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Further opportunities for digital imaging in dental epidemiology

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ABSTRACT

Dental epidemiological research permits accurate tracking of the prevalence and distribution of oral disease across population groups, enabling planning and evaluation of public health interventions and healthcare service provision.

This first section of this paper aimed to review traditional assessment methods in dental epidemiology and to consider the methodological and logistical benefits provided by digital imaging, both generally and specifically in relation to an established dual-camera system.

The remainder of this paper describes the results of a semi-structured examination of an image archive from previous research utilising a dual-camera system, exploring whether the diagnostic yield of the images might be increased. Common oral conditions are presented alongside suggestions of the diagnostically useful data displayed in example images. Possible scoring mechanisms are discussed with consideration of the limitations that might be encountered for each condition. The retrospective examination suggests further data is obtainable from images acquired using the dual-camera system, however, consideration should be given to how best to validate this clinically. Additionally, other imaging modalities are discussed whilst taking into account the potential limitations of the dual-camera system.

1. Introduction

Significant improvements in oral health have been observed over the past 30 years, particularly in industrialised countries [1–3]. Despite these improvements, oral diseases remain highly prevalent across global populations and burden many with pain, infection and an overall reduced quality of life [3,4]. When the preventable and, in many cases, reversible nature of commonly occurring oral diseases are considered, there is a clear need for continued efforts to address the enduring effects that these conditions have on the majority of the world's population. Of particular relevance to both clinicians and public health bodies, these efforts should target those of lower socio-economic status who are burdened most by poorer oral health [4,5].

In order to remain informed of shifting population needs and to foster advancements in scientific knowledge, the World Health Organisation stipulates the importance of established "oral health information systems" [1]. A major component of these systems is epidemiological surveillance, capable of tracking the prevalence of oral diseases and their distribution across population groups. This essential data provides a contemporary understanding of oral health, enabling healthcare policy makers to both plan and assess the effectiveness of public health interventions and healthcare service provision [1,6].

1.1. Limitations of traditional epidemiology studies

Traditionally, oral epidemiological studies are designed around visual or visuo-tactile methods of assessment, whereby clinical examiners directly assess large numbers of the target population using relevant indices in relation to the condition(s) of interest [6,7]. Whilst the use of direct clinical assessment is well tested and 'simple' by design, the subjectivity of this method may lead to potential forms of bias [7].

Of particular note, the inability to blind examiners to factors such as the socio-economic status or residential location of the participant may lead to observer bias [6–8]. This issue is of particular relevance in epidemiological studies measuring fluorosis prevalence and severity, a legislative requirement in England for areas with artificial water fluoridation [9]. The York Review, a systematic review investigating the safety and efficacy of water fluoridation, highlighted the heterogeneity of both study design and analysis plans in epidemiological fluorosis research. In particular, the lack of examiner blinding to the fluoride exposure status of the participant was criticised due to the subsequent introduction of subjectivity and bias into the assessment method [10].

Attempts to address this issue have included transportation of study participants to a central location, as well as removal or masking of

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identifiers on participant clothing [11]. These strategies present their own logistical issues, particularly in relation to consent and safety. They would be instantly undermined should a participant disclose any information to the examiner, either explicitly through a statement that directly discloses their school or residential location, or, indirectly through the examiner's conscious or unconscious evaluation of a subject's accent, vocabulary, dress, or mannerism.

Further limitations of direct clinical assessment include the risk of examiner fatigue, particularly with high numbers of subjects and/or if multiple conditions are being measured. Additionally, onerous assessment procedures may impact on participant co-operation, particularly in children and adolescents. Lastly, direct assessment of large samples requires the physical presence of multiple examiners with associated support staff in each study site, a potentially limiting factor in relation to the financial burden and time consumption imposed by these requirements [8].

1.2. Digital imaging in oral epidemiology

Digital imaging has been utilised in oral epidemiology in an effort to overcome some of the limitations of direct clinical assessment. Recent studies have demonstrated successful mitigation of observer bias through the use of digital imaging, with the option to remotely score anonymised images facilitating effective examiner blinding [6,9,11,12]. Beyond reduction of bias in the assessment, remote scoring enables simultaneous assessment by multiple examiners across multiple locations, reduces the time between training/calibration of examiners and image assessment, and permits standardisation of examination conditions, further reducing environmental confounders [7,8].

