area was cleaned using a cotton pellet soaked in 3% hydrogen peroxide followed by 0.2% chlorhexidine (Hörsted-Bindslev et al., 2003). Using an operative microscope (Labomed Prima; Labomed), the gross caries was non-selectively removed, initially using a diamond bur in a high-speed handpiece under water coolant, prior to using a sterile round steel bur in a slow handpiece. The absence of carious dentine was confirmed using FIND (Fluorescence Inspect and Determine system) present in Ledex WL90+ (DentMate). The area in closest proximity to the pulp was cleaned manually with a sharp hand excavator. If after non-selective caries removal, the pulp was exposed, a further 2–3 mm of pulp was removed with a fresh sterile carbide bur in a high-speed handpiece under abundant water coolant (Figure 2). After rinsing the pulp with NaOCl 2.5% solution, a cotton pellet soaked in a 2.5% NaOCl was pressed against the exposed pulp and haemostasis was checked every minute up to 6 min (Figure 2c). The time required for the pulpal tissue to stop bleeding was recorded.

Biodentine™ was mixed according to the manufacturer instructions and applied with gentle pressure directly onto the pulpal wound surface (Figure 2d) and used to fill the entire cavity and setting time of the material was recorded. Setting time was defined, as the time taken for the material to harden to the extent that light pressure with an amalgam plugger did not penetrate more than 1 mm. The patient was scheduled to return after 1 week, when 2–3 mm of the Biodentine™ restoration was removed and a permanent resin-based composite (RBC) restoration was placed (Figure 2e,f). Pulp sensibility (Endofrost) was checked at 1 week, 3 months, 6 months, 1 year and was considered positive if the patient consistently reported even mild sensitivity to cold. After 1 year, a periapical radiograph was taken with a 6-month radiograph taken in selected cases.

Preoperatively and post-restoration of the tooth, the colour of the crown was recorded on both the buccal and lingual aspect of the tooth. In order to standardize the conditions of light and visibility, the shade of the tooth was taken under magnification 10× and maximum light intensity using a microscope with LED white light (Labomed Prima) and the Vita Classic shading guide (VITA). During the subsequent follow-up appointments, discoloration was further monitored and recorded.

Outcome evaluation

At every follow-up appointment (1 week, 3, 6 and 12 months), the teeth were assessed for the presence of signs and symptoms of pulpitis, whilst pulp vitality was verified and recorded. This involved carrying out a percussion test and a cold test at −50°C (Endofrost). The integrity of the coronal restoration was verified visually under the microscope. After 12 months, a periapical radiograph supplemented the history and clinical examination. For practical reasons, the pulp sensibility testing was carried out by the practitioner; however, the 12-month radiographs were assessed blindly by a second evaluator (HD) not involved in the provision of treatment. At all review points, the teeth were categorized as either "successful," "unresponsive but successful" or "failed." Treatment was considered "successful" when the tooth responded positively (including a consistently reduced response) to cold test, the response did not linger, was symptom-free and not tender to percussion, and there was no evidence of an apical radiolucency. Unresponsive teeth that did not demonstrate any apical radiolucency and were symptom-free but did not respond to the cold tests were noted as "unresponsive but successful." A treatment failure was noted if either the patient reported pain, the tooth was tender to percussion and/or a periapical radiolucency was present.

Statistical analysis

Arrest of bleeding and Biodentine™ setting time were submitted to a Shapiro–Wilk test of normality ($p < .05$ samples are not normally distributed). A non-parametric

TABLE 3 Record of clinical features and 1-year success rate

Classification (number of cases)	Subdivision (number)	Bleeding time (average)	Tenderness to percussion (%)	Success at 1 year (%)	Success at 1 year (%) If unresponsive classed as failure
AAE (2013) (41)	Reversible pulpitis (18)	1 min 32 s	7/18 (39%)	13 Success 5 Unresponsive success (100%)	13 Success 5 Unresponsive failure (72%)
	Irreversible pulpitis (23)	1 min 37 s	19/23 (83%)	14 Success 5 Unresponsive success 4 Failures (83%)	14 Success 5 Unresponsive failure 4 Failures (61%)
Wolters et al. (2017) (41)	Mild (19)	1 min 9 s	7/19 (37%)	14 Success 5 Unresponsive success (100%)	14 Success 5 Unresponsive failure (74%)
	Moderate (17)	1 min 8 s	14/17 (82%)	11 Success 4 Unresponsive success 2 Failures (88%)	11 Success 4 Unresponsive failure 2 Failures (65%)
	Severe (5)	2 min 6 s	5/5 (100%)	2 Success 1 Unresponsive success 2 Failures (60%)	2 Success 1 Unresponsive failure 2 Failures (40%)

Kruskal–Wallis test was used to analyse differences in bleeding time between Wolter's diagnostic groups and Mann–Whitney *U*-tests were used to analyse bleeding time between reversible and irreversible pulpitis. The Wilcoxon rank-sum test was used for differences in setting time. Differences in the outcome of partial pulpotomy with each diagnosis of pulpitis were tested and cross-tabulated with contingency tables, chi-square analysis and Fisher's exact test. Data analysis used SPSS (v25; IBM) ($p < .05$). For radiographic caries, depth assessment interobserver agreement was calculated using Cohen's κ test (K) according to the scale for strength of agreement $K < 0.20$: poor, $K = 0.21$–0.40: fair, $K = 0.41$–0.60: moderate, $K = 0.61$–0.80: good, $K = 0.81$–1.00: very good (Altman, 1990).

TABLE 4 Cross-tabulation of pulpal classifications according to preoperative symptoms and tests

Pulpitis	Mild	Moderate	Severe	Total
Reversible	18	1	0	19
Irreversible	1	17	5	23
Total	19	18	5	

Note: This table highlights that by symptoms moderate and severe form effectively a sub-classification of irreversible pulpitis. $p < .001$ significant correlation between the two classification systems.

RESULTS

Sample characteristics

Eighty-seven patients were assessed for eligibility having presented with a symptomatic carious lesion in a premolar or molar tooth. Of those patients, 25 were excluded due to preferring RCT/extraction (12 patients), refusing to participate (6 patients) and not meeting inclusion criteria for deep/extremely caries (7 patients) (Figure 1). Sixty-two teeth were enrolled for this study and 11 were subsequently excluded intraoperatively. Of those 11 cases, seven (one with severe, two with moderate and four with mild pulpitis) did not have carious pulp exposure after non-selective removal of caries and they were treated either with RBC restorations or with an indirect pulp capping and a calcium hydroxide lining (Figure 3a,b). Subsequently, one of the teeth without pulp exposure but with a diagnosis of moderate pulpitis required RCT after 5 months as it displayed signs of pulpal necrosis and apical radiolucency. Of the remaining 4 cases, one case provisionally diagnosed with mild pulpitis and three cases with severe pulpitis were treated immediately with RCT as after access to the pulp chamber partial pulpal necrosis was diagnosed (Figure 3c,d).

