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Dental Practitioners' Thresholds for Restorative Intervention in Carious Lesions: A Survey-Based Systematic Review Update

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Keywords
Caries · Restorative dentistry · Minimally invasive dentistry · Treatment planning · Evidence-based dentistry

Abstract
Introduction: Despite evidence supporting the clinical and cost-effectiveness of minimally invasive dentistry (MID), its adoption by the dental profession has been slow. A systematic review in 2016 found the majority of dentists intervene invasively earlier than necessary. The aim was to update this review of the assessment of dental practitioners' thresholds for providing restorative treatment for carious lesions given changes in evidence, teaching, and guidelines since 2016. The primary outcome was dental practitioners' restorative thresholds (the extent of the lesion when they would decide to intervene restoratively). Secondary outcomes were changes over time, caries risk, regional differences, and primary/permanent dentition. ***Methods:*** This updated review replicated the methodology for the initial review, following the PRISMA 2020 guidelines (PROSPERO; CRD42023431906). Embase, MEDLINE (via PubMed), and Web of Science databases were searched (2016–2023) for observational studies reporting on dental clinicians' thresholds for restorative interventions in adults and children without language, time, or quality restrictions. Screening, data extraction, and risk of bias assessment (Modified Newcastle-Ottawa Scale) were carried out independently and in duplicate. Meta-analyses were performed using a random-effects model. No funding sought. ***Results:*** Overall, 47 publications (30 from original publication and 17 from updated search) met the inclusion criteria and 65 datasets were included in the meta-analyses: 19 for occlusal lesions (16 pre-2016 and 3 post-2016; n = 11,946) and 46 for proximal lesions (38 pre-2016 and 8 post 2016; n = 20,428). The meta-analyses found that for occlusal lesions confined to enamel, there were fewer practitioners intervening invasively: 5% (95% confidence interval [CI]; 1–20%) post-2016, compared with 15% (95% CI; 9–23%) pre-2016. The opposite was found for proximal lesions with increased intervention levels, 27% (95% CI; 18–40%) for lesions confined to enamel post-2016, compared with 19% (95% CI; 12–29%) pre-2016, and for lesions extending up to the enamel-dentine junction 61% (95% CI; 36–81%) post-2016, compared with 39% (95% CI; 29–51%) pre-2016. There was variance between regions

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but too few studies to draw conclusions on individual regions. ***Conclusion:*** There was a suggestion of less invasive treatment of occlusal lesions over time; however, this was not evident for proximal lesions.

Introduction

Minimally invasive dentistry (MID) involves managing the dental caries process to prevent new lesions developing, remineralising active lesions through non-surgical interventions, and minimally invasive operative interventions for active lesions which cannot be remineralised [1–3]. Evidence for moving away from traditional invasive, operative techniques, to manage carious lesions, towards MID [4, 5] has not been followed by a change in practice [6, 7].

The decision between remineralisation of a carious lesion and intervening operatively to restore the damaged area presents a clinical dilemma. The decision to restore depends on the extent of the lesion and factors related to the tooth, mouth, and the patients themselves. Consensus guidelines and MID principles describe how this decision should be based primarily on lesion activity, cavitation and cleansability [8, 9] while considering aesthetics, form and function. The main tenets for managing occlusal lesions in the early stages are that non- or micro-cavitated occlusal lesions confined to enamel should be managed using non-invasive, e.g., remineralisation, and/or micro-invasive interventions e.g., sealing, and those that reach the outer third of dentine should be managed using micro-invasive interventions, e.g., sealing. For proximal lesions, those radiographically restricted to enamel should be managed using non-invasive, e.g., remineralisation, and/or micro-invasive methods, e.g., sealing or infiltration as they are unlikely to be cavitated [8, 9].

It does not appear as if these less invasive approaches have been followed with a systematic review and meta-analyses [10] finding that 48% (95% CI, 40–56%) of dental practitioners would intervene operatively for proximal lesions extending radiographically to the enamel-dentine junction (EDJ) and 74% (95% CI, 56–86%) of occlusal lesions extending to the outer third of dentine. Since the publication of that review, there have been further publications including evidence-based statements [8, 9, 11], dissemination of further clinical trials and observational studies in journals, changes in guidelines [12] and education curricula [13] towards more minimal approaches. Changes in guidelines are important to standardise the management of carious lesions, ensuring that practitioners adhere to the most current evidence-based practices. Additionally, curricula frameworks should be regularly updated to ensure new graduates are taught the latest best practices which is firmly grounded in evidence. Changes towards improved use of MID have been reported with an increase in the use of selective caries removal over the last 10 years in Lithuania (44% in 2021; 27% in 2011) [14]. Although this improvement is promising, there are still further improvements needed to ensure everyone is utilising a MID approach. This article aimed to update the review from 2017 [10] using aims and methodology aligned to the original review, to determine whether there have been changes globally in practitioner behaviour towards less invasive management of carious lesions.

The primary outcome was to identify dental practitioners' restorative thresholds (the extent of the lesion when they would decide to intervene restoratively) when managing carious lesions in adults and children (primary or permanent teeth). Secondary outcomes were to assess for differences that exist in restorative thresholds overtime as well as differences that exist between educationally similar groups of countries (Asia, Australia, Eastern Europe, Latin America/South America, North America, Scandinavia, Western Europe) for restoring carious lesions. If appropriate, we planned to also investigate how other factors, such as; patient age, gender, socioeconomic status, caries risk and tooth type (primary or permanent dentition), influence the dental practitioners' decision-making process.

Methods

As this review is an update of a previously published systematic review, the methodology has been aligned to the original publication [10]. The protocol for this update was published in PROSPERO, registration number CRD42023431906 (05/06/23; https://www.crd.york.ac.uk/PROSPERO/display_record.php?RecordID=431906). It was reported following PRISMA 2020 guidelines (online suppl. Material 1; for all online suppl. material, see https://doi.org/10.1159/000546194) [15].

Searches

Searches were performed in Embase, MEDLINE (via PubMed), and Web of Science databases on November 3, 2023, with a date restriction from January 1, 2016, to November 2, 2023. The search strategy was kept the same as the original review, which was broad to maximise the

capture of studies as the keywords might not be easily detected. The following three search areas were developed for each database (online suppl. material 2) and combined the following:

- ((((((restorative) OR restoration) OR invasive) OR drilling) OR cutting) OR filling) AND
- (((((decision) OR threshold) OR cut-off) OR intervene) OR survey) OR questionnaire AND
- (((caries) OR carious) OR decay) OR white spot

The search differed from the original review as there was also a process of manual searching which included the following:

- reviewing articles could not be accessed at the time of the original publication;
- searching for any articles that cited the original review; and
- searching the references of the included articles.