The ability to archive the images presents obvious benefits in relation to data storage and research governance. Furthermore, this archiving permits re-assessment of conditions using different indices, if desired, as well as robust follow-up assessment in longitudinal studies [7–9,13]. Acquired image sets can be used for training and calibration purposes, with favourable evidence supporting the inter- and intra-examiner reliability achievable through this endeavour [14].

The use of digital imaging enables inclusion of other members of the dental team into the data collection process; nurses and hygienists could be trained to capture images, reducing the logistical complexities and cost of labour and consumables associated with mobile examination units manned by examiners across multiple sites [15,16].

A number of processing techniques exist which are capable of improving the diagnostic performance and variable quality of digital images, i.e. contrast optimisation, colour standardisation, noise reduction and artefact reduction [17]. Additionally, digital imaging modalities result in the ability to resize images. When these image enhancement options are coupled with the increased viewing time permitted by image assessment, it has been shown that conditions may be more readily apparent, resulting in higher prevalence rates than those found with clinical assessment [7].

As with all methods of assessment, there are limitations on the use of digital imaging in dental epidemiology. The loss of tactile feedback and an inability to assess oral structures from different positions using different lighting conditions results in a loss of holistic clinical judgement [18]. Additionally, some surfaces may not be recorded adequately enough to enable remote assessment, even if multiple images are captured from differing angles [8]. Depending on the imaging modality, the cost of developing or purchasing suitable equipment as well as provision of satisfactory training in its use can be a barrier to implementation [7]. The use of imaging increases the objectivity of assessment through reduction of bias, however, remote scoring is still subjective in nature due to the use of clinical indices. Whilst outside the scope of this paper, automatic detection by digital software should continue to be considered for digital imaging modalities to further improve the objectivity of the assessment [7].

Whilst image enhancement offers advantages for assessment, inappropriate use of this feature could result in falsification of the presence or absence and severity of conditions. Additionally, the ability to view the images for potentially unrestricted time periods can lead to inefficiency, examiner fatigue and 'second-guessing' of initial diagnosis [18].

1.3. Dual-camera system in oral epidemiology

Returning to fluorosis epidemiology specifically, in an effort to address the limitations of conventional clinical assessment, a dual-camera system was developed and successfully employed in large-scale fluorosis studies; a full description of the technical components of this system is available elsewhere [7,9]. This system simultaneously captures polarised white light (PWL) images as well as quantitative light-induced fluorescence (QLF) images of anterior teeth, permitting remote visual scoring of fluorosis and computer analysis of the change in fluorescence respectively. The use of a geometry-stabiliser improves image quality and intra- and inter-subject reproducibility.

The use of this technology was validated in a sample of 190 children in Chang Mai, Thailand [7], subsequently, this imaging system was used to assess almost two thousand children across four cities in England, UK [9]. Following successful validation of this technology, the system has been employed in national epidemiology programmes to monitor fluorosis prevalence; most notably, it forms part of the oral health component of the National Health and Nutrition Examination Survey (NHANES) conducted by National Centre for Health Statistics, USA [19].

As discussed, one of the benefits of digital imaging is the ability to archive images for future use and as would be expected from the subject numbers involved, the resulting image archive from the aforementioned studies is substantial. Feedback from those capturing the images as well as the examiners involved in remote scoring suggests that the images might carry diagnostically useful information for conditions other than fluorosis. As a result of this feedback and the availability of archived images, a semi-structured examination of previously acquired images was conducted to explore the potential of increasing the diagnostic yield of this imaging system.

2. Exploration of images

An informal review of images previously acquired using the dual-camera system offers potential insight into other oral conditions; however, the diagnostic value of this insight remains unknown. This section aims to introduce the oral conditions visible in the images, discuss possible scoring mechanisms for each condition and consider potential limitations of the system on a condition specific basis. As the dual-camera system captures anterior teeth only, this can be considered a universal limitation of the system; whilst this has been shown not to significantly impact on prevalence estimates of fluorosis [7], the same cannot be assumed of other conditions. Each section, therefore, will consider the impact of the loss of posterior data on accurate assessment of the condition.