Fifty-one teeth were finally included and treated within this study, with 41 teeth reviewed after 1 year (Figure 1). The diagnostic breakdown of the initial sample by Wolters criteria (Wolters et al., 2017) includes five cases of severe pulpitis, 22 of moderate pulpitis and 24 with mild pulpitis. By the traditional AAE pulpal diagnostic system, there were 23 reversible pulpitis and 28 irreversible pulpitis (AAE, 2013). All the cases were treated with partial pulpotomy (removal of 3–4 mm pulp tissue), rinsed with 2.5% NaOCl and capped with Biodentine™. All treated patients reported mild postoperative discomfort on the day of the treatment, which was managed with "over the counter" analgesics as required. Postoperative pain generally disappeared within 24 h; however, in the 7 days following the procedure more than 50% of the sample reported an increased sensitivity to cold stimuli that gradually subsided during the following 3 months. One patient with irreversible/ severe pulpitis developed unbearable pain within a week and had a pulpectomy carried out which was categorized as failure; this was the only painful failure within the 1-year period. Ten patients did not re-attend for 1-year review and were excluded from the study (5 reversible, 5 irreversible pulpitis; 5 moderate, 5 mild pulpitis) (Figure 1). Specifically, four of the ten patients did not attend the second appointment for permanent filling placement; however, they subsequently attended the clinic as an emergency presenting with pain and sensitivity due to dislodgement of the Biodentine™ restoration. All four teeth had subsequent RCT. The remaining 6 patients returned to get the permanent restoration placed, but not the subsequent 1-year review.

Generally, the response to pulp sensibility testing was less intense after treatment. As a result, in four cases because of lack of response at the second appointment, the permanent filling was performed without administering local anaesthetic and the cold test was repeated after removing part of the Biodentine™; the response was positive in all four cases. Three patients were initially classified as unresponsive, but at the subsequent review appointment at 6 months demonstrated a mild response to a cold test. The visualization of a hard tissue bridge radiographically was a variable finding being present on only 12 postoperative review radiographs at 1 year (Figure 4). Two consecutive patients, one 15-year-old and one 16-year-old patient presented with deep carious lesions in two mandibular second molar teeth (Figure 5), which after completion of partial pulpotomy remained responsive to pulp sensibility testing at review. The mandibular left second molar in the 15 years old, although remaining positive to sensibility testing developed internal resorption in the middle third

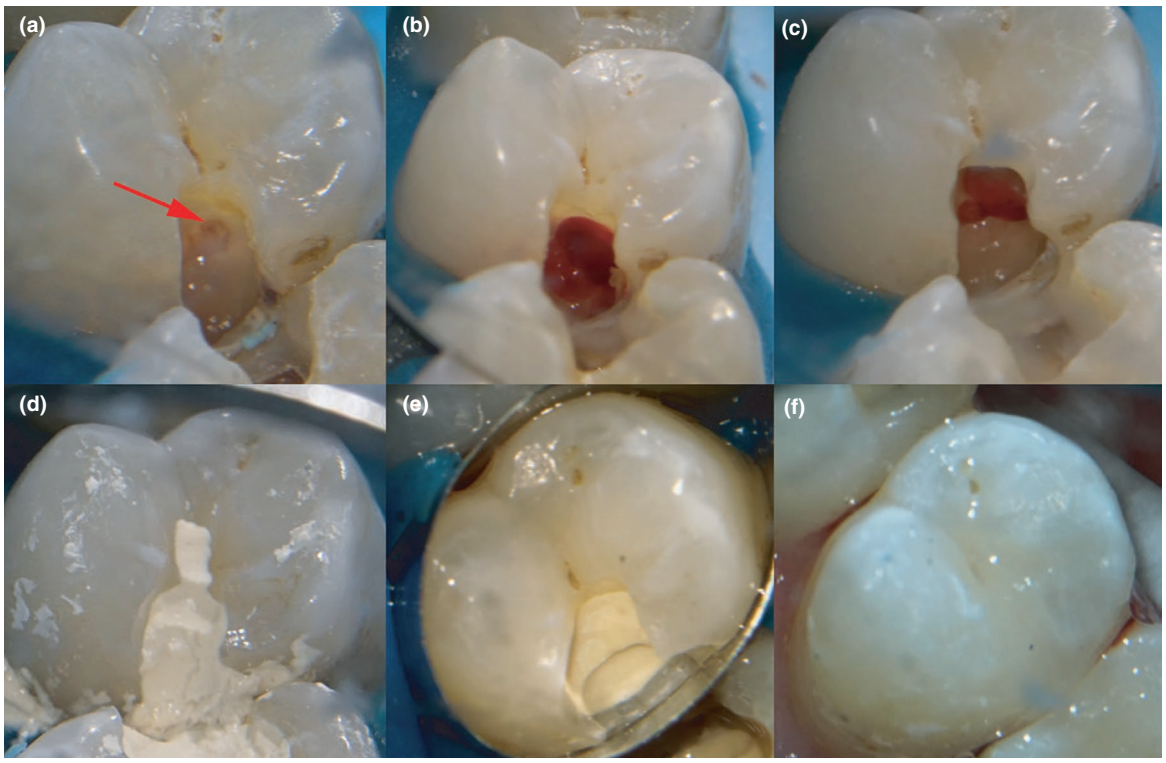

FIGURE 2 Partial pulpotomy clinical protocol. (a) Pulp exposure after non-selective caries removal (red arrow). (b) Superficial pulp tissue removed (to depth of 2–3 mm). Pulpal haemorrhage evident. (c) Haemostasis obtained after several minutes by placing cotton pellet soaked in 2.5% NaOCl, pressed against the exposed pulp tissue. (d) Biodentine™ used to restore the entire cavity. (e) Superficial removal of Biodentine™ at the second visit 1 week later. At least 3 mm of material is left above the exposure site before restoration. (f) Tooth permanently restored with resin-based composite material

of both the mesial and distal roots and was classified as a treatment failure (Figure 5f).

