A Century of Change towards Prevention and Minimal Intervention in Cariology

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Cariology: A Century of Change in Prevention and Minimal Intervention

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Abstract

Better understanding of dental caries and other oral conditions has guided new strategies to prevent disease and manage its consequences at individual and public health levels. This paper discusses advances in prevention and minimal intervention dentistry over the last century by focussing on some milestones within scientific, clinical and public health arenas, mainly in cariology but also beyond, highlighting current understanding and evidence, along with future prospects.

Dentistry was initially established as a surgical specialty. Dental caries (similar to periodontitis) was considered to be an infectious disease 100 years ago. Its ubiquitous presence and rampant nature - coupled with limited diagnostic tools and therapeutic treatment options - meant that these dental diseases were managed mainly by excising affected tissue. The understanding of the diseases, a change in their prevalence, extent and severity, together with evolutions in operative techniques, technologies and materials have enabled a shift from surgical to preventive and minimal intervention dentistry approaches. Future challenges to embrace include: continuing the dental profession's move towards a more patient-centered, evidence-based, less invasive management of these diseases, focused on promoting and maintaining oral health in partnership with patients. In parallel, public health needs to continue to, for example, tackle social inequalities in dental health, develop better preventive and management options for existing disease-risk groups, such as the growing ageing population, and the development of reimbursement and health outcome models that facilitate implementation of these evolving strategies. A century ago, almost every treatment involved injections, a drill or scalpel, or a pair of forceps. Today, dentists have more options than ever before available to them. These are supported by evidence, have a minimal intervention focus and result in better outcomes for patients. The profession's greatest challenge is moving this evidence into practice.

Introduction

The concept of minimal (or minimum) intervention dentistry (Kearns et al. 2015) within oral healthcare has moved from a fringe topic, taken seriously by only a few, to the centre of oral healthcare. The advances in understanding of dental diseases, human behaviour, diagnostics, biomaterials, clinical operative techniques and technologies have all contributed to our understanding of why MID, as a patient-centred, biological and economical paradigm is the contemporary way to deliver dental care. This paper focuses on the gradual shift from surgical to minimal intervention and preventive dentistry over the past century and the implications of this shift for public health. We present some MID milestones within the scientific, clinical and public health arenas and consider the future prospects of MID.

MID

For most of human history, the cornerstones of dentistry have been removing carious enamel and dentin (Oxilia et al. 2015), excising infected periodontal tissues, and extracting teeth (and sometimes replacing them). With great foresight, in 1896 GV Black expressed a hope that "The day is surely coming, when we will be engaged in practising preventive, rather than reparative dentistry." (Joseph 2005). Yet establishing the dental profession as a surgical specialty in the late 19th and early 20th century seems to have set the path for a mainly operative approach towards managing dental diseases. This surgical approach was initially grounded in the necessity to treat rampant caries, periodontal disease and associated pain or infection with very limited means available. The growing understanding of dental caries, and simultaneously periodontitis, as lifestyle-mediated biofilm diseases, led to a feeling of futility associated with simply trying to "fix" symptoms without managing the disease or its causes. Improved diagnostics, operative techniques and biomaterials led to the emergence of novel concepts for preventing and controlling dental caries, followed by a change towards minimally interventive approaches towards other oral and dental conditions (Figure 1).

Dental Caries

The recognition of the role of bacteria as a cause of "fermentation" leading to dissolution of tooth substance (Miller 1890) led to the idea that dental caries was an infectious disease, requiring "excision" of affected tissues. Generations of dentists were taught a highly invasive, operatively-based approach to managing carious lesions (Black 1908), and this prevailed for almost a century. All contaminated (previously known as "infected") or demineralized (previously known as "affected") dental tissue was excised. The appreciation that certain bacteria, notably Streptococcus mutans, were more commonly associated with the disease (Keyes 1960; Loesche 1986) supported this approach, as did early successes in managing other, non-dental infectious diseases using antibiotics or vaccination. For dental caries, these approaches (i.e., managing caries as an infectious disease) largely failed to yield significant individual or public health benefits, evidenced by the widespread experience of rampant caries until the 1980s in most high-income countries.