Study Eligibility

- Observational peer-reviewed studies without language, time, or quality restrictions
- Reporting on dentists' or therapists', or dental or therapist students' thresholds (clinically, radiographically, or using other caries detection tools) for carrying out restorative interventions on active proximal or occlusal carious lesions, for adults or children and in primary or permanent dentitions.

Screening

The articles from the search results were de-duplicated using Endnote [16] with title and abstract screening performed in duplicate and independently by two reviewers (H.J.L. and N.I.); full texts were included if there was uncertainty over inclusion and full text screening was similarly in duplicate and independently with texts included after agreement, through discussion, of both authors. The reference lists of identified full texts were screened, and potential articles screened by two reviewers in duplicate and blinded (H.J.L. and K.R.).

Data Extraction

Data were extracted in duplicate and independently by a team of reviewers working in pairs and agreement achieved through discussion. The data extraction form was developed based on the previous review, then updated and piloted to ensure clarity and consistency. All data were checked by H.J.L. and P.W. Demographic data included year of survey, role of dental practitioner, country, sample size, and response rate. Outcome data included primary or permanent dentition, lesion location, lesion progression classification system used, number of dentists intervening at each lesion progression level (number and percentage), caries risk status, patients' age, gender, and socioeconomic status. Patient age, gender, and socioeconomic status were stated in the protocol, as if present, we wished to explore for differences in decision-making based on these factors, but these data were not presented in the publications identified so was not collected.

Lesion progression levels were restricted to those that could be managed non-invasively, e.g., remineralisation, or micro-invasively, e.g., sealing or infiltration (Fig. 1). For occlusal surfaces two categories were used based on written descriptions and/or images. Grades 1–2 included lesions showing visual changes in enamel, minor tooth

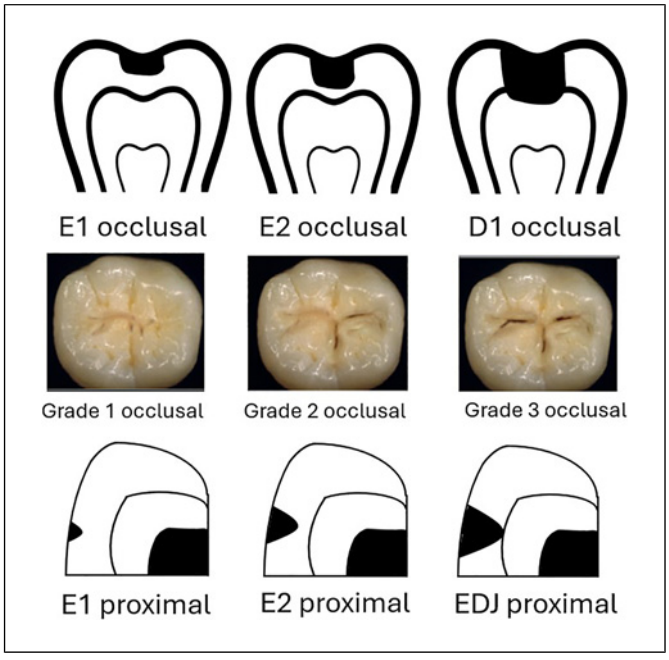

Fig. 1. Lesion progression levels used. Occlusal grades 1–2 included clinical grades 1 and 2 and radiographic grades E1 and E2. Grade 1 represents white or brownish discoloration in the enamel, no cavitation, no radiographic signs of caries. Grade 2 shows minor loss of tooth substance with a break in the enamel surface or discoloured surface or discoloured fissures with grey or opaque enamel or caries confined to the enamel, no radiographic signs of caries, E1 represeMohernts lesions extending to the outer half of enamel radiographically, E2 inner half of enamel radiographically. Occlusal grade 3 includes clinical grade 3 and radiographic grade D1, where clinical grade 3 represents moderate loss of tooth substance or caries in the outer one-third of the dentine according to the radiograph and D1 lesions radiographically, where the lesion extends to the outer third of the dentine radiographically. Proximal lesions were defined as enamel lesions if the lesion was confined to enamel (E1 or E2) or extending to the enamel-dentine junction (EDJ).

structure loss in enamel clinically and confined to enamel radiographically. Grade 3 included lesions that have moderate tooth substance loss but no visible dentine or underlying shadow and radiographically the lesion is no deeper than the outer third of dentine (D1). For proximal lesions, two categories were also used: lesions involving enamel only and those extending to the EDJ. Most of the grading systems used radiographs or images to depict radiographic depth except one where they stated the depth with written descriptors (online suppl. material 6). If there were any missing data attempts would be made to contact the authors to ask for permission to access the missing data.

Data Synthesis

For the primary outcome, dental practitioners' restorative thresholds (defined as the extent of the lesion when they would decide to intervene restoratively) were compared. In line with the original review, different intervention depths were separated into occlusal and proximal lesions and pooled as follows:

Occlusal (clinically or radiographically):

1. Confined to enamel (E1, E2);
2. Confined to enamel or in outer dentine (E1, E2, EDJ, D1).

Proximal (clinically or radiographically):

1. Confined to enamel (E1, E2);
2. Confined to enamel or extending up to enamel dentine junction (E1, E2, EDJ).

Subgroup analyses were as follows:

1. Pre- and post-2016; as this is when the previous review was carried out.
2. Region – countries were grouped according to region (Asia, Australasia, Eastern Europe, Latin/South America, North America, Scandinavia, Western Europe). No studies from Africa were identified. Some studies were carried out across different countries and results were split to reflect country, so that each data point related to the country rather than the study.
3. High and low caries risk (as defined in any studies that include this measure).
4. Primary/permanent dentitions.

Statistical Analysis

Meta-analysis of proportions was performed using the "meta" package, using the "metaprop" function, to pool proportions from multiple studies. The analysis was structured to include the study label, the number of events, total observations, and grouped by the year of data collection. Heterogeneity was measured using the I^2 statistic, and publication bias was tested using Peter's test statistic [17] using the "metabias" function. To account for the heterogeneity between studies, a random-effects model was used for the meta-analyses. To compare dental practitioners' restorative thresholds, forest plots were created to visually represent the pooled restorative thresholds across different studies for occlusal and proximal lesions within each subgroup. Funnel plots were completed to assess for any evidence of bias. All statistical analyses were conducted using R (version 4.4.0) [18].