Outcome

For the 41 patients attending at 1-year review, of the 19 mild pulpitis cases treated, 14 were deemed successful and five unresponsive but successful, whilst of the 17 cases of moderate pulpitis 12 were considered successful, three unresponsive but successful with two failures. For teeth presenting with severe pulpitis, two cases were considered as success, one was unresponsive but successful and two failed (one within a week) (Table 3). Grouping success and unresponsive but successful, the outcome for partial pulpotomy at 1 year was 90%. Relating outcome to preoperative diagnosis, revealed that teeth with reversible pulpitis and pulp exposure treated by partial pulpotomy were 100% successful and irreversible pulpitis 78% successful at 1 year. Using Wolters classification, a preoperative diagnosis of mild pulpits was 100% successful, 88% moderate pulpitis successful and severe pulpitis 60% successful at 1 year. If the results are reconsidered and unresponsive is a failure, reversible pulpits were 72% successful and irreversible pulpitis cases 61% successful at 1 year, whilst using Wolters classification mild pulpitis was 74%, moderate pulpitis 65% and severe pulpitis 40% successful (Table 3).

The 1-year outcome with unresponsive considered a *success* was compared between groups classified as being reversibly and irreversibly inflamed, with no significant difference being reported ($p = .32$). Outcomes at 1 year were also compared using the three Wolters diagnostic groups with no significant difference between "mild" and "moderate" pulpitis ($p = .49$) and "moderate" and "severe" pulpitis groups ($p = .19$). When "mild" and "severe" pulpitis success rates were compared at 1 year, the "mild" group had a significantly better outcome than the "severe" pulpitis group ($p = .04$). When unresponsive was a reconsidered, a *failure* overall success dropped to 66% at 1 year; however, there were no significant differences between reversible and irreversible cases ($p = .52$) and any of the "mild," "moderate" or "severe" groups ($p > .28$) (Table 3). Notably, when the two classification systems were cross-tabulated according to symptoms (Table 4), it can be seen that whilst there was good correlation between the classification systems ($p < .001$), moderate and severe pulpitis essentially represented a subdivision of irreversible pulpitis;

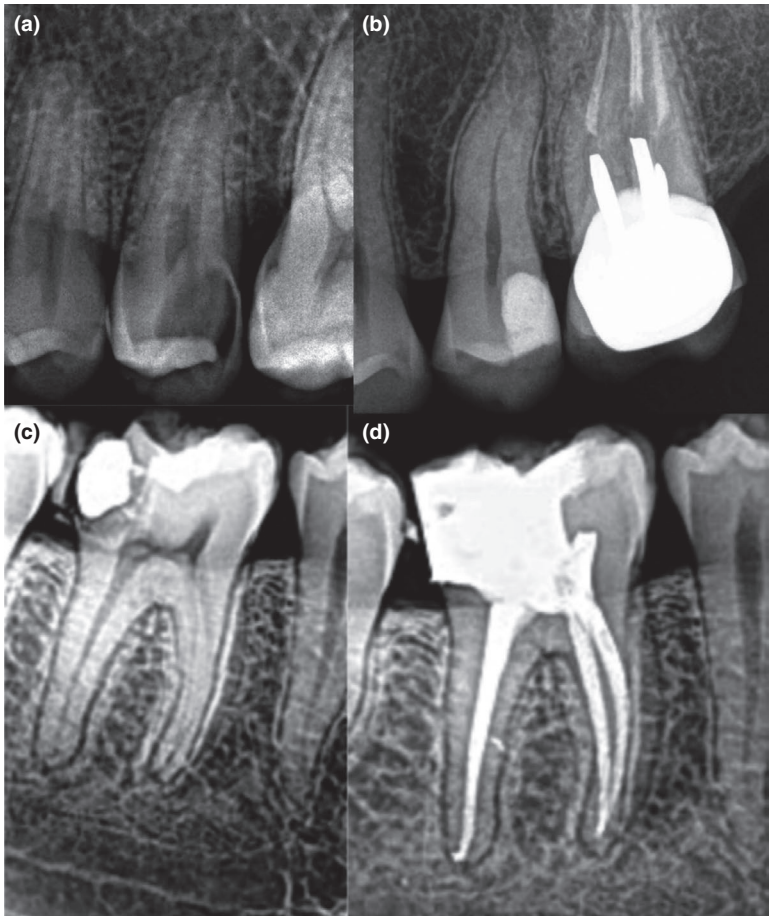

FIGURE 3 Deep carious lesions that were excluded from the study. (a) Preoperative view of an upper left second premolar with a deep carious lesion, which after non-selective removal did not have a pulp exposure. (b) Postoperative view of another upper left second premolar in which the pulp was not exposed after non-selective caries removal and was treated with indirect pulp capping. (c) Tooth 46 responsive to vitality test presenting a deep carious lesion. (d) Same tooth in figure c treated with RCT and temporary restored with glass–ionomer as presenting clear signs of necrosis were evident in the exposed pulp tissue on visual inspection

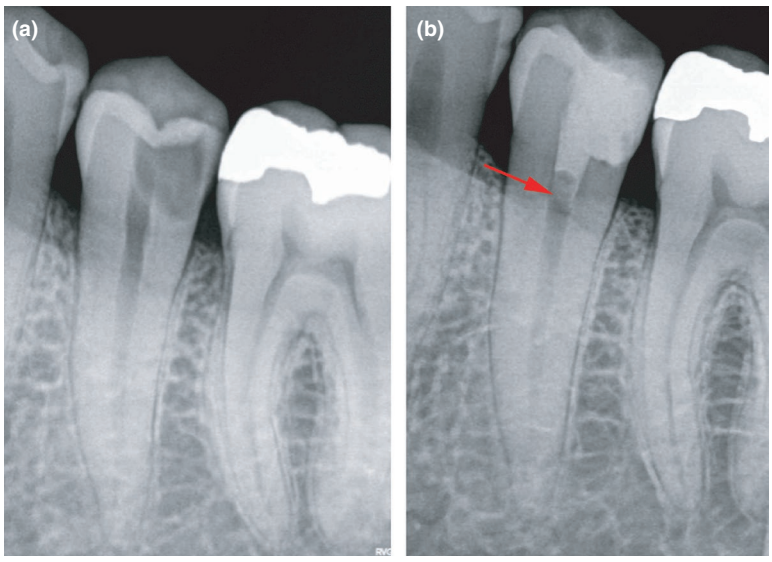

FIGURE 4 Lower left second premolar presented with moderate (irreversible) pulpitis treated with partial pulpotomy using Biodentine™. (a) Preoperative periapical radiograph of the tooth with coronal radiolucency indicative of extremely deep caries. (b) Twelve-month radiographic evaluation showing hard tissue bridge formation (red arrow). The tooth responded positively to pulp sensibility testing and was asymptomatic

with the subdivision related to treatment outcome with 12% failure in the moderate pulpitis group and 40% in the severe pulpitis group at 1 year (Table 3).