2.1. Plaque accumulation

Plaque levels are of continuous interest in research, particularly to those investigating caries, periodontal health, compliance with oral hygiene interventions or new oral care products [20]. From an epidemiological perspective, the measurement of plaque can provide a deeper understanding of whole mouth health when combined with measurement of other conditions, as well as the typical characteristics of different population groups in relation to oral hygiene habits [21].

Various plaque indices have been utilised in research, notably, those developed by Silness and Loe, Greene and Vermillion and Quigley and Hein (later modified by Turesky et al.)[22–26]. With regards to remote scoring of plaque deposits, selection of an appropriate index would be

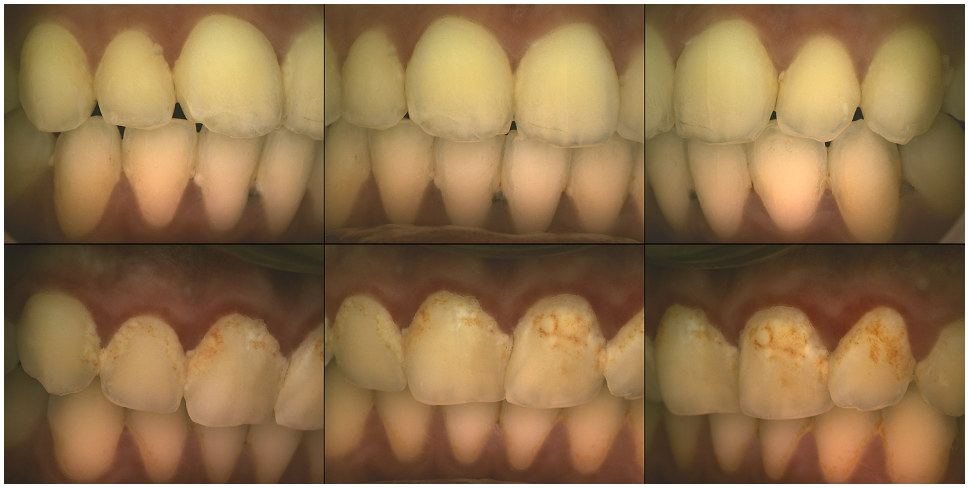

Fig. 1. (Top) Light plaque accumulation on anterior teeth with suggestion of previous trauma.
(Bottom) Heavy plaque accumulation with evidence of gingivitis and possible demineralisation of enamel