Quality Assessment

Study quality was assessed using a Modified Newcastle-Ottawa Scale [19] adapted for cross-sectional studies and in line with the original review [10] (online suppl. material 3a). Only studies identified in the new search were assessed with studies from the previous review having scores carried forwards. Assessment was performed independently by two reviewers (D.P.R. and H.J.L.) with scores then agreed via discussion. Studies that received ≥7 points were considered high quality, 4 to 6 moderate quality and 0 to 3 low quality.

Results

The search found 7,725 studies (7,430 from databases, 288 from citation chaining and 7 from manual searching); of which 17 met the inclusion criteria (Fig. 2). When added to the 30 articles from the original review, there were 47 studies for inclusion in this review [20–66]. The studies ranged from 1985 to 2022 and covered 22 countries across the 7 regions. Of the 17 newly included studies, 14 had data allowing them to be included in the meta-analysis; the other three studies' findings have been described narratively (Table 1). Full details of study characteristics and extracted data can be found in online supplementary material 4 and 5.

The protocol stated that patient age, gender and socioeconomic status would be extracted; to explore differences in decision-making based on these factors, but these data were not presented in the publications, so could not be extracted or analysed. This is identified as a gap in information.

There were seven articles identified through manual searching and all were carried out prior to 2016. The author of one study [50] was contacted for additional details and responded. The quality of the included studies varied, with four being high quality, 34 of moderate quality and nine of low quality (Fig. 3; with full details available in online supplementary material 3b).

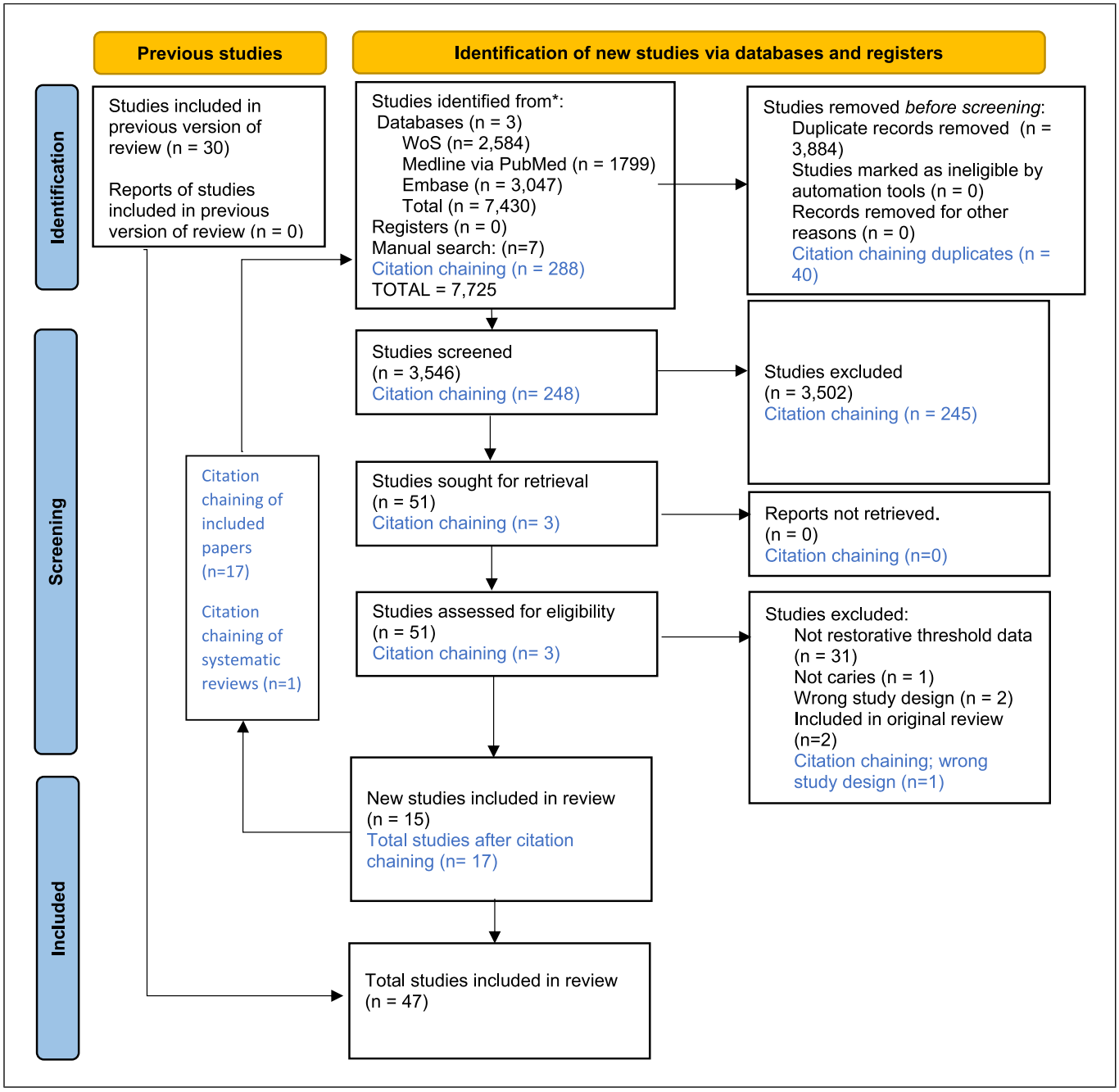

Fig. 2. PRISMA flowchart of identification, screening, and assessing studies for inclusion eligibility, taken from a study by Moher et al. [67].

Meta-Analysis

The meta-analyses included 65 data sets from 47 publications. There were 19 data sets for occlusal lesion interventions (16 pre-2016 and 3 post-2016) for both E1/E2 and D1 levels. For proximal lesion interventions, there were 46 data sets at E1/E2 level (36 and 8); 30 which looked at management of lesions up to the EDJ (26 and 4). Furthermore, publication bias seems low as the p values for all subgroups were ≤0.05, indicating no funnel plot asymmetry across all subgroups (online suppl. material 8).