The time taken for pulpal haemostasis ranged from 1 to 4 min. In all cases, pulpal haemorrhage could be arrested. Notably, there was only a small difference between the average duration of bleeding for mild and moderate pulpitis (mild pulpitis—average 1 min 9 s; moderate pulpitis—average 1 min 8 s); however, bleeding time was increased in the cases with severe pulpitis to an average of 2 min 6 s (Table 3). This difference between the groups was not significant ($p = .26$). There was also no significant association between outcome and time to achieve haemostasis ($p = .6$). Although all severe pulpitis cases were tender to percussion, compared with

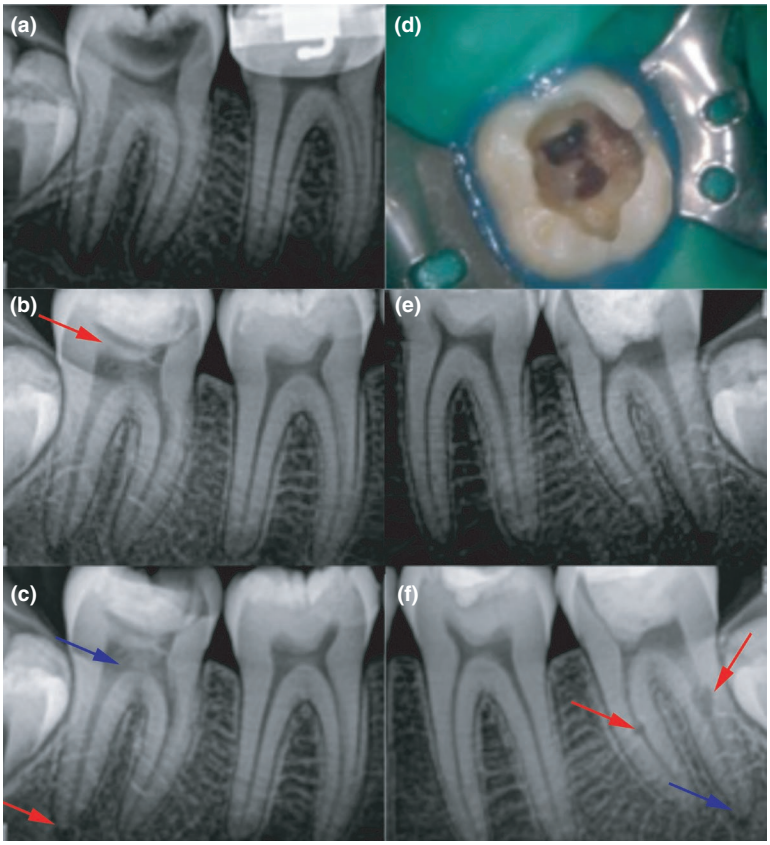

FIGURE 5 Two separate patients presented with extremely deep carious lesions on teeth 47 and 37, respectively. Both teeth treated with partial pulpotomy using Biodentine™. (a) Deep carious lesion on tooth 47 presented with discomfort. (b) Six months after partial pulpotomy hard tissue bridge evident (red arrow). Pulp sensibility testing confirmed a positive response. (c) Twelve months after partial pulpotomy, there is no evidence of an emerging radiolucency (red arrow). Presence of radiopaque material indicative of ectopic hard tissue deposition in pulp chamber (blue arrow). (d) Deep carious lesion removal and partial pulpotomy procedure on tooth 37. (e) At 3 months, sensibility was maintained at a positive reading and there are no adverse signs or symptoms. (f) Twelve months after partial pulpotomy, the tooth responded to pulp sensibility tests, no evidence of an emerging radiolucency (blue arrow), but areas of internal resorption were evident in the 37 (red arrow) denoting treatment failure

82% of samples with moderate pulpitis and 37% of cases with mild pulpitis (Table 3), there was no significant correlation between tenderness and increased failure rate ($p = .61$).

The results were subdivided by preoperative caries depth (judged radiographically) into "deep" and "extremely" deep caries where it can be seen the majority of cases included in the study were "extremely deep" ($n = 50$), rather than "deep" ($n = 12$) caries (Table 5). Of the 12 "deep" cases, 7 were later excluded as the pulp was not exposed after non-selective caries removal, whilst all the "extremely" deep cases were exposed; 4 were excluded as the pulp was necrotic on entry to the pulp chamber. The 4 deep "caries" cases were all successful, albeit one case with irreversible/moderate pulpitis was unresponsive to sensibility testing, whilst all 5 failures presented within the "extremely" deep caries group (Table 5). The two "blinded" evaluators demonstrated a moderate level of agreement in assessing caries depth from an intraoral periapical radiograph ($\kappa = 0.57$).

This study was designed as a single-visit partial pulpotomy procedure with a second visit scheduled 1–2 weeks later for permanent restoration placement. Restoration of the entire cavity with Biodentine™ is recommended by the manufacturers (Septodont); however, this is reliant on the material setting. In only two cases did the material set within the manufacturer's stated time of 12 min, with one case taking 45 min to set. The average setting time for Biodentine™ was 22 min. A Wilcoxon rank-sum test revealed between the average setting time to be significantly different from the manufacturer's claim ($p < .05$). In all 41 cases reviewed at 1 year, no visual discolouration of tooth substance was detected.

DISCUSSION

Partial pulpotomy is defined as the removal of a small portion of coronal pulp tissue after exposure, followed by

TABLE 5 Cases subdivided on caries depth (deep or extremely deep)

Cases meeting inclusion criteria	Subdivision due to caries depth (number)	Exclusions (reason)	Number enrolled	Number reviewed (reason for drop out)	Preoperative diagnosis	Outcome (success %)
62	Deep (12)	7 (non-selective caries removal not exposed)	5	4 (1 did not attend follow-up)	*Reversible*: 3 *Irreversible*: 1	*Reversible*: 3 Success (100%) *Irreversible*: 1 Unresponsive success (100%)
					Mild: 3 *Moderate*: 1 *Severe*: 0	*Mild*: 3 Success (100%) *Moderate*: 1 Unresponsive success (100%) *Severe*: 0
	Extremely deep (50)	4 (necrotic on entry to pulp)	46	37 (9 did not attend follow-up)	*Reversible*: 15 *Irreversible*: 22	*Reversible*: 10 Success; 5 Unresponsive success (100%) *Irreversible*: 14 Success; 4 Unresponsive success; 4 Failures (82%)
					Mild: 16 *Moderate*: 16 *Severe*: 5	*Mild*: 11 Success; 5 Unresponsive success (100%) *Moderate*: 11 Success; 3 Unresponsive success, 2 Failures (87%) *Severe*: 2 Success, 1 Unresponsive success, 2 Failures (60%)

Note: Unresponsive cases were classed as a success.

application of a biomaterial directly onto the remaining pulp tissue prior to placement of a permanent restoration (ESE, 2019). Partial pulpotomy has been advocated as the preferred treatment for cariously exposed pulp tissue as it removes both the biofilm on the surface of the pulp tissue and the superficially inflamed pulp and it has been recognized as suitable treatment for permanent teeth with signs of pulpitis and even irreversible pulpitis (Massler, 1959; Taha & Khazali, 2017). It has been advocated as a possible management strategy for young cariously exposed teeth with no clinical symptoms, with success in excess of 90% reported at 1 year for cases treated with partial pulpotomy and capped with calcium hydroxide (Mejàre & Cvek, 1993; Zilberman et al., 1989). Indeed, the results of this study using HCSC in a range of ages are in accordance with the outcome of these studies (Mejàre & Cvek, 1993; Zilberman et al., 1989) highlighting an overall success of 90% for partial pulpotomy after carious exposure, but with associated symptoms. Indeed, the high rate of success in the current study may be partly attributed to the use of an enhanced technique using an operating microscope, disinfection of the pulpal wound, strict asepsis using rubber dam and placement a HCSC in what has been described as a class II VPT procedure (Bjørndal et al., 2019).

