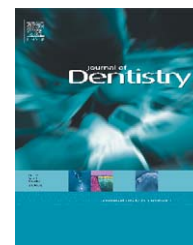


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Review

The bleaching of teeth: A review of the literature

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ABSTRACT

Objectives: To review current knowledge of tooth whitening with respect to external bleaching methods.

Data: The scope is the external bleaching of vital teeth and focuses on mechanisms; in vivo and in vitro measurement methods, and factors influencing the efficacy of the whitening process.

Sources: “Medline” and “ISI Web of Science” databases from 1966 and 1974, respectively were searched electronically with key words tooth, teeth, colo*r, white*, bleach* and peroxide.

Conclusions: The importance of tooth whitening for patients and consumers has seen a dramatic increase in the number of products and procedures over recent years, with a concomitant rise in publications on this topic. Literature suggests that the mechanisms of tooth whitening by peroxide occur by the diffusion of peroxide through enamel to cause oxidation and hence lightening of coloured species, particularly within the dentinal regions. A number of approaches are available for measuring changes in tooth colour. These include visual measurements by trained clinicians and instrumental measurements using spectrophotometry, chromameters and digital image analysis. The key factors that affect tooth whitening efficacy by peroxide containing products are concentration and time. In general, higher concentrations are faster than lower concentrations. However, lower concentrations can approach the efficacy of higher concentrations with extended treatment times. Alternative bleach systems to peroxide have received only minor attention. The efficacy of light activated systems versus non-light activated controls in clinical studies is limited and conflicting. Other factors which can influence tooth bleaching outcome include type of stain, initial tooth colour and subject age.

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Aesthetics of the teeth is of great importance to patients, including tooth colour. For examples, in the UK it has been reported that 28% of adults are dissatisfied with the appearance of their teeth¹ and in the USA that 34% of an adult population are dissatisfied with their current tooth colour.² In addition, in a survey of 3215 subjects from the UK 50% perceived they had some kind of tooth discolouration.³

The colour of the teeth is influenced by a combination of their intrinsic colour and the presence of any extrinsic stains that may form on the tooth surface.^{4,5} Intrinsic tooth colour is associated with the light scattering and adsorption properties of the enamel and dentine, with the properties of dentine playing a major role in determining the overall tooth colour.^{6,7} Extrinsic stains tend to form in areas of the teeth that are less

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accessible to tooth brushing and the abrasive action of a toothpaste⁸ and is often promoted by smoking, dietary intake of tannin-rich foods (e.g. red wine) and the use of certain cationic agents such as chlorhexidine, or metal salts such as tin and iron.^{4,9-11}

Tooth colour can be improved by a number of methods and approaches including whitening toothpastes, professional cleaning by scaling and polishing to remove stain and tartar, internal bleaching of non-vital teeth, external bleaching of vital teeth, microabrasion of enamel with abrasives and acid, placement of crowns and veneers.¹²⁻¹⁴ The scope of the current literature review is restricted to the external bleaching of vital teeth and will focus on the following topics; mechanisms of tooth bleaching; in vivo and in vitro evaluation methods, and factors influencing the efficacy of the tooth bleaching process.

There are a number of methods and approaches that have been described in the literature for the bleaching of vital teeth. For examples, methods utilising different bleach agents, concentrations, times of application, product format, application mode and light activation.¹⁵⁻¹⁷ However, three fundamental bleaching approaches exist, namely, dentist-supervised nightguard bleaching, in-office or power bleaching and mass market bleaching products.¹⁸ Nightguard bleaching typically uses a relatively low level of whitening agent applied to the teeth via a custom fabricated mouth guard and is worn at night for at least 2 weeks.^{15,16,19} In-office bleaching generally uses relatively high levels of whitening agents, for example 25-35% hydrogen peroxide containing products, for shorter time periods. The whitening gel is applied to the teeth after protection of the soft tissues and the peroxide may be further activated by heat or light.^{15,16} The in-office treatment can result in significant whitening after only one treatment visit^{15,16} but may require multiple treatment appointments for optimum whitening.^{20,21} Mass market products typically contain low levels of whitening agent (e.g. 3-6% hydrogen peroxide) that are self-applied to the teeth via gum shields, strips or paint-on product formats and typically require twice per day application for up to 2 weeks.²²⁻²⁴