Table 1. Findings of included studies that were not incorporated into meta-analyses and reasons for exclusion

Article	Summary	Reason why not included in meta-analyses
Leal et al. [60] 2019	Investigated at which point 61 members of the Brazilian Association of Paediatric Dentistry would intervene restoratively when restoring a carious occlusal surface in a primary tooth • Distinct visual change in enamel, with or without localised enamel breakdown 10/61 (17.3%) would restore • Internal caries-related discolouration of dentine, visible through enamel 37/61 (43.8%) would restore	1. Not enough data on primary dentition to include in meta-analyses 2. Only study to use CAST system so no comparison possible
Hanes et al. [56] 1992	Investigated the point at which 1245 dentists (723 general dental practitioners and 522 paediatric dentists) in USA, would intervene for proximal lesions in primary teeth based on radiographs • Radiograph with no caries visible – 15% (n = 186; 108 GDPs and 78 PDs) would restore the tooth • Radiograph showing caries into outer half of dentine 75% (n = 930) would restore the tooth • Radiograph showing carious lesion extended to the inner half of dentine 96% (n = 1,199) would restore the tooth	1. Not enough data on primary dentition to include in meta-analyses 2. Used radiographs with thresholds at different points to other studies
Carvalho et al. [50] 2018	Investigated 81 dental professionals (dentists and dental hygienists) agreement with best practice management by expert consensus and in line with guidelines • There was a high level of agreement (κ = 0.68) between practitioners and experts on whether to intervene using a non- or micro-invasive approach versus an operative minimally invasive approach • Wide variation (κ = 0.22) when deciding which non operative approach to use on occlusal surfaces	1. Data received from author did not have the data items to allow for identification of restorative threshold, only consensus between two groups

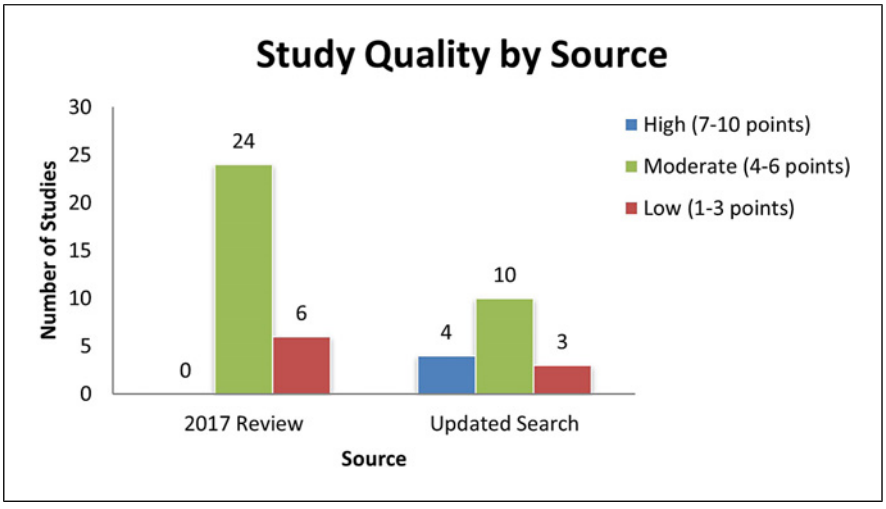

Fig. 3. Chart demonstrating the number of studies falling into low, moderate, and high quality based on the Newcastle Ottawa Scale.

Occlusal Surfaces

Nineteen data sets (16 pre-2016 and 3 post-2016) investigated dental practitioner's restorative thresholds for managing carious occlusal lesions using six different grading systems (online suppl. material 6). There were 11,946 participants (10,611 pre-2016 and 1,335 post-2016).

Lesions Confined to Enamel (E1, E2)

A total of 13% (95% CI; 8–20%) of practitioners are using restorative strategies to manage lesions confined to the enamel.

Lesions Confined to Enamel and Those Extending to Outer Dentine (E1, E2, EDJ, D1)

A total of 73% (95% CI; 57–84%) of practitioners are using restorative strategies to manage lesions that extend to the outer third of dentine.

Proximal Surfaces

Forty-six studies investigated dental practitioner's restorative threshold for managing carious proximal lesions.

Lesions Confined to Enamel (E1, E2)

For lesions confined to enamel, there were 20,428 participants (17,456 pre-2016 and 2,972 post-2016), with 21% (95% CI; 14–29%) stating they would manage a lesion confined to enamel restoratively.

Lesions Confined to Enamel or Extending up to Enamel Dentine Junction (E1, E2, EDJ)

For these lesions, there were responses from 15,077 participants (13,562 pre-2016 and 1,515 post-2016) with 42% (95% CI; 32–53%) stating they would manage the lesions restoratively.

Subgroup Analyses

Changes over Time (Pre- and Post-2016) Occlusal Lesions

There was evidence of a change pre- and post-2016 for the management of occlusal lesions extending to the outer third of dentine with 78% (95% CI; 62–88%) of practitioners reporting that they would intervene at this depth pre-2016 compared to only 40% (95% CI; 22–61%) post-2016 and this difference was found to be significant ($p < 0.01$) as shown in Figure 4. However, there was less strong evidence of a change in behaviour when looking at practitioners who would intervene restoratively for occlusal non-cavitated, non-discoloured enamel-only lesions with 15% (95% CI; 9–23%) of practitioners reported that they would intervene restoratively pre-2016 compared to 5% (95% CI; 1–20%) post-2016 as shown in Figure 5.

Changes over Time (Pre- and Post-2016) Proximal Lesions

For proximal lesions, there is no definitive change in practice evident over time, although the data may suggest practitioners becoming more invasive, with 19% (95% CI; 12–29%) and 27% (95 CI; 18–40%) of dental practitioners intervening restoratively for enamel only lesions and 39% (95% CI; 28–51%) and 61% (95% CI; 36–81%) of dental practitioners intervening restoratively for lesions extending to the EDJ pre- and post-2016 studies, respectively, as shown in Figures 6 and 7. Due to the low number of data sets post 2016, care must be taken within this sub-group analysis.

Regional Differences

There were 22 countries represented within the data with wide variation in the number of data sets and sample size investigated (Table 2) (range 11–2,375), but the data gave some indications of trends around levels for initiating treatment within regions (online suppl. material 7). For occlusal surface lesions, there is a suggestion of regional differences, although there was no statistical significance so findings should be interpreted with care. Practitioners from Australia, Asia, and Scandinavia were less likely than dentists from any other region to apply the principles of MID for enamel-only lesions with only 4% (95% CI; 2–8%), 7% (95 CI; 6–9%), and 9% (95% CI; 5–14%), respectively, reporting they would restoratively manage lesions confined to enamel, where conversely North American clinicians reported lower thresholds with 22% (95% CI; 12–36%) intervening invasively on enamel lesions, compared to 13% (95% CI; 8–20%) of practitioners globally. Clinicians in Asia and Australasia reported being less likely to intervene for D1 lesions, with 47% (95% CI; 40–54%) and 33% (95% CI; 30–36%) restoring lesions extending to the outer third of dentine, respectively, lower than the global average of 73% (95% CI; 58–84%).