A principal problem of treating particularly deep, and to a lesser extent, extremely deep caries is the decision as to whether carious dentine should be left in a one visit or stepwise excavation technique with the avoidance of pulp exposure (Bjørndal et al., 2010, 2019); or whether the carious dentine should be completely removed and the pulp exposure examined and managed (Ricucci et al., 2020). In this study, all teeth presented with symptoms associated with a deep or extremely carious lesion, so a decision was made to non-selectively remove the carious tissue in all cases. Although this could be considered overtreatment by some (Schwendicke et al., 2016), others have reported excellent outcome by non-selective carious removal and careful restoration of the exposed pulp (Marques et al., 2015). Notably, in the current study all teeth were symptomatic so partial pulpotomy was selected and both deep and extremely deep caries groups were included. Indeed, only cases that were not exposed after non-selective removal were treated by indirect pulp capping and excluded from the study even though they were symptomatic. This was carried out for methodological reasons as within the design it was critical that "sound" dentine was not breached in order to expose the pulp. Interestingly, 2 moderate and 1 severe pulpitis (or 3 irreversible pulpitic teeth) were contained within this group and although one case of moderate pulpitis failed, the other two cases did not fail within the designated review period. It may be stressed, however, that these cases were not included within the review protocol and the outcome of indirect pulp capping in symptomatic pulpitis was not an aim of this study. Nonetheless, it is an interesting observation that warrants future study. Further subanalysis of the results highlights that the majority of the included cases were extremely deep (90%) rather than deep caries. This likely represents an increased chance of extremely deep caries being symptomatic, which was an inclusion criterion for this study. Notably, all extremely deep cases were exposed, whilst only 42% of the deep cases were exposed after non-selective removal and all failure cases were in the extremely deep caries group highlighting the importance of caries depth in the outcome of VPT (Bjørndal et al., 2019). Two experienced dentists, independently and blinded to outcome evaluated the radiograph dividing them into deep and extremely deep caries with a moderate level of inter-operative agreement ($\kappa = 0.57$). This agreement may have been expected to be higher, but perhaps reflects the difficulty (and arbitrary nature) of objectively analysing a two-dimensional radiograph and separating into distinct categories, particularly for borderline cases as well as periapical radiograph distortion. In this study, discussion afterwards resulted in consensus regarding the depth of caries. Finally, all the failure cases occurred in the extremely deep caries group, which highlights the potential prognostic benefit of establishing and recording radiographic caries depth preoperatively.

As a result of an improved understanding of the pulp's response to injury (Smith et al., 2016) and the advent of HCSCs such as MTA and Biodentine™, there has been renewed interest and improved outcomes in the area of conservative treatment of pulp exposure (Aeinehchi et al., 2003; Nair et al., 2008; Parirokh et al., 2017). However, a continual challenge for strategies aimed at preserving the pulp is the establishment of an accurate assessment of the clinical features that reflect the "true" histological condition of the pulp, as it has been shown that infection and inflammation reduce the outcome of the therapy (Al-Hiyasat et al., 2006). It has long been considered that the correlation between signs and symptoms of pulpitis and histological cell infiltrate was poor (Dummer et al., 1980); however, a recent study highlighted a good association between symptoms and histological status of pulpitis (Ricucci et al., 2014). The finding that inflammation is generally localized to the area sub-adjacent to the carious lesion stimulated new research into the preservation of pulp tissue and conservative management in cases with reversible and irreversible pulpitis (Simon et al., 2013). Indeed, even more recent data on the histological and bacterial profile of the carious teeth in advance stages of disease could also support the data that inflammation is localized to the pulp chamber and relates to the carious lesion penetration, whilst underlining the importance of caries depth (Demant et al., 2021).

In the current pragmatic study carried out in one general dental practice, partial pulpotomy was generally effective with an overall success rate of 90% with only one painful failure occurring within the year-long review. These results differ from a recent study investigating pulp capping of asymptomatic carious exposures with HCSC, which reported a high level of early failure (Ballal et al., 2020). This can perhaps be explained by the fact that all pulpal wounds within this study were washed with NaOCl, which has been shown to reduce painful failure in the study (Ballal et al., 2020) and also that partial pulpotomy was used rather than simply pulp capping, a technique that removes the superficially inflamed and infected dentine and pulp tissue and is recommended for procedures with increased pulpal damage (ESE, 2019).

As a result of the success of VPT procedures being advocated in cases of irreversible pulpitis, a new classification system has been proposed and linked to treatment indications (Wolters et al., 2017). The diagnostic system proposed by Wolters and co-workers was used in this study as a way of investigating how the nature and severity of symptoms affected outcome. The influence of exposure on the outcome of VPT remains controversial with multi-centre trial evidence reporting a negative prognostic effect (Bjørndal et al., 2010), whilst several principally single-arm studies carried out in Endodontic practice reporting high VPT success after carious exposure (Bogen et al., 2008; Marques et al., 2015; Taha & Khazali, 2017). In this study of symptomatic teeth, it was elected to non-selectively remove all carious dentine in every case and if the pulp was exposed carry out a partial pulpotomy. This approach was previously adopted when treating both symptomatic and asymptomatic teeth with partial pulpotomy (Mejàre & Cvek, 1993).