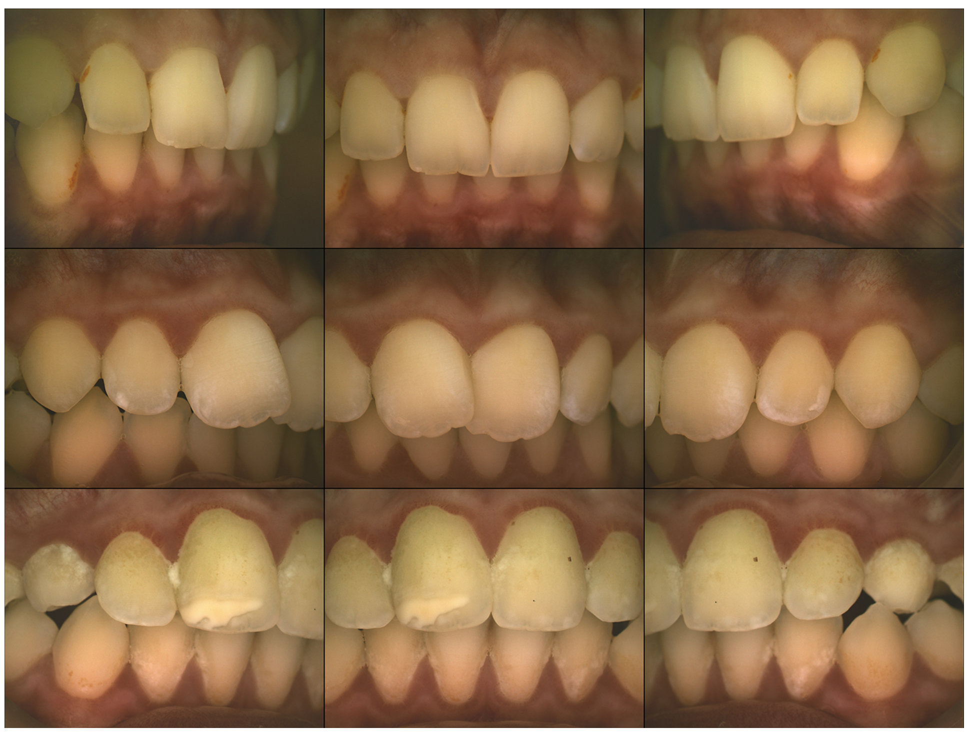

Fig. 2. (Top) Mild gingivitis with early signs of erythema and blunting of papilla.
(Middle) Mild to moderate gingivitis with more pronounced erythema and loss of definition due to oedema
(Bottom) Established gingivitis with marked erythema and oedema. Demarcated enamel defect on right central incisor.

dependent upon the level of detail required and should likely be linked to a corresponding gingival index to further confirm the established relationship between both conditions [27].

Visible plaque deposits are perhaps the most commonly occurring finding from previously acquired images. The presence of plaque is readily apparent as shown in Fig. 1, even without the use of disclosing agents. Due to the high-quality magnification of the images, it would seem feasible to score the plaque on the upper anterior teeth using the previously cited indices. The use of specific indices should balance the desire for quantification against efficient recording of epidemiologically useful information. If required, captured images could be rescored with different indices to explore additional outcomes in the same population.

Recent studies investigating the prevalence of plaque and gingivitis in adults found plaque accumulation on posterior teeth to be greater than anterior teeth [28,29]. This suggests assessment of plaque using only the anterior teeth may lead to an underestimation of plaque accumulation. It should be noted, however, that the anterior-posterior discrepancy in these studies was most pronounced in the severity of the plaque accumulation and not the dichotomised presence or absence (98.5% anterior sites plaque present, 99.7% posterior sites plaque present) [28]. Full mouth, clinical plaque scores should be recorded if attempting to validate the use of the dual-camera system for plaque scoring; this will permit exploration of whether anterior scores derived from the dual-camera images are reliably predictive of full mouth plaque accumulation in different populations.

If scoring the photographs for plaque accumulation alone, the use of a disclosing solution could be considered in combination with automatic scoring using planimetric analysis [20]. However, this would almost certainly interfere with the scoring of other conditions, particularly caries and gingivitis.

2.2. Gingivitis

Gingivitis is ubiquitous and non-discriminatory of age, gender, race, or geographical locality; various global epidemiological studies investigating both oral and general health confirm the universal prevalence of gingivitis. In its most common form, plaque-induced, this preventable condition presents in 50–90% of adults worldwide [27]. When we consider that gingivitis is the precursor to, and associated with, the more severe periodontitis, the sixth most common disease affecting humans, it is crucial that efficient means of tracking this disease continue to be investigated [30].

After reviewing the archived images, it would appear that the gingival condition in the upper anterior region is detailed enough to provide diagnostically useful data. Magnification of structures by virtue of the imaging assessment method is of particular value in relation to gingival assessment. Specifically, this magnification is particularly useful in differentiating the severity of gingivitis (Fig. 2); early signs of erythematous and oedematous change are clearly visible.

The visible differences in severity displayed in Fig. 2 suggest a range of gingival indices could be utilised to score this condition, as with plaque scoring, this would depend upon the desire for severity data versus simple dichotomised prevalence. Some gingival indices use 'bleeding on probing' to separate 'mild' and 'moderate' scores [22]. As tactile methods of assessment are not possible when scoring images, the use of a visual only index is necessary; the Modified Gingival Index could be suitable for this purpose and would increase the generalisability of results due to its extensive employment in oral epidemiology [31].