For proximal lesions and regional differences, Latin/South American practitioners reported initiating operative treatment earlier with 40% (95% CI; 14–72%) of practitioners managing enamel only lesions restoratively, a higher proportion than the 21% (95% CI; 14–29%) global average, and conversely only 3% (95% CI; 0–16%) of Scandinavian practitioners. When managing lesions that extend to the EDJ, Asia and

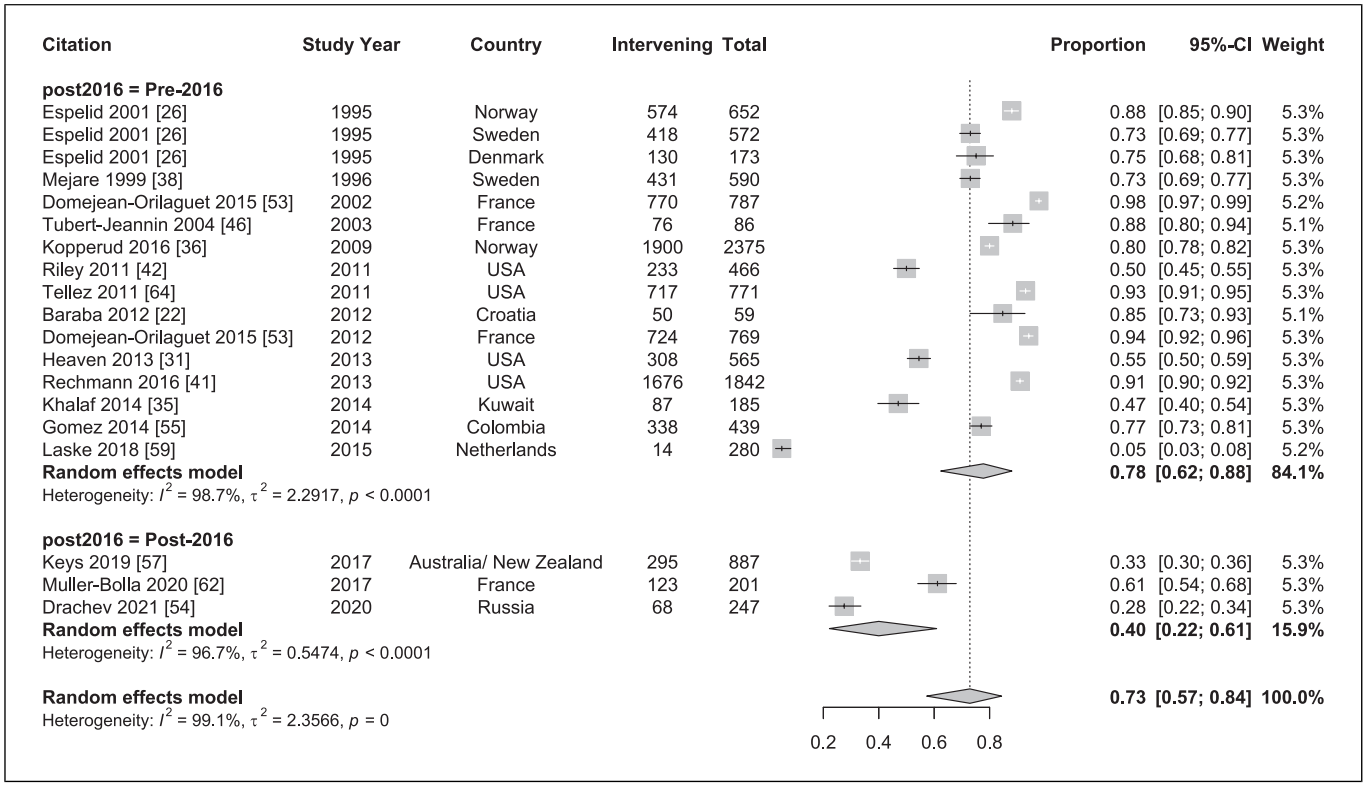

Fig. 4. Forest plot of restorative thresholds for occlusal lesions extending into the outer third of dentine based on year; pre- and post-2016.

Scandinavia are outliers with 23% (95% CI; 4–65%) and 24% (95% CI; 7–60%), respectively, reporting they would manage these lesions restoratively, which is much less than the global average of 42% (95% CI; 32–53%). No other regional differences were noted in the proximal threshold data.

Caries Risk

Only one additional publication [55] since the original review provided quantitative data on this so a meta-analysis was not possible. However, it found practitioners to be more invasive in high caries risk patients when restoring occlusal enamel lesions with 44% (n = 100/228) compared to 29% (n = 62/211) in low-risk patients. For deeper occlusal lesions extending to the outer third of dentine, similar trends were visible with 72% (n = 154/215) intervening restoratively in the high-risk group compared to 57% (n = 127/224) for low-risk patients. However, minimal differences were seen when restoring proximal surfaces. This is similar to the findings of the previous review which found a relative ratio of dentists intervening in high versus low caries risk factors of 1.49 (95% CI; 1.37, 1.62).

Primary/Permanent Dentitions

Primary teeth were included in the search as it is important to understand what is happening across the spectrum of dentistry; however, only two studies showed data on primary dentition: one investigating occlusal surfaces [60] and one on the proximal surfaces [56]. Data were not comparable, so sub-group meta-analysis was not possible. However, 15% (n = 186) of practitioners surveyed using radiographs to show proximal lesion depth said they would restore invasively despite no caries being visible on the radiograph [60] and 17% (n = 10) for non-cavitated enamel-only occlusal lesions.

Further to the planned sub-group analysis, one publication [50] investigated 81 dental professionals (dentists and dental hygienists) in agreement with best practice management by expert consensus and in line with guidelines. Although attempts were made to find the restorative thresholds by asking for the primary data set from the author, the data could not be included in the data synthesis. However, it is worth noting that there was a high level of agreement (κ = 0.68) between practitioners and experts on whether to