Over the past 100 years, the futility of this traditional surgically-focused approach has become acknowledged (Fejerskov 2004). Alongside this, a growing recognition of the restorative "spiral" (Elderton 1990) and the escalating invasiveness of re-treatments, initiated by placement of the first restoration, is increasingly seen as part of the problem, rather than being the solution for managing caries. In contrast, an emerging understanding of the complexity of dental biofilm (Costerton 1995), supported by modern analytic technologies such as genomics, microbiomics and metabolomics, facilitated a change in approaching dental caries management. Knowledge of bacterial species' interdependence and communication systems (Kolenbrander et al. 2010) and the role of extracellular matrices (Koo et al. 2013) has clarified how bacteria need particular conditions, like the population of a city, to thrive (Marsh 2005). The shift between stages of physiologic biofilm conditions and dysbiosis is a response to environmental pressures (Neilands et al. 2014), a concept which invites management focussing on rebalancing and modulating the biofilm composition (Marsh 2006) and activity, and not attempting to eradicate the biofilm *per se*.

New technologies for detecting and treating dental caries were developed in parallel. These fuelled a change from managing the signs of the disease through excision and restoration towards preventing it or controlling its activity. Adhesive dentistry, initiated by the introduction of enamel acid-etching and resin bonding to dental tissues (Buonocore 1955), enabled dentists for the first time to remove only the tissue affected by bacterial contamination, instead of cutting cavities according to material demands (e.g., following the cavity preparation rules which G.V. Black had introduced for dental amalgam restorations). The ability to detect lesions at earlier stages using radiography, and later other technologies, may initially have driven earlier intervention to manage the disease at enamel and pre-cavitation stages (Innes and Schwendicke 2017), however there is trend that this is reversing and ultimately early detection has enabled targeted, less invasive management of early-stage disease.

There was a slow shift towards rebalancing the oral biofilm composition and activity (Elderton 1985; Handelman et al. 1976; Massler 1967; Walsh and Brostek 2013). The emerging health concept of modulating microbiomes via probiotics (i.e., live microorganisms conveying health benefits) has begun to be applied also to managing dental caries and periodontal disease oral biofilms (Mira 2018). Probiotics can replace pathogenic bacteria (such as S. mutans), modulating pathogenicity or altering the resulting immune response. However, their efficacy and the sustainability of any effect for caries prevention and management remains debatable. Notably, most probiotic bacteria are themselves acidogenic and aciduric (these properties are part of the mechanism that contributes to their health benefits, when applied to the skin or in the gut, for example). This may, in part, explain the heterogeneity in findings from clinical studies of caries prevention and management using probiotics.

Contemporary dentistry has turned towards strategies to arrest or even heal carious lesions. This success is illustrated by the dramatic decline in caries in children in most high-income countries (Lagerweij and van Loveren 2015). Use of fluoride in general and especially the regular use of fluoride toothpaste for preventing dental caries and arresting carious lesions is supported by strong and consistent evidence (Marinho et al. 2003; Marinho et al. 2013; Walsh et al. 2010; Wong et al. 2011). In fact, combined, home-based toothbrushing with fluoride toothpaste is likely to have had the greatest contribution to the reduction in dental caries prevalence and experience (Bratthall et al. 1996).

There have been developments of alternative/ supplemental strategies for lesion prevention/ mineralization (Featherstone et al. 2018; Fontana 2016; Ten Cate 2012). While calcium-based strategies still have inconsistent evidence for their effectiveness (Slayton et al. 2018; Urquhart et al. 2018), others seem promising, such as fluoride combined with antimicrobials (e.g. Stannous Fluoride and Silver Diamine Fluoride, or with arginine (Wolff and Schenkel 2018)). Novel remineralization methods, such as use of peptides to enhance deeper remineralization (Alkilzy et al. 2018), are showing promise.