As with plaque accumulation, recent evidence suggests gingivitis to be both more common and more severe in posterior regions. In particular, the presence or absence of gingivitis differed significantly between anterior and posterior teeth (90.29% anterior sites gingivitis present vs. 97.43% posterior sites gingivitis present) [28,29]. A validation study should record full mouth gingivitis scores in tandem with image capture to permit exploration of the predictive nature of anterior gingivitis scores in different populations. As previously discussed, prevalence rates from image assessment can be higher due to magnification and enhanced viewing conditions and this may reduce the potential discrepancy between anterior and posterior scores.

2.3. Caries

Dental caries does not discern between population groups around the world and should continue to be viewed as a global problem carrying significant burden [32]; indeed, cavitated dentinal caries remains the most common disease affecting humans globally [30]. When the preventable nature of this disease is considered alongside the potentially profound impact it may have in its more advanced stages, it is unsurprising that it remains of highest priority in dental epidemiology [30,33]. Numerous indices have been developed to facilitate caries epidemiology, with the DMFT/dmft index dominating for over 60 years [34]. More recently, newer indices capable of recording the full process of de- and re-mineralisation are being utilised in both clinical practice and research with evidence supporting their accuracy and reproducibility [35–37].

Upon examination of the images, it would seem possible to not only differentiate between sound and obviously decayed surfaces but also to separate early and established carious lesions (Fig. 3). Again, magnification aids greatly in this process, accentuating the colour changes associated with both early and moderate decay. This suggests an index capable of recording both early enamel and more advanced dentinal caries could be utilised, however, the inability to assess surface roughness with tactile feedback may impact on detection of initial lesions. Whilst air-drying was not part of the fluorosis assessment that produced these images, it might be considered as part of a caries imaging protocol to improve detection of the very earliest of caries lesions. Direct assessment of caries lesions often involves evaluation from varying angles with reflection of the operating light to build a three-dimensional view of the lesion; images taken in a fixed position, therefore, do not permit a holistic assessment of the lesion.

More so than with any other condition discussed in this section, scoring of this condition using images of anterior teeth alone will lead to the most significant loss of relevant full-mouth data. Although the presence of caries in the anterior region is predictive of posterior caries and highlights high-risk individuals, it will lead to gross underestimation of caries prevalence due to a lack of posterior data. Whilst this should be confirmed through comparison with clinical assessment data gathered during validation, it is consistently shown that posterior teeth, particularly first and second permanent molars, are responsible for the majority of caries experience [38].

2.4. Enamel defects

As previously discussed, the remote scoring of dental fluorosis using this imaging method has been successfully validated, as such, this section will refer to non-fluorotic defects of enamel only.

Developmental defects of enamel (DDE) result from disturbances during formation of the teeth and can be found in both the primary and permanent dentitions [39]. If the defect results in a reduced thickness of enamel with normal mineral content, it is viewed as a quantitative defect and is often termed 'hypoplasia'. If, however, the enamel is of normal thickness but presents with a reduced mineral content, the defect is viewed as qualitative and is referred to as 'hypomineralisation' [40]. Hypomineralisation presents clinically as an opacity in the enamel; these opacities can be further divided into those that are well demarcated or those that are diffuse [40,41]. First permanent molars are most commonly affected by hypomineralisation, with permanent incisors often affected in tandem; in the presence of at least one affected first permanent molar, the condition is described as molar-incisor hypomineralisation (MIH) [42].

Enamel defects, particularly MIH, can impact the affected patient's quality of life and dental care [43–45]. Aesthetically, defects are often clearly visible if anterior teeth are affected and in cases of hypomineralisation, where the enamel is weakened due to increased porosity, further degradation of appearance may occur [41]. From a functional perspective, MIH is associated with increased sensitivity to thermal stimuli soon after tooth eruption [44]. Clinically, particularly in relation to defects resulting from hypomineralisation, the affected teeth can be difficult to anaesthetise and to restore using bonded restorations and may lead to severe dental anxiety. This can be problematic if trying to improve the appearance or function of these teeth from both a technical perspective of placing adequate restorations as well as management of patient expectations *peri*- and post-operatively [43,44].