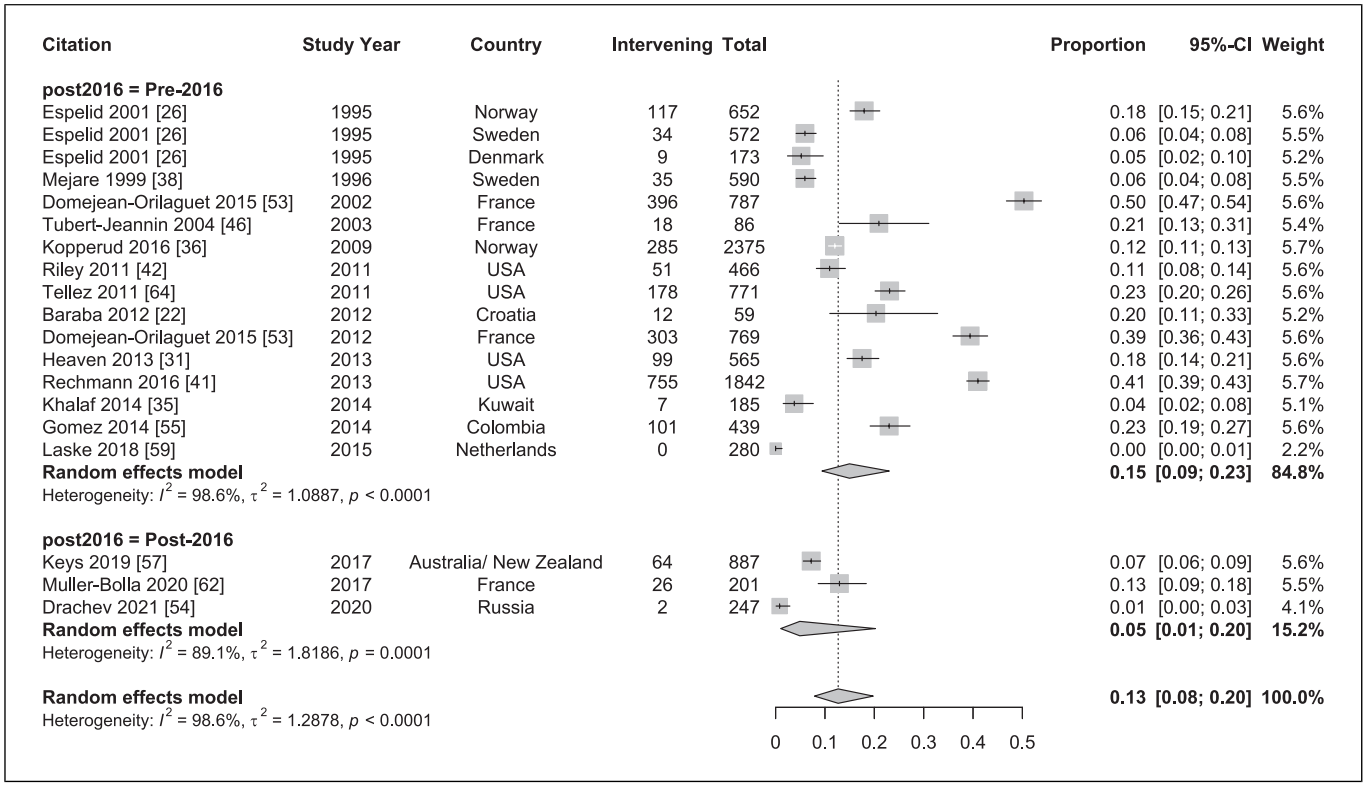

Fig. 5. Forest plot of restorative thresholds for occlusal enamel only lesions based on year; pre- and post-2016.

intervene using a non- or micro-invasive approach versus an operative minimally invasive approach. However, wide variation (κ = 0.22) was observed when deciding which non-operative approach to use on occlusal surfaces.

Heterogeneity

The heterogeneity was assessed using the I^2 statistic, which quantifies the percentage of total variation across studies that is due to heterogeneity rather than chance. In all subgroups, there was an I^2 score of 99%, which indicates a very high likelihood of heterogeneity among the studies included in our meta-analyses. To compensate for this, we have performed random-effects modelling for the meta-analysis, which considers both within-study and between-study variability in the pooled estimates.

Discussion

By comparing data from the two timeframes using the same methodology, we were able to see that there had been a shift in some practitioner's self-reported behaviour. We found evidence for change between pre-2016 original study publication date for the management of occlusal lesions but not for proximal lesions. There were more data available for proximal lesions than occlusal lesions.

In the 19 articles (16 from pre-2016 and 3 post-2016), where dentists were asked about whether they would intervene invasively for occlusal lesions extending into the outer third of dentine with no cavitation, before 2016, 78% (n = 8,236) of dentists would, and after 2016, this reduced to 40% (n = 486). For lesions that involved enamel only pre-2016, 15% (n = 2,400) would intervene, whereas this was reduced to 5% (n = 92) post-2016. There were only three studies (with a relatively small number of participants) included in the post-2016 analyses, so there should be caution in interpretation and there is a likelihood of positive bias with researchers more interested in investigating practitioners where there may have been a change. Nevertheless, the data indicate the possibility of less invasive treatment being undertaken for the management of occlusal minimal lesions.

There were more data (46 data sets) available for management of proximal lesions limited to enamel (38 pre-2016 and 8 post-2016) and 30 data sets (26 pre-2016 and 4