Although the direct causal link between sugar and caries development was established through studies as far back as the 1950s and 60s [the Vipeholm (Gustafsson et al. 1954), Hopewood House (Harris 1963), Tristan da Cunha (Holloway et al. 1962) and Turku sugar studies (Scheinin et al. 1976)], sugar has only recently become of serious interest within dentistry. This omission may have been supported by a range of underlying agendas (Kearns et al. 2015). Only lately has the addictive potential of sugar begun to be understood; with sweet foods' stimulation of the human reward system, encouraging repeated over-consumption. In addition, there is only recent acknowledgement of the role of sugar in a wide range of health conditions acting through modification of the microbiome and inflammasome. The robust evidence linking both frequency, and amount, of sugar intake to caries increment and the recognition of the sugar "epidemic" as a problem for broader health, with sugar being a common risk factor for several important non-communicable diseases, has led to prioritization of approaches to reduce sugar consumption. However, there is still limited evidence to support strategies to promote behaviour change at an individual level (Albino and Tiwari 2016; Harris et al. 2012). Hence, public health efforts (such as reducing access to sugar-sweetened beverages, reformulation of foods and drinks, and sugar taxation) have increasingly become the focus of existing efforts (Schwendicke et al. 2016), and dentistry is increasingly involved in advocating for these measures. Linking our preventive efforts with those of other health disciplines will likely be to the benefit of our patients, the wider public and our profession (FDI World Dental Federation 2018; GBD Risk Factors Collaborators 2016; NCD Alliance 2018; World Health Organisation 2018).

Using restorative materials to seal carious lesions are another group of strategies that modify the environment and thereby the microbiome composition, aiming to arrest the lesion (Handelman et al. 1976). Studies on sealing sound and later carious tissue, showed that sealants impede acid diffusion into—and mineral diffusion out of—the dental tissue, and also isolate sealed bacteria from their dietary carbohydrate source (Griffin et al. 2008) These were carried out initially only for enamel, and later also for non-cavitated lesions, using sealant materials (Slayton et al. 2018; Wright et al. 2016), then cavitated ones extending into dentin using more mechanically robust materials (Mertz-Fairhurst et al. 1987). Sealing lesions is less mechanically destructive and more protective of the dental pulp than techniques involving removing all carious tissue (Mertz-Fairhurst et al. 1987; Ricketts et al. 2013). The understanding that bacteria can be sealed (Oong et al. 2008) was the pillar for less invasive carious tissue removal prior to placing a restoration, as cariogenic bacteria and carious tissue were allowed to be left and sealed in proximity to the pulp. Concepts such as stepwise or selective removal of carious tissue are built on this foundation, reducing the risk of pulp exposure and its sequelae. For primary teeth, the Hall Technique combines sealing of carious tissue with restoration using a stainless steel crown (Schwendicke et al. 2016).

Prevention and minimally invasive therapy: concepts crossing disciplines

Over the past century and alongside or following the changes towards minimally invasive treatments for caries (Table 1), other dental disciplines have adopted the concepts of prevention and MID. These include periodontology and oral and maxillofacial surgery.

The science of periodontology, for example, and the concepts of periodontal etiopathogenesis have evolved from the early descriptions of "alveolar pyorrhea" to the current concepts of "microbial dysbiosis". During this time, the clinical discipline of periodontics has seen many paradigm changes (Heitz-Mayfield and Lang 2013). Until the 1960s, removal of diseased tissues was considered necessary, and this led to invasive surgical interventions with removal of gingival tissue and/or bone. Later, surgical pocket elimination became the main objective of periodontal therapy and either gingivectomies or apically positioned flap procedures were widely undertaken. In the 1980s, with more knowledge of periodontal biology, pathogenesis and wound healing, the necessity for pocket elimination was challenged. The focus shifted to surgical flap procedures enabling access to the root surfaces for scaling and root planing. At the same time, it was demonstrated that non-surgical periodontal therapy was effective even in deep pockets (Badersten et al. 1984), and the concepts of intentional gingival curettage and excessive removal of contaminated cementum were abandoned. A critical probing depth was determined above which periodontal surgery led to more pocket reduction and clinical attachment gain than scaling and root planning (Lindhe et al. 1982). It was also established that the long-term success of periodontal therapy was critically dependent on the quality of maintenance care and plaque control (Axelsson and Lindhe 1981; Ramfjord et al. 1987). Important advances were also made in regenerative periodontal surgery for advanced intra-bony defects. Minimally invasive procedures show advantages in wound healing outcomes, recession and patient morbidity (Cortellini and Tonetti 2009; Trombelli et al. 2012). Twenty-year outcomes of regenerative therapy are promising (Cortellini et al. 2017). Novel periodontal tissue bioengineering is also under development (Fretwurst et al. 2018).