Any classification of pulpitis should ideally guide a subsequent decision as to whether the pulp can be maintained; however, the task of accurately ascertaining whether the pulp is actually irreversibly inflamed remains a significant challenge (Bjørndal et al., 2019; Mejáre et al., 2012). Multiple recent reports highlighting high success rates for partial and full pulpotomy in teeth with signs and symptoms of irreversible pulpitis (Simon et al., 2013; Taha & Khazali, 2017; Uesrichai et al., 2019) underline the need for a more sensitive classification of pulpal disease. This need has stimulated research groups to suggest new classifications or subdivisions of pulpitis that may be more reflective of the likelihood of the pulp to respond to conservative treatment (Hashem et al., 2015; Wolters et al., 2017). One such classification (Wolters et al., 2017) divided pulpitis into four practical categories, three of which were associated with symptoms. On closer examination (Table 2), two of Wolters proposed groups moderate and severe pulpitis simulate a division of the AAE irreversible pulpitis group (AAE, 2013; Wolters et al., 2017). The current study demonstrates that such a division may be helpful in predicting which cases are likely to fail after treatment as the severe group had significantly more failure (60% successful) than the mild group; however, the moderate group was not significantly different from the mild group. Notably, these differences were lost when the broader descriptor irreversible pulpitis was employed. This offers the potential for symptoms and the use of Wolters subdivisions to offer a prognostic guide for clinicians when deciding whether to embark on VPT. Indeed, within the limitations of this work subdivision of patient preoperative symptoms was a more useful indicator of success than preoperative features such as TTP or the intraoperative assessment of pulpal haemostasis. Furthermore, the increased complexity by adding more divisions to the new classification system was considered simple to use and in practical terms only involved small extensions to existing pain history relating to the nature and duration of the pain (Table 2).

Bleeding has long been considered important to both the success and practicality of VPT (Accorinte et al., 2008; Matsuo et al., 1996). Recently, time to arrest haemorrhage was highlighted as a potential prognostic indicator in primary teeth (Mutluay et al., 2018). In the current study, variation in bleeding was evident with copious haemorrhage evident in teeth displaying very mild symptoms, and alternatively symptomatic teeth displaying only a small amount of bleeding. Although bleeding time was increased in severe and irreversible pulpitis categories (Table 3), there was no significant correlation between bleeding time and outcome. Clearly uncontrolled haemorrhage can indicate a severely damaged pulp as well as influencing the placement of certain restorative materials, for example resin-based materials (Accorinte et al., 2008); however, this may not be so critical for hydrophilic materials such as HCSCs. Notably, in this study there were no cases in which the bleeding could not be arrested prior to material placement.

When considering the clinical features to assess pulpitis, it was decided to use the most reliable findings in order to label the teeth. Indeed, pain and response to vitality test were the principal characteristics assessed. It is difficult to predictably quantify the level of TTP, so this variable was dichotomized into TTP positive or negative. Surprisingly, TTP was frequently evident in mild and moderate pulpitis, whilst it was present in all severe pulpitis cases; however, its preoperative presence was not significantly linked to failure in this study. An unusual finding in this study was the fact that 10 patients (1 deep and 9 extremely deep caries [Table 5]) were unresponsive to pulp sensibility testing after 1 year, which is at odds with previous partial pulpotomy studies using cold

testing (Taha & Khazali, 2017), which did not highlight this as a feature in their results. Within this study, these cases were grouped as a success as there was no sign of an emerging apical radiolucency or other sign of failure, which in line with a recent ESE position statement (ESE, 2019). Interestingly, pulp sensibility responses were temporarily lost in several cases, which is relatively common after dental trauma (Bastos et al., 2014). Longer term follow-up demonstrated recovery in the majority of cases, highlighting the necessity for continuing review (ESE, 2019). However, it is conceded that tooth sensibility tests may have been restored in more cases if the follow-up had been extended to 2 years. Success in this study was a composite measure of patient-reported and clinician-reported outcomes (Duncan et al., 2021), that included signs and symptoms of failure, response to pulp sensibility testing (responsive/ unresponsive) and radiographic analysis. It is possible that even in the absence of signs, symptoms and radiographic apical breakdown that the pulp may be necrotic and for this reason the results were recalculated as a "worst-case" scenario with all "non-responsive" cases having failed (Table 3). If unresponsive cases are considered as a failure, the overall success of partial pulpotomy after 1 year drops to 66%; however, the same trends related to pulp classification are evident with mild pulpitis 84%, moderate pulpitis 71% and severe pulpitis 40% successful, respectively. The problem with reliable sensibility testing after VPT although, not previously highlighted in partial pulpotomy studies of symptomatic cases (Taha & Khazali, 2017), has been highlighted as a concern after complete pulpotomy in the recent deep caries position statement, which suggested that a positive responsive to sensibility testing was unlikely in these cases (ESE, 2019).

Ten of the 51 included teeth were excluded because they failed to attend recall appointments or have the definite restoration placed (19.5% drop out). Of the 10 exclusions, four attended the clinic in pain within 6 months and were managed with RCT. In all four cases, the patient did not return for the second visit as planned, and after several months, the pulp was necrotic and the Biodentine™ was dislodged. These anecdotal data question the manufacturer's claims that the material is suitable as a long-term temporary restorative material. In one molar, internal resorption was evident in both roots, which although the tooth was otherwise a success this is still classed as an unusual type of failure (ESE, 2006).

Biodentine™ is marketed as a single-visit VPT material with a setting time that should be 12 min. Mixing and dispensing the material according to the manufacturer instructions did not prevent differences in the consistency of the Biodentine™ once the mixing process was complete. Some samples demonstrated a "creamy" aspect whilst some others had a dry and brittle consistency. Once placed in the cavity, Biodentine™ assumed a soft and flowable consistency. The material generally took significantly longer to set than would be practical in one session with an average setting time of 22 min, which is almost double the manufacturers indicated time. As VPT is often carried out as an emergency procedure, the potential attractiveness of a single-visit treatment is considerable; however, a longer setting time may lead to the dentist to opt for a two-stage procedure, reducing the advantage of Biodentine™ over the classic formulation of MTA (which sets in several hours). Notably, Biodentine™ was not associated with any postoperative discolouration or staining which have been a feature of other MTA materials (Camilleri, 2015). With the limitations of this study, the results confirm the studies carried out on Biodentine™ discolouration (Camilleri, 2015; Kohli et al., 2015; Yoldaş et al., 2016).

Although this work is the first to analyse the effectiveness of a new classification of pulp condition, it has certain limitations. The study had only one operator, which although reducing intraoperative variability and increasing practicality, as it was set in primary care, does reduce generalizability of the data as only one individual carried out the operator elements of the work. In order to reduce potential bias, the radiographs were blinded and assessed by a second operator; however, for practical reasons the review appointments were carried out by the operator. It is accepted that larger studies with multiple operators will be required in the future to verify the results of this study. Furthermore, there was no control group in the study as the study was designed as an outcome study to assess the relative effectiveness of a new pulp classification to which the patients could not be randomized. Finally, Wolters and co-workers designed a new classification system as part of an overall strategy to guide subsequent endodontic management (Wolters et al., 2017). In the current study, the management recommendations were not followed and every pulp that was exposed after non-selective caries removal was treated by partial pulpotomy. Although this limits the applicability of the management arms of that study, it was carried out to limit bias and allow comparison of the management of the exposed pulp using two differ pulpal diagnosis classifications.