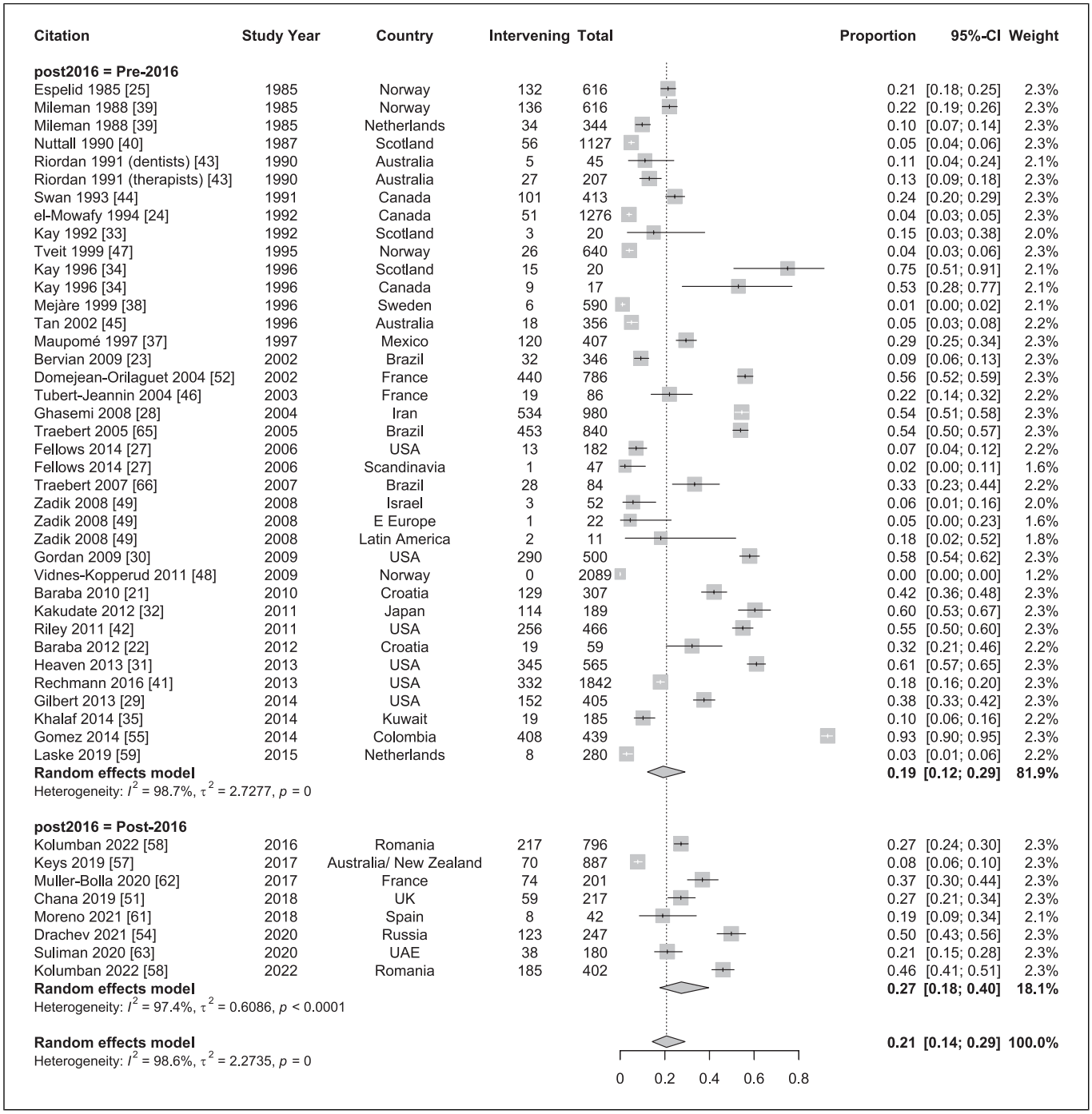

Fig. 6. Forest plot of restorative thresholds for proximal enamel only lesions based on year; pre- and post-2016.

post-2016) looking at management of lesions up to the EDJ. For lesions extending to the EDJ, studies from pre-2016, 39% (n = 5,496) would intervene, whereas for post-2016 this increased to 61% (n = 694). Similarly, there was a small increase in the number of dental practitioners intervening when lesions had not spread beyond the enamel, from 19% (n = 4,337) to 27% (n = 774). Overall, there was no suggestion of a reduction in the level of intervention for proximal carious lesions at early stages of development and a possibility of an increase.

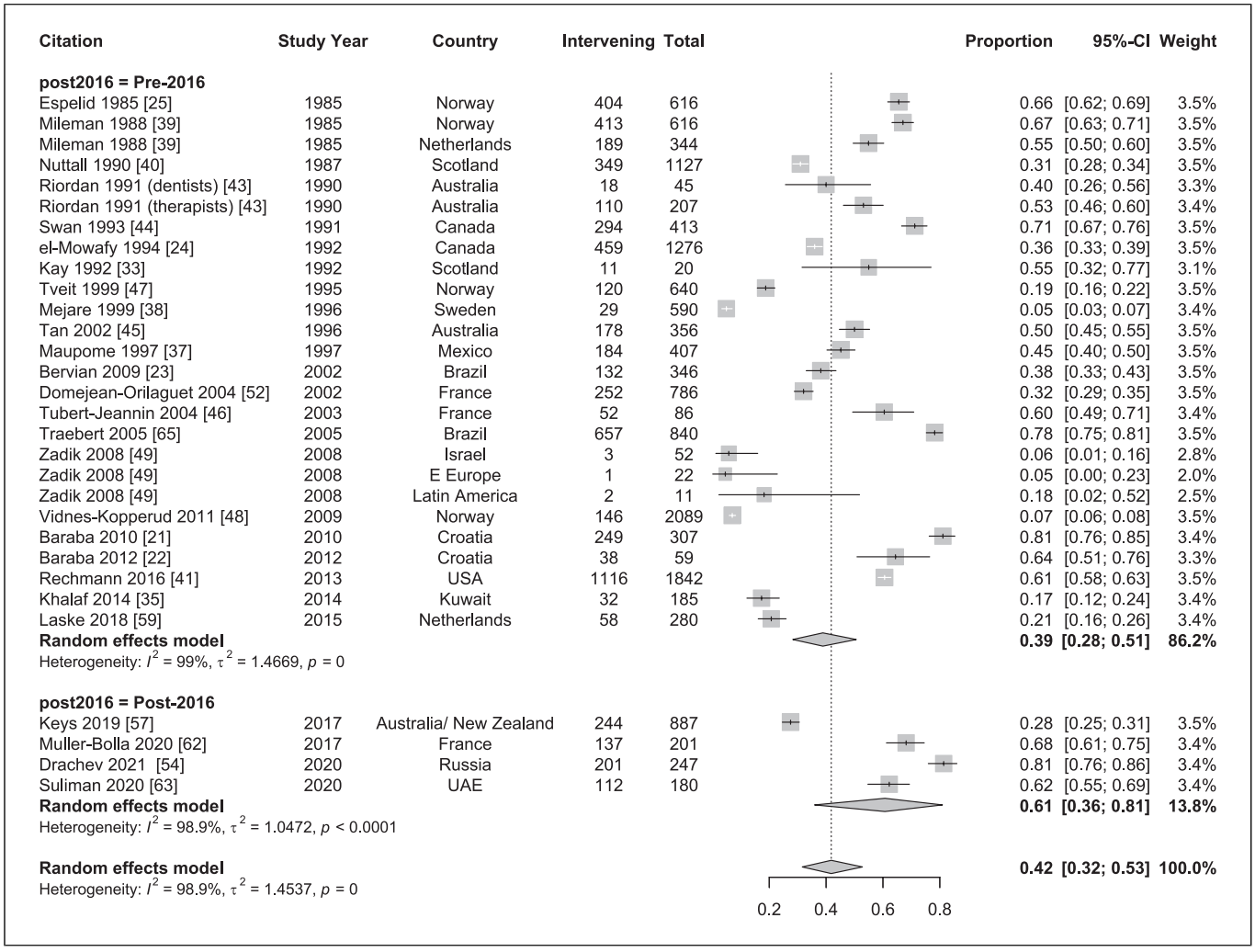

Fig. 7. Forest plot of restorative thresholds for proximal lesions extending to the EDJ based on year; pre- and post-2016.

Differences in trends between the management of occlusal and proximal lesions could be due to practitioners believing they are able to monitor occlusal lesions via direct observation more easily, so they are happier to use less invasive approaches in these lesions compared to proximal lesions. It could also be due to difference in the ability of diagnostic tools to correctly diagnose caries on different surfaces. Further investigation into the decision-making process to understand why practitioners make the choices they do would be beneficial to aid future implementation strategies of MID.