Recent research suggests the prevalence of DDEs is increasing [41,46]. Due to the increased burden these defects can impose on patients, clinicians and healthcare systems, it would seem prudent to identify additional methods of tracking the presence of this condition [45].

The examples displayed in Fig. 4 demonstrate the overt visibility of DDEs in the acquired images. The detail present on the images would permit scoring using the commonly utilised Modified DDE index [47], providing descriptive prevalence data linked to a reliable and validated index.

As mentioned previously, first permanent molars are most commonly affected by enamel defects and whilst the presence of incisor defects is linked to molar defects, it is not possible to ascertain the prevalence of affected molars using only anterior images.

Fig. 3. (Top) Interproximal demineralisation evident between lateral and central incisors, presenting as white spot lesions.
(Bottom) Established carious lesions present on the mesial surfaces of the lateral incisors and the right central incisor. Visible discolouration due to underlying dentinal caries.

2.5. Orthodontic conditions

Current research struggles to identify a causal relationship between malocclusions and oral health due to the heterogeneity of the evidence base [48]. However, despite a lack of proven causality, there are at least associations between orthodontic problems and poorer oral health. Evidence suggests increased caries and periodontal disease prevalence in those presenting with malocclusions: the intuitive assumption being that rotated, crowded or displaced teeth may be more difficult to clean [48]. Focussing on the potential psychosocial impact of malocclusions, evidence suggests patients with malocclusions present with poorer oral health-related quality of life (OHRQoL) [49]. Specifically, emotionally and social wellbeing are impacted by the presence of malocclusions affecting the aesthetic zone [49,50].

A more established link is that between malocclusions and dental trauma; certain orthodontic presentations, particularly increased overjets, raise the risk of dental trauma; furthermore, the severity and number of teeth involved in traumatic injuries is also higher in the presence of increase overjets [51,52]. It should be noted, however, the common age of orthodontic intervention often falls after the peak period of when trauma occurs and early orthodontic intervention is necessary if attempting to mitigate this risk [53]. The potential impact of malocclusions on dental health and psychosocial wellbeing of affected individuals raise the importance of gathering accurate data related to orthodontic conditions; this is of particular relevance in countries with some form of state-funded orthodontic treatment. Indeed, digital images capable of providing data on caries and periodontal conditions in combination with orthodontic treatment need could elucidate the potential relationship between these conditions.

As shown in Fig. 5, various orthodontic presentations are visible in the dual-camera images. Displacement and crowding of teeth are readily apparent; as are anterior crossbites, open bites and deep overbites. Of particular value, the option to move the camera to a more oblique position offers a useful perspective of the subject's overjet, whether increased or reversed (Fig. 6).

Many indices have been developed to permit assessment of malocclusions, either qualitatively or quantitatively. Some indices are designed to capture not only the physical characteristics of malocclusions

Fig. 4. Examples of diffuse and demarcated enamel defects affecting permanent incisors.