1. Mechanism of tooth bleaching

Bleaching is a decolourisation or whitening process that can occur in solution or on a surface.²⁵ The colour producing materials in solution or on a surface are typically organic compounds that possess extended conjugated chains of alternating single or double bonds and often include heteroatoms, carbonyl, and phenyl rings in the conjugated system and are often referred to as a chromophore. Bleaching and decolourisation of the chromophore can occur by destroying one or more of the double bonds in the conjugated chain, by cleaving the conjugated chain, or by oxidation of other chemical moieties in the conjugated chain.²⁵ Hydrogen peroxide oxidises a wide variety of organic and inorganic compounds. The mechanisms of these reactions are varied and dependent on the substrate, the reaction environment, and catalysis.²⁶ In general, the mechanism of bleaching by hydrogen peroxide is not well understood and it can form a number of different active

oxygen species depending on reaction conditions, including temperature, pH, light and presence of transition metals.²⁶ Under alkaline conditions, hydrogen peroxide bleaching generally proceeds via the perhydroxyl anion (HO_2^-). Other conditions can give rise to free radical formation, for example, by homolytic cleavage of either an O-H bond or the O-O bond in hydrogen peroxide to give $\text{H}^\bullet + \bullet\text{OOH}$ and 2^\bulletOH (hydroxyl radical), respectively.²⁶ Under photochemically initiated reactions using light or lasers, the formation of hydroxyl radicals from hydrogen peroxide has been shown to increase.²⁷

The mechanism by which teeth are whitened by oxidising materials such as hydrogen peroxide and carbamide peroxide are currently not fully understood.^{17,28} Considering the available literature, evidence points towards the initial diffusion of peroxide into and through the enamel to reach the enamel dentine junction and dentine regions. Indeed, in vitro experiments by a number of authors have demonstrated the penetration of low levels of peroxide into the pulp chambers of extracted teeth after exposure times of 15-30 min from a range of peroxide products and solutions.^{23,29-33} The levels of peroxide measured in these experiments is considerably much lower than that needed to produce pulpal enzyme inactivation.³²

As peroxide diffuses into the tooth, it can react with organic coloured materials found within the tooth structures leading to a reduction in colour. This is particularly evident within dentine as demonstrated by McCaslin et al.³⁴ who showed, using hemi-sectioned human teeth mounted on glass slides, that following external bleaching with carbamide peroxide, colour changes occurred throughout the dentine. Indeed, the treatment of dentine specimens with 10% carbamide peroxide, 5.3% and 6% hydrogen peroxide has been shown to give a significant reduction in yellowness and an increase in whiteness.^{35,36} In addition, Sulieman et al.³⁷ showed using sectioned extracted teeth stained internally with black tea chromophores that significant bleaching occurred within the dentine, particularly on the buccal surface where a 35% hydrogen peroxide gel had been applied.

For tetracycline stained teeth, the colour is derived from photo-oxidation of tetracycline molecules bound within the tooth structures.³⁸ In some cases, it is possible to bleach these teeth to give significant and long lasting tooth whitening.³⁹ The mechanism by which peroxide affects the tetracycline stain is considered to be by chemical degradation of the unsaturated quinone type structures found in tetracycline leading to less coloured molecules.^{40,41} However, in contrast there appears to be a paucity of information available in the literature regarding the nature and chemical composition of the coloured materials naturally found within the dental hard tissues and the mechanistic effects of peroxide on these structures. Thus, this is clearly an area that requires further research if the chemical mechanistic aspects of tooth bleaching are to be significantly resolved.

2. Clinical measurement of tooth whitening

A number of methods are available for measuring the colour of teeth and the colour changes undergone during tooth

whitening procedures.⁵ One of the most common methods is the simultaneous comparison of the tooth with a standard shade guide.⁴² This has been used in a large number of tooth whitening studies where longitudinal changes in tooth colour have been measured.^{17,19,43-47} It is a subjective method and a number of factors can influence this process. For examples, lighting conditions, experience, age, fatigue of the human eye, make-up, room decor and colour blindness.^{4,48} Therefore, care must be taken to standardise and control these factors. Indeed, the tooth colour discriminatory ability of individuals can be improved with training and experience^{4,49} and it is often reported that investigators undergo a number of colour calibration exercises and training with shade guides when conducting tooth whitening studies.^{43-45,47,50}

Colourimeters are instruments designed to measure the colour of objects. The colour is often expressed in terms of the Commission Internationale de l'Éclairage (CIE) Lab colour space. The CIE Lab colour space represents a uniform colour space, with equal distances corresponding to equal perceived colour differences. In this three-dimensional colour space the three axes are L^* , a^* and b^* . The L^* value is a measure of the lightness of an object and is quantified on a scale such that a perfect black has an L^* value of zero and a perfect reflecting diffuser an L^* value of 100. The a^* value is a measure of redness (positive a^*) or greenness (negative a^*). The b^* value is a measure of yellowness (positive b^*) or blueness (negative b^*). The a^* and b^* co-ordinates approach zero for neutral colours (white, greys) and increase in magnitude for more saturated or intense colours.⁵¹ The use of a colourimeter to measure tooth colour in vivo requires the fabrication of a custom positioning jig to ensure reproducible intra-oral positioning of the instrument's aperture onto the tooth surface.⁵² This approach has been utilised in a number of studies for measuring longitudinal changes in tooth colour following tooth whitening procedures.^{44,53-55}