CONCLUSIONS

Partial pulpotomy using Biodentine™ was successful in 90% of analysed cases for the treatment of symptomatic carious exposures of the pulp after 1 year, but included cases where pulp vitality could not be confirmed. Within the limitations of this study, it can be concluded that cases with signs and symptoms indicative of irreversible pulpitis were as successful as cases with reversible pulpitis;

however, using Wolters classification cases with severe pulpitis all presented with extremely deep caries and were significantly less successful than cases with mild pulpitis, which highlights a potential prognostic benefit in diagnostically subdividing cases with more severe symptoms. Bleeding time and tenderness to percussion were not significant indicators of the outcome of partial pulpotomy procedure and although Biodentine™ did not induce discolouration after 1 year, the setting time was significantly longer than the manufacturers claim.

CONFLICT OF INTEREST

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

AUTHOR CONTRIBUTIONS

RC carried out all experimental work and review of patients as well as drafting parts of the manuscript. HD planned study, assess radiographs, drafted and edited sections of the manuscript.

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REFERENCES

Accorinte, M.L.R., Loguercio, A.D., Reis, A. & Costa, C.A.S. (2008) Response of human pulps capped with different self-etch adhesive systems. *Clinical Oral Investigations*, 12, 119–127.

Aeinehchi, M., Eslami, B., Ghanbariha, M. & Saffar, A.S. (2003) Mineral Trioxide Aggregate (MTA) and calcium hydroxide as pulp-capping agents in human teeth: a preliminary report. *International Endodontic Journal*, 36, 225–231.

Al-Hiyasat, A.S., Barrieshi-Nusair, K.M. & Al-Omari, M.A. (2006) The radiographic outcomes of direct pulp-capping procedures performed by dental students: a retrospective study. *Journal of the American Dental Association*, 137, 1699–1705.

Altman, D.G. (1990) *Practical statistics for medical research*. London: Chapman and Hall/CRC Texts in statistical science.

American Association of Endodontists (2013) Endodontic Diagnosis. [WWW document]. Available at: https://www.aae.org/specialty/wp-content/uploads/sites/2/2017/07/endodonticdiagnosisfall2013.pdf [Accessed 8th April 2021].

Ballal, N.V., Duncan, H.F., Rai, N., Jalan, P. & Zehnder, M. (2020) Sodium hypochlorite reduces postoperative discomfort and painful early failure after carious exposure and direct pulp capping-initial findings of a randomized controlled trial. *Journal of Clinical Medicine*, 9, 2408.

Bastos, J.V., Goulart, E.M. & de Souza Côrtes, M.I. (2014) Pulpal response to sensibility tests after traumatic dental injuries in permanent teeth. *Dental Traumatology*, 30, 188–192.

Bjørndal, L., Reit, C., Bruun, G., Markvart, M., Kjaeldgaard, M., Näsman, P. et al. (2010) Treatment of deep caries lesions in adults: randomized clinical trials comparing stepwise vs. direct complete excavation, and direct pulp capping vs. partial pulpotomy. *European Journal of Oral Sciences*, 118, 290–297.

Bjørndal, L., Simon, S., Tomson, P.L. & Duncan, H. (2019) Management of deep caries and the exposed pulp. *International Endodontic Journal*, 52, 949–973.

Bogen, G., Kim, J.S. & Bakland, L.K. (2008) Direct pulp capping with mineral trioxide aggregate: an observational study. *Journal of American Dental Association*, 139, 305–315.

Camilleri, J. (2015) Staining potential of neo MTA plus, MTA plus, and biodentine used for pulpotomy procedures. *Journal of Endodontics*, 41, 1139–1145.

Careddu, R. & Duncan, H. (2018) How does the pulpal response to Biodentine and ProRoot mineral trioxide aggregate compare in the laboratory and clinic? *British Dental Journal*, 225, 743–749.

Chailertvanitkul, P., Paphangkorakit, J., Sooksantisakoonchai, N., Pumas, N., Pairojamornyoot, W., Leela-apiradee, N. et al. (2014) Randomized control trial comparing calcium hydroxide and mineral trioxide aggregate for partial pulpotomies in cariously exposed pulps of permanent molars. *International Endodontic Journal*, 47, 835–842.

Cushley, S., Duncan, H.F., Lappin, M.J., Tomson, P.L., Lundy, F.T., Cooper, P. et al. (2019) Pulpotomy for mature carious teeth with symptoms of irreversible pulpitis: a systematic review. *Journal of Dentistry*, 88, 1031–1058.

Demant, S., Dabelsteen, S. & Bjørndal, L. (2021) A macroscopic and histological analysis of radiographically well-defined deep and extremely deep carious lesions: carious lesion characteristics as indicators of the level of bacterial penetration and pulp response. *International Endodontic Journal*, 54, 319–330.

Dummer, P.M.H., Hicks, R. & Huws, D. (1980) Clinical signs and symptoms in pulp disease. *International Endodontic Journal*, 13, 27–35.

Duncan, H.F., Cooper, P.R. & Smith, A.J. (2019) Dissecting dentine-pulp injury and wound healing responses: consequences for regenerative endodontics. *International Endodontic Journal*, 52, 261–266.

Duncan, H.F. & Cooper, P.R. (2020) Pulp innate immune defense: translational opportunities. *Journal of Endodontics*, 46, S10–S18.

Duncan, H.F., Nagendrababu, V., El-Karim, I.A. & Dummer, P.M.H. (2021) Outcome measures to assess the effectiveness of endodontic treatment for pulpitis and apical periodontitis for use in the development of European Society of Endodontology (ESE) S3 level clinical practice guidelines: a protocol. *International Endodontic Journal*, 54, 646–654.

Elmsmari, F., Ruiz, X.F., Miró, Q., Feijoo-Pato, N., Durán-Sindreu, F. & Olivieri, J.G. (2019) Outcome of partial pulpotomy in cariously exposed posterior permanent teeth: a systematic review and meta-analysis. *Journal of Endodontics*, 45, 1296–1306.

European Society of Endodontology (ESE) developed by, Duncan, H.F., Galler, K.M., Tomson, P.L., Simon, S., El-Karim, I., et al. (2019) European Society of Endodontology position statement: Management of deep caries and the exposed pulp. *International Endodontic Journal*, 52, 923–934.

European Society of Endodontology (2006) Quality guidelines for endodontic treatment: consensus report of the European Society of Endodontology. *International Endodontic Journal*, 39, 921–930.

Farges, J.-C., Alliot-Licht, B., Renard, E., Ducret, M., Gaudin, A., Smith, A.J. et al. (2015) Dental pulp defence and repair

mechanisms in dental caries. *Mediators of Inflammation*, 2015, 230251.