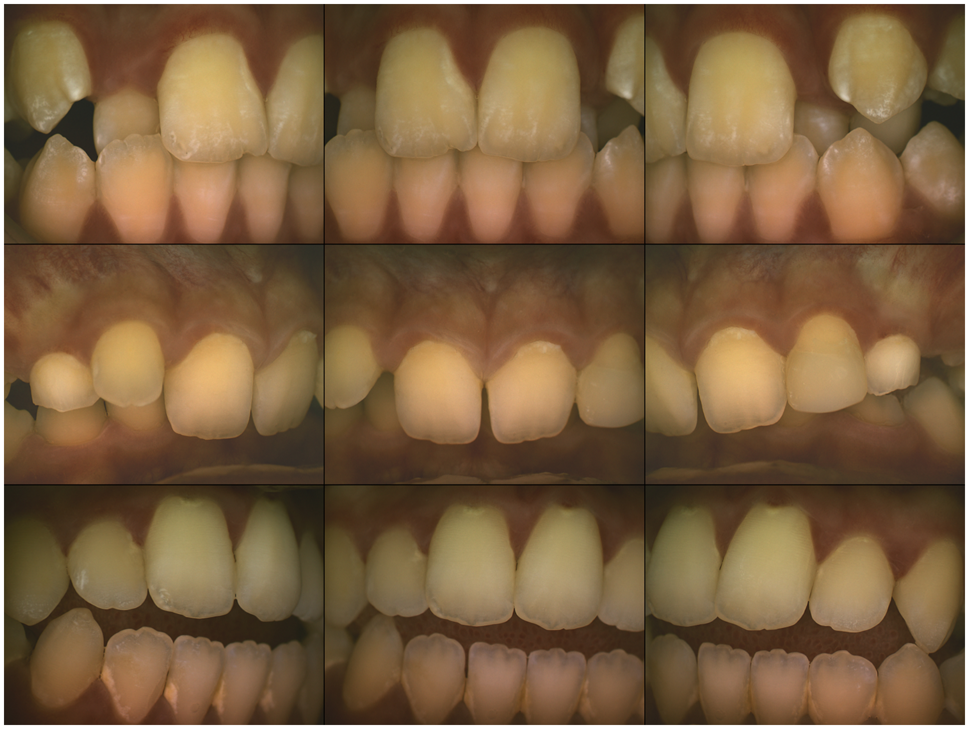

Fig. 5. (Top) Marked displacement of anterior teeth with anterior crossbites.
(Middle) Deep and complete overbite, displacement of left lateral incisor may suggest ectopic canine
(Bottom) Anterior open-bite with evidence of demineralisation on incisors

(crowding, displacement of teeth, hypodontia etc.) but also the perceived aesthetic impact due to the aforementioned link to reduced quality of life [54]. The ready appearance of anterior malocclusion in the images could permit the use of reliable indices for purposes of remote scoring. Almost all components of the Dental Aesthetic Index (DAI), for example, could be assessed [55], particularly if a reference scale could be added onto the images for millimetre measurements. The Index of Orthodontic Treatment Need (IOTN) requires greater consideration of posterior teeth [56], as does the long-established Angle's classification; subsequently, accurate scoring using these indices might be more challenging. Whilst comprehensive orthodontic assessment may not be possible using only anterior images, the availability of anterior data is still of epidemiological value. Validation of remote orthodontic assessment using the dual-camera system should incorporate quantitative clinical measurement of malocclusion features (i.e. overjet, overbite, contact point displacement) as well as assessment with established indices. This will permit exploration of the detection and quantification of orthodontic problems using the dual-camera images, as well as any potential utility of established orthodontic indices. Additionally, it might be possible for orthodontic treatment need to be assessed using the images to explore the relationship with treatment need determined by clinical assessment.

2.6. Additional considerations

A review of archived images acquired using the dual camera system suggests there may be further diagnostic utility associated with this already established and continually used imaging system. However, the