Similar to caries, the concepts of primary and secondary prevention are crucial in periodontology (Tonetti et al. 2015). Periodontitis is preventable through effective management of gingivitis and promotion of healthy lifestyles at both population and individual levels (Chapple et al. 2015; Jepsen et al. 2017). Risk profiling and stratification is of key importance (Giannobile et al. 2013) Overwhelming evidence shows that, in the majority of patients, periodontitis can be treated and effectively managed by a series of sequential phases of care, along with appropriate, sustained changes to self-care and smoking habits (Tonetti et al. 2017).

Oral and maxillofacial surgery has also become less invasive, with comparable reductions in morbidity. Instead of open approaches, techniques using endoscopes, microscopes or robotic systems are now routine in many procedures, such as those involving the sinuses, the temporo-mandibular joint or salivary glands, but also in tumor surgery and some aesthetic procedures. As an example, the field of trans-oral robotic surgery has seen dynamic development during the last years, with the number of papers published rising from three 2006 to 123 in 2016 alone (Poon et al. 2018). Minimal invasive surgery can also involve virtual planning based on 3D image data and its transfer using individual drill guides, robotic systems, patient-specific implants or navigation systems (Heiland et al. 2004). However, these systems need further refinement. Notably, though, these strategies require more preoperative data, possibly involving greater radiation exposure, and are more expensive than conventional approaches. More robust evidence of the benefits to patients is also needed.

Implications and the future

In most high-income countries, there have been improvements in dental health. Dental caries experience in children has been declining for decades (although early childhood caries remains a problem), and a simultaneous reduction has been seen recently in adults and seniors (Lagerweij and van Loveren 2015). More teeth are being retained in adults and seniors than ever before, with the need for removable prostheses decreasing dramatically. Despite the retention of more teeth, the number of periodontally-affected teeth does not seem to be increasing and this has been linked to falling smoking rates (Haisman-Welsh and Thomson 2012). While it would be pretentious to assume that these successes are grounded only in the changing approach of the profession towards dental health – from surgery to MID and prevention – this shift in managing dental disease has certainly contributed to it. Arising from these successes, however, are implications for how we manage dental caries and other conditions. Future shifts in morbidity and population demographics will further impact the direction of our profession. There are a number of aspects which need highlighting; these are considered below.

Firstly, dentistry is becoming more complex. Fifty years ago, a dentist would usually be presented with a fairly homogeneous group of patients: most were seen every 6 months, had cavitated lesions, required (mainly amalgam) restorations, and they lost teeth early on. With the differential, age- and socially-specific decline in the number of carious, restored or missing teeth, dentists nowadays are faced with a highly heterogeneous clientele. Hence, there is a need for more targeted diagnostics and personalized management to ensure that each of these very different patients receives the best treatment. So far, the tools for identifying the specific preventive and therapeutic needs of a patient rely largely on history-taking and clinical and/or radiographic findings. Most caries risk assessment systems, for example, use a range of risk indicators (caries experience, dietary habits, oral hygiene, fluoride intake), weight them and then assign the individual's risk status. The same is true for periodontal risk assessment tools and the recent re-classification of periodontal diseases, with multidimensional staging and grading (Papapanou et al. 2018). Based on such risk assessment or classification, active and supportive care can be determined, along with treatment thresholds (Schwendicke 2018). However, most risk assessment or disease classification systems have been only sparsely validated, show limited accuracy, and are not truly "personalized", but allow only a rough stratification of individuals according to risk. It can be assumed that, with progress in systems medicine allowing deeper insights into individual disease mechanisms based on clinical, imagery, (saliva or blood) sample or routine (also non-health) data, new insights into individual risk and current health conditions will be possible. Digital technologies will enable the best use of these data, eventually paving the way for "4P dentistry": precision, personalized, preventive and participatory dental care (Hood and Flores 2012). Such an approach promises considerable health gains at an individual level. However, at a population level, it could increase inequality, as those with the disease are less likely to seek or afford care (Knight and Thomson 2018).