Harms, C.S., Schäfer, E. & Dammaschke, T. (2019) Clinical evaluation of direct pulp capping using a calcium silicate cement-treatment outcomes over an average period of 2.3 years. *Clinical Oral Investigations*, 23, 3491–3499.

Hashem, D., Mannocci, F., Patel, S., Manoharan, A., Brown, J.E., Watson, T.F. et al. (2015) Clinical and radiographic assessment of the efficacy of calcium silicate indirect pulp capping: a randomized controlled clinical trial. *Journal of Dental Research*, 94, 562–568.

Hörsted-Bindslev, P., Vilkinis, V. & Sidlauskas, A. (2003) Direct capping of human pulps with a dentin bonding system or with calcium hydroxide cement. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, Endodontics*, 96, 591–600.

Kohli, M.R., Yamaguchi, M., Setzer, F.C. & Karabucak, B. (2015) Spectrophotometric analysis of coronal tooth discoloration induced by various bioceramic cements and other endodontic materials. *Journal of Endodontics*, 41, 1862–1866.

Marques, M.S., Wesselink, P.R. & Shemesh, H. (2015) Outcome of direct pulp capping with mineral trioxide aggregate: a prospective study. *Journal of Endodontics*, 41, 1026–1031.

Massler, M. (1959) Pulp-curettage; a review. *ASDC Journal of Dentistry for Children*, 26, 154–157.

Matsuo, T., Nakanishi, T., Shimizu, H. & Ebisu, S. (1996) A clinical study of direct pulp capping applied to carious-exposed pulps. *Journal of Endodontics*, 22, 551–556.

Mejàre, I.A., Axelsson, S., Davidson, T., Frisk, F., Hakeberg, M., Kvist, T. et al. (2012) Diagnosis of the condition of the dental pulp: a systematic review. *International Endodontic Journal*, 45, 597–613.

Mejàre, I. & Cvek, M. (1993) Partial pulpotomy in young permanent teeth with deep carious lesions. *Dental Traumatology*, 9, 238–242.

Möller, A.J., Fabricius, L., Dahlén, G., Ohman, A.E. & Heyden, G. (1981) Influence on periapical tissues of indigenous oral bacteria and necrotic pulp tissue in monkeys. *Scandinavian Journal of Dental Research*, 89, 475–484.

Mutluay, M., Arıkan, V., Sarı, S. & Kısa, Ü. (2018) Does achievement of hemostasis after pulp exposure provide an accurate assessment of pulp inflammation? *Pediatric Dentistry*, 40, 37–42.

Nair, P.N.R., Duncan, H.F., Pitt Ford, T.R. & Luder, H.U. (2008) Histological, ultrastructural and quantitative investigations on the response of healthy human pulps to experimental capping with mineral trioxide aggregate: a randomized controlled trial. *International Endodontic Journal*, 42, 422–444.

Özyürek, T. & Demiryürek, E.Ö. (2016) Comparison of the antimicrobial activity of direct pulp-capping materials: Mineral trioxide aggregate-Angelus and Biodentine. *Journal of Conservative Dentistry*, 19, 569–572.

Parirokh, M., Torabinejad, M. & Dummer, P.M.H. (2017) Mineral trioxide aggregate and other bioactive endodontic cements: an updated overview - part I: vital pulp therapy. *International Endodontic Journal*, 51, 177–205.

Rechenberg, D.K. & Zehnder, M. (2020) Call for a review of diagnostic nomenclature and terminology used in Endodontics. *International Endodontic Journal*, 53, 1315–1317.

Ricucci, D., Loghin, S. & Siqueira, J.F. (2014) Correlation between clinical and histologic pulp diagnoses. *Journal of Endodontics*, 40, 1932–1939.

Ricucci, D., Siqueira, J.F. Jr, Rôças, I.N., Lipski, M., Shiban, A. & Tay, F.R. (2020) Pulp and dentine responses to selective caries excavation: a histological and histobacteriological human study. *Journal of Dentistry*, 100, 103430.

Schwendicke, F., Frencken, J.E., Bjørndal, L., Maltz, M., Manton, D.J., Ricketts, D. et al. (2016) Managing carious lesions: consensus recommendations on carious tissue removal. *Advances in Dental Research*, 28, 58–67.

Simon, S., Perard, M., Zanini, M., Smith, A.J., Charpentier, E., Djole, S.X. et al. (2013) Should pulp chamber pulpotomy be seen as a permanent treatment? Some preliminary thoughts. *International Endodontic Journal*, 46, 79–87.

Smith, A.J., Duncan, H.F., Diogenes, A., Simon, S. & Cooper, P.R. (2016) Exploiting the bioactive properties of the dentin-pulp complex in regenerative endodontics. *Journal of Endodontics*, 42, 47–56.

Taha, N.A. & Abdelkhader, S.Z. (2018) Outcome of full pulpotomy using Biodentine in adult patients with symptoms indicative of irreversible pulpitis. *International Endodontic Journal*, 51, 819–828.

Taha, N.A. & Abdulkhader, S.Z. (2018) Full pulpotomy with biodentine in symptomatic young permanent teeth with carious exposure. *Journal of Endodontics*, 44, 932–937.

Taha, N.A. & Khazali, M.A. (2017) Partial pulpotomy in mature permanent teeth with clinical signs indicative of irreversible pulpitis: a randomized clinical trial. *Journal of Endodontics*, 43, 1417–1421.

Tronstad, L. & Mjör, I.A. (1972) Capping of the inflamed pulp. *Oral Surgery, Oral Medicine, Oral Pathology*, 34, 477–485.

Uesrichai, N., Nirunsittirat, A., Chuveera, P., Srisuwan, T., Sastraruji, T. & Chompu-Inwai, P. (2019) Partial pulpotomy with two bioactive cements in permanent teeth of 6- to 18-year-old patients with signs and symptoms indicative of irreversible pulpitis: a noninferiority randomized controlled trial. *International Endodontic Journal*, 52, 749–759.

Wolters, W.J., Duncan, H.F., Tomson, P.L. et al. (2017) Minimally invasive endodontics: a new diagnostic system for assessing pulpitis and subsequent treatment needs. *International Endodontic Journal*, 50, 825–829.

Yoldaş, S.E., Bani, M., Atabek, D. & Bodur, H. (2016) Comparison of the potential discoloration effect of bioaggregate, biodentine, and white mineral trioxide aggregate on bovine teeth. *Vitro Research Journal of Endodontics*, 42, 1815–1818.

Zilberman, U., Mass, E. & Sarnat, H. (1989) Partial pulpotomy in carious permanent molars. *American Journal of Dentistry*, 2, 147–150.

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