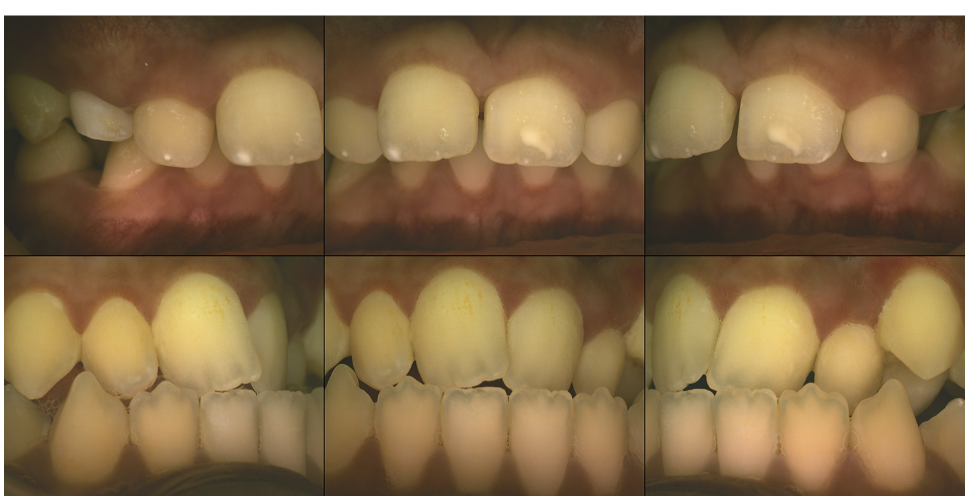

Fig. 6. (Top) Increased overjet, particularly evident in top-right example due to oblique angle.
(Bottom) Marked crowding of anterior segment with reverse overjet

true value of this additional data, in terms of clinical relevance and reliability, remains unknown.

Robust testing in an epidemiological setting is required to explore whether the diagnostic yield of this imaging system could be increased. An appropriate population should be identified, ideally one that presents a range of oral conditions with differing severity levels. Whilst the limitations of direct clinical assessment have been discussed, its employment is necessary in order to validate the use of images to score other conditions. The agreement between clinical and remote scores requires investigation to validate the accuracy, reliability and reproducibility of image assessment for each condition.

The significance of the loss of posterior data due to the anterior-only capture of the dual-camera system should be explored on a condition specific basis. Primarily, this could be achieved through correlation of image scores with full-mouth clinical scores to explore whether a relationship exists between abbreviated and full data sets. Crucially, this will quantify the difference in prevalence of each condition depending on the assessment method, highlighting the conditions for which dual-camera imaging in isolation is insufficient.

The absence of posterior data will likely significantly underestimate the true prevalence of conditions such as caries and enamel defects. Efforts to address this could include the use of other imaging modalities in a 'combined image assessment' approach.

Previous work utilising intraoral digital imaging in epidemiology demonstrated favourable intra- and inter-examiner reliability for caries assessment as well as good agreement with visual examination [6,16]. The use of an intraoral camera, perhaps only on the first permanent molars, could provide the key data missing from the dual-camera method for both caries and enamel defects. Efficient data capture is key to the logistics of epidemiology, as such, further use of an intraoral camera could include video capture of all teeth with post-processing to create a full-mouth image set for scoring purposes.

Interproximal data is not captured with white light imaging methods, a combined approach, therefore, could include the use of non-irradiating diagnostic tools such as near-infrared transillumination (NIR) [57]. Whilst more research is required to explore the reliability and accuracy of NIR, current evidence suggests this to be a valid and reliable diagnostic tool for interproximal caries diagnosis [57–59]; the use of NIR as an adjunct to dual-camera imaging merits further investigation.

The rationale for combined imaging methodologies is based upon the enhancement of an already established technology used continually in epidemiology; looking more speculatively into the future, more advanced technologies may be suitable as adjuncts or replacements of the dual-camera system. Handheld, intraoral high-definition video devices are already commonplace, and three-dimensional intraoral scanners are commercially available and successfully used for restorative and orthodontic purposes in clinical dentistry [60,61]. To date, the use of full-mouth video or intraoral scanners in large epidemiological studies remains unexplored; as the accuracy and volume of information captured by scanners increases, consideration should be given to the possibility of remote scoring using these modalities. This method could circumvent all previous discussion on lost posterior data and permit more holistic evaluation of various conditions.

Should the diagnostic utility of the dual-camera system be increased, the benefits could be twofold. Retrospectively, it might be possible to extract more data from archived images by rescoring for other oral conditions, increasing the epidemiological yield in the process. Prospectively, particularly in continuous programmes such as NHANES, the number of conditions assessable via remote scoring could be increased; this would bring with it the benefits described earlier in this review, namely, increased assessment objectivity. In tandem with clinical validation, the potential efficiencies in cost and time should be explored to contextualise any logistical and clinical benefits provided by the dual-camera system. Any attempt to increase the yield of this system requires validation through comparative analysis of remote scoring and direct clinical assessment. The use of additional imaging modalities should be considered to pre-emptively address the loss of posterior data and the impact this might have on accurate epidemiological assessment.

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Conflict of interest

None.

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