This leads to the second aspect; while dentistry has changed for the better, not everyone has benefitted unequivocally from improvements in oral health. Its chronic, cumulative behaviour-mediated diseases mean that dentistry shares the problem of inequality with other non-communicable diseases; the common conditions disproportionately affect those of lower social position. This is grounded in inequality but aggravated by numerous social, structural and/or institutional factors. There is compelling evidence that dental services utilization, for example, is also highly unfairly distributed among different social, ethnic, economic, and educational groups. Dental care is therefore unlikely to reduce inequalities in health and may accentuate them. Increasing the application of public health policies—such as promoting fluoridation, anti-smoking policies or healthy diets—may help to reduce such social inequality. Moreover, preventive care and MID need to be made available to billions of people currently without access to conventional dental care, such as through using the Atraumatic Restorative Technique (Frencken et al. 2012), or through interprofessional collaborations .

Thirdly, with older people living longer and retaining more teeth but having multiple morbidities, the focus of dental care will need to change. Cumulative (lifelong) caries experience is unlikely to reduce (Broadbent et al. 2013; Knight and Thomson 2018), but shifted into older age (a phenomenon known as "morbidity compression"). Periodontal diseases will be mostly affected and this need will have to be addressed in elderly individuals (Schwendicke et al. 2018). Prevention and MID will need to account for this, with new concepts and products being required specifically for older people.

Finally, disease detection and assessment need to adapt. The concept that lesions can be active or inactive means that the "scar" of the disease (such as a discoloured, inactive lesion, or a residual radiographic radiolucency) is not necessarily a problem or a health risk for the patient. This is an important conceptual hurdle for the profession because the traditional approach has been to aim for a fully restored dentition as the gold standard. However, contemporary dentistry often involves neither removal (because this would do more harm than good, as discussed above) nor healing (because we are currently unable to do so) of carious lesions; thus, it is vital to be able to categorise a lesion as "arrested" or "active" and monitor this. Only a few validated systems to assess lesion activity are available; these include the International Caries Detection and Assessment System (ICDAS) (Pitts 2004) and the Nyvad Criteria (Nyvad and Baelum 2018). Moreover, the radiographic detection of carious lesions has been found to be limited in accuracy. Proximal radiographic examination has low sensitivity to detect small lesions (Schwendicke et al. 2015) and low agreement when used by general dentists. Machine learning, in particular the application of deep convolutional neural networks (CNNs) in order to build predictive models for radiographic imagery data, may help to improve accuracy in diagnosis.

Conclusion

In dentistry (and specifically cariology), we take for granted many of the things we now do on a daily basis, and it is easy to forget that there was little understanding of the pathogenesis of dental caries and other conditions 100 years ago, with almost every treatment involving injections, a drill, a scalpel or a pair of forceps. Today, we have a far better understanding of etiopathology of dental caries as a biofilm-based but behaviour-mediated disease. Dentists have a larger number of options and evidence available and, in parallel with other oral conditions, are moving towards more minimal intervention, evidence supported but personalised treatment options. that focus on promoting and maintaining oral health. Preventive and public health efforts across the globe have achieved a great deal in this, although the benefits are not yet universal.

We nevertheless face many challenges, some of which we have discussed above. However, one of the greatest challenges lies not in future developments, as important as these are, but in implementing what we know is most effective, and making the best use of what we already have developed and available to us: translating the science, ideas and concepts of cariology and minimally invasive dentistry into practice.

Author Contributions

All authors contributed to the conception and design of the manuscript. N.P.T. Innes and F Schwendicke drafted the manuscript outline and all authors contributed to writing and critical revision iteratively, gave final approval and agree to be accountable for all aspects of the work.

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Conflict of Interest

The authors declare no potential conflicts of interest with respect to the authorship and/or publication of this article.

Figure 1. Past, present and future aspects of prevention and minimal intervention.

Table 1. Milestones in the development of cariology.

Year	Development
1890	Non-specific plaque hypothesis described by Millar Periodontal disease described as pyorrhea by Riggs
1895	Roentgen discovers x-rays. Two weeks later, (January 1896), Walkhoff takes the first dental x-ray. X-rays. Roentgen wins the first Nobel Prize in Physics (1901).
1896	G V Black describes classical cavity preparations
1900	Focal theory; teeth are the reasons for systemic infections
1909	Role of fluoride in fluorosis established
1925	Raper introduces the bitewing technique.
1945	Grand Rapids initiates water fluoridation for caries prevention
1948	Introduction of panoramic radiography.
1954	Buonocore introduces acid-etching technique, allowing adhesive dentistry
1950s and 60s	Central role of sugar established through studies such as the Vipeholm, Hopewood House and Tristan da Cunha
1965	The association between plaque and periodontal disease is established by Loe
1970s	Costerton develops concepts of the biofilm and complex biofilm communities