Limitations of this study are that an assessment of certainty (or confidence) in the body of evidence for each outcome assessed and a subgroup analysis of differing levels of quality determined by the Newcastle Ottawa Scale has not been undertaken. There were too few studies post-2016 to draw any conclusions around changes in behaviour of clinicians in individual regions.

When deciding whether to manage the lesion invasively or not, practitioners may be assessing whether they believe new lesions will develop and the ability of the patient to modify cariogenic behaviours; therefore, caries risk is often considered. However, no additional studies were included which provided details on the impact of a caries risk assessment on the clinical decision-making of when to intervene restoratively. There is a suggestion that practitioners are more likely to intervene invasively in patients with a higher caries risk category [68], which is consistent with the findings in the original review. Further research in this area by considering caries risk when carrying out cross-sectional surveys investigating restorative thresholds for managing carious lesions may

Table 2. Summary of number of studies and sample sizes based on region, surface, and depth of carious lesion

Region	Enamel only (E1/E2)		Outer third of dentine (D1)	
	studies, *n*	sample size	studies, *n*	sample size
Occlusal				
North America	4	3,644	4	3,644
Western Europe	8	5,323	8	5,323
Scandinavia	2	1,162	2	1,162
Eastern Europe	2	306	2	306
Australia/Asia	2	1,072	2	1,072
Latin/South America	1	439	1	439
Total	19	11,946	19	11,946
Region	Enamel only (E1/E2)		Enamel-dentine junction (EDJ)	
	studies, *n*	sample size	studies, *n*	sample size
Proximal				
North America	9	5,666	3	3,531
Western Europe	14	7,084	11	6,785
Scandinavia	2	637	1	590
Eastern Europe	6	1,833	4	635
Australia/Asia	9	3,081	7	1,912
Latin/South America	6	2,127	4	1,604
Total	46	20,428	30	15,057

help further understand this part of the decision-making process.

In reality, a clinician would determine their management of a carious lesion by the use of clinical examination and radiographs as this has higher sensitivity compared to one method alone [69]. Not all surveys included radiographic examination in their scenarios, which could reduce the validity of the findings. However, when assessing management in the primary dentition, radiographic examination is less sensitive [70] and care for interpretation should be considered. Radiographic examination should be included in future cross-sectional surveys to ensure it mimics reality as much as possible.

The level of heterogeneity in the data was high, possibly due to different clinicians being studied, a variable number in each study and slightly different surveys being used to assess when dental practitioners would intervene invasively as there were 6 different methods for occlusal and 20 for proximal surfaces. Although 14 data sets used the most common one for occlusal and 6 for proximal (online suppl. material 6), there is a need for the development of a validated tool assessing dental practitioners' threshold for surgical intervention to allow continued assessment in response to new guidelines and reduce the heterogeneity between data sets. Lesion depth is no longer the only factor a clinician considers when deciding whether to intervene restoratively, and it would be advantageous for the tool to also assess lesion activity, presence of cavitation, and cleansability of the lesion. Consideration of the tool's reliability and validity is essential, and development processes should also include qualitative methods, including the target audience, to validate the tool as it is possible for these to be biased, with practitioners tending to self-report their behaviours favourably to align with professional expectations [71].

It is difficult to know whether the sample in this study is representative of clinicians in their countries and response bias is always a potential problem in surveys with self-report of behaviour. The funnel plots suggest low risk of bias; however, there is more confidence in the data for proximal lesions with 5,401 additional practitioners from 13 studies across five regions (12 countries) for proximal lesions being included. Whereas there might be less confidence in the result for occlusal lesions which shows some evidence of a change in clinicians' behaviour to be less invasive because there were only 3 additional studies (n = 1,615) in the post 2016 dataset, all from different countries.

Other factors may have influenced decisions to intervene. For example, additional training and the use of magnification was investigated and seemed to make dentists more likely to restore earlier and more invasively [68]. This might be due to a feeling of improved clinical diagnostic accuracy for carious lesions. However, this study only included five practitioners, so the findings are limited due to the small sample size. It is also worth noting that although progress has been made towards implementing MID in the cariology teaching in undergraduate curricula, evidence suggests there is still wide variability in teaching [72, 73], likely impacted by the variability in clinical guidelines. Although there are moves towards the use of non- or micro-invasive interventions for the management of early lesions, these are not standard across all guidelines [73]. Continued collaboration to standardise guidance based on known and emerging evidence and implementation of this into undergraduate curriculums would be beneficial. Standardisation within guidelines and education would be helpful for curriculum design. Updating and provision of the educational curriculum, such as that in Columbia for undergraduate students [13], aligning to MID alongside the transition evidence and evidence-based recommendations into guidelines would help support further implementation of MID. This may help practitioners decide when to use specific minimally invasive approaches techniques as variability has been found [50]. However, it must be highlighted that often there are multiple minimally invasive options which would be suitable for a carious lesion.

Conclusion

Considering differences between the data pre- and post-2016, for occlusal lesions, there was a suggestion of less invasive treatment becoming more common with a lower proportion of dentists intervening in enamel lesions; however, for proximal lesions, there was no suggestion of a reduction in the number of dentists who would intervene for lesions at E1/2 or up to the EDJ. There were limited data to base assumptions on regional changes and to investigate differences in practitioner decision-making between the permanent and primary dentitions or caries risk. A validated questionnaire to allow continued assessment of current practice would be of benefit to allow for continued monitoring of clinician's clinical decision-making when it comes to practitioners deciding when they would intervene invasively with a drill. We advise it includes information on occlusal and proximal lesions (clinical and radiographic), caries risk, and patient age and investigates primary and permanent teeth. This would allow for a proxy assessment of whether practitioners are adapting their behaviour in line with evidence and improved meta-analyses with less heterogeneity between studies.

Statement of Ethics

An ethics statement is not applicable because this study is based exclusively on published literature.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

Searches were performed by N.I. Screening was performed by N.I. and H.J.L. Citation chaining was done by H.J.L. and K.R. Data extraction was performed by H.J.L., P.W., J.G., A.D., D.P.R., R.J., S.B., G.G.-R., and W.A. Quality assessment was performed by H.J.L. and D.P.R. Data analysis was performed by V.P., F.S., H.J.L., and N.I. The report was written by H.J.L., P.W., V.P., and N.I.

Data Availability Statement

All data generated or analyzed during this study are included in this article and its supplementary material files. Further enquiries can be directed to the corresponding author.

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