	Sealing-in caries first demonstrated as viable strategy
1976	Loesche describes the specific plaque hypothesis.
1983	Development of cone-beam computed tomography (CBCT). Hafferjee and Socransky describe clusters of periodontal pathogens
1980s	Machine-driven periodontal instrumentation introduced
1987	Intraoral digital radiography introduced.
1990-2000s	Genetic links in periodontitis and caries established
1991	Marsh describes the ecological plaque hypothesis
2018	Robot performs a surgical implant with only human programming prior to the procedure at University of Beijing and the Fourth Military Medical University Stomatological Hospital in China
2018	Machine learning systems allow detection of carious lesions, periodontal bone loss and apical lesions with accuracies similar or superior to experienced dentists

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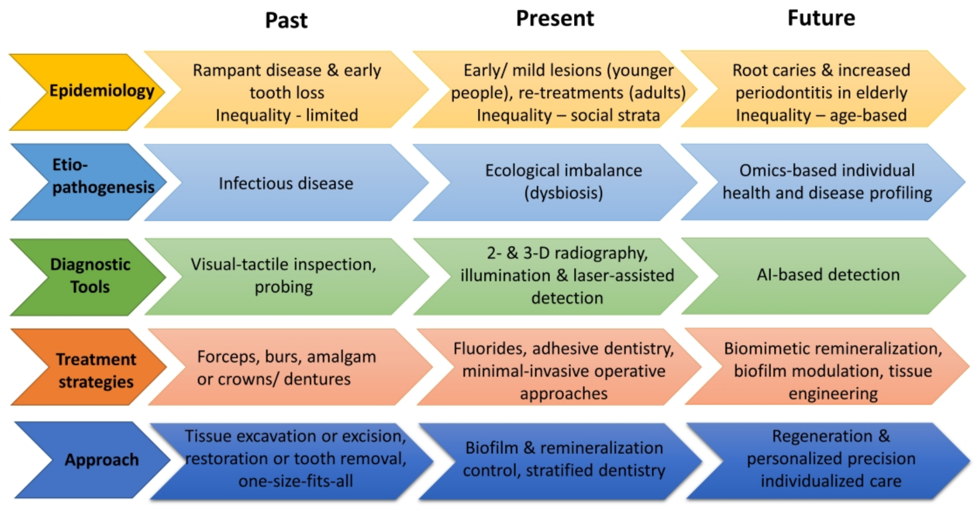

Past, present and future aspects of prevention and minimal intervention

Table 1. Milestones in the development of cariology.

Year	Development
1890	Non-specific plaque hypothesis described by Millar Periodontal disease described as pyorrhea by Riggs
1895	Roentgen discovers x-rays. Two weeks later, (January 1896), Walkhoff takes the first dental x-ray. X-rays. Roentgen wins the first Nobel Prize in Physics (1901).
1896	G V Black describes classical cavity preparations
1900	Focal theory; teeth are the reasons for systemic infections
1909	Role of fluoride in fluorosis established
1925	Raper introduces the bitewing technique.
1945	Grand Rapids initiates water fluoridation for caries prevention
1948	Introduction of panoramic radiography.
1954	Buonocore introduces acid-etching technique, allowing adhesive dentistry
1950s and 60s	Central role of sugar established through studies such as the Vipeholm, Hopewood House and Tristan da Cunha
1965	The association between plaque and periodontal disease is established by Loe
1970s	Costerton develops concepts of the biofilm and complex biofilm communities Sealing-in caries first demonstrated as viable strategy
1976	Loesche describes the specific plaque hypothesis.

1983	Development of cone-beam computed tomography (CBCT). Hafferjee and Socransky describe clusters of periodontal pathogens
1980s	Machine-driven periodontal instrumentation introduced
1987	Intraoral digital radiography introduced.
1990-2000s	Genetic links in periodontitis and caries established
1991	Marsh describes the ecological plaque hypothesis
2018	Robot performs a surgical implant with only human programming prior to the procedure at University of Beijing and the Fourth Military Medical University Stomatological Hospital in China
2018	Machine learning systems allow detection of carious lesions, periodontal bone loss and apical lesions with accuracies similar or superior to experienced dentists