Another approach for measuring tooth colour is by using non-contact camera-based digital imaging and analysis

systems.⁵⁶⁻⁶⁰ Typically, an image of the anterior teeth is captured under controlled lighting conditions by a digital camera together with suitable calibration tiles or standards and then subsequently analysed via computer software to determine the colour of the individual teeth, often expressing them in terms of CIE Lab values. For example, after 14 days use of a 10% carbamide peroxide tray-based system, the mean change from baseline in L^* and b^* were 2.07 and -1.67, respectively.⁵⁷

3. In vitro models for tooth whitening

The use of in vitro models is often important for the initial evaluation of prototypes and the optimisation of treatment conditions. In addition, these models can be used to gain important information on the safety of the product in terms of its effect on the hard tissues and provide mechanistic understanding of the bleaching process. There have been numerous in vitro models described in the literature which have been used to evaluate the efficacy of tooth whitening products and these are summarised in Table 1. The majority of these models use whole or cut human or bovine tooth specimens and utilises their pre-existing colour. However, some in vitro models increase the levels of intrinsic tooth colour by pre-staining with black tea or blood components. In general, the changes in tooth colour are measured by instrumental means.

4. Factors influencing tooth whitening

4.1. Type of bleach

The majority of contemporary tooth whitening studies involve the use of either hydrogen peroxide or carbamide peroxide. This latter material is an adduct of urea and hydrogen

Table 1 – Summary of in vitro models used for evaluation of tooth bleaching materials

Reference	Substrate	Bleaching agents	Colour measurement
Leonard et al. ⁴⁵	Human anterior teeth	5%, 10% and 16% CP	Visual assessment with shade guide
Lenhard et al. ⁶¹	Human anterior teeth	10% CP	Colourimeter
Jones et al. ⁶²	Human incisors	35% HP, 20% and 10% CP	Colourimeter
Joiner and Thakker ³²	Human incisors and premolars	6% HP	Colourimeter
Haywood et al. ⁶³	Human anterior teeth and premolars	10% CP, 1.5% HP	Colourimeter
Rosenstiel et al. ⁶⁴	Human anterior teeth	35% HP	Colourimeter
Kwon et al. ⁶⁵	Bovine incisors	30% HP	Spectrophotometer
Wetter et al. ⁶⁶	Bovine incisors, artificially stained	35% HP + light	Spectrophotometer
White et al. ³⁶	Human enamel blocks	5.3% HP, 10% CP	Spectrophotometer
White et al. ⁶⁷	Human enamel blocks	5.3% and 6.5% HP, 10% and 20% CP	Image analysis
Joiner et al. ³⁵	Human enamel blocks	6% HP	Colourimeter
Suliman et al. ⁶⁸	Human molars, cut and stained internally with black tea	35% HP	Visual assessment, colourimeter and image analysis
Van der Burgt et al. ⁶⁹	Human premolars stained in pulp by blood components	None	Visual assessment vs. colour standards
Marin et al. ⁷⁰	Human premolars stained in pulp by blood components and sectioned	30% HP and sodium perborate	Reflection densitometer

CP – carbamide peroxide, HP – hydrogen peroxide.

peroxide which on contact with water breaks down to urea and hydrogen peroxide. For example, a 10% (w/w) carbamide peroxide gel would yield a maximum of 3.6% (w/w) hydrogen peroxide. In general, the efficacy of hydrogen peroxide containing products are approximately the same when compared with carbamide peroxide containing products with equivalent or similar hydrogen peroxide content and delivered using similar format and formulations, either tested *in vitro*³² or *in vivo*.^{71,44} For example, Nathoo et al.⁷¹ demonstrated in a clinical study that a once a day application of either a 25% carbamide peroxide gel or a 8.7% hydrogen peroxide gel both gave a statistically significant tooth shade lightening after 2 weeks use compared to baseline, but found no statistically significant differences between products.

An alternative source of hydrogen peroxide is sodium percarbonate and this has been used in a silicone polymer containing product that is painted onto the teeth forming a durable film for overnight bleaching procedures.⁷² The peroxide is slowly released for up to 4 h⁷³ and gave significant tooth colour improvement after 2 weeks versus baseline. However, the relative clinical or *in vitro* efficacy of sodium percarbonate versus hydrogen peroxide tested in the same product format and conditions has not been reported.

A tooth bleaching system based on sodium chlorite applied to the tooth surface and activated under acidic conditions has been described in the literature,^{74,75} however, no efficacy data has been reported to date. Similarly, other potential vital tooth bleaching systems have been outlined in the literature with limited supporting evidence for their efficacy. These include sodium perborate,⁷⁶ peroxymonosulphate,^{77,78} peroxide plus metal catalysts^{21,79-82} and oxidoreductase enzymes.⁸² The long-term acceptability and relative efficacy of these alternative tooth bleaching systems requires significant further research.

4.2. Concentration and time

Two of the key factors in determining overall tooth whitening efficacy from peroxide containing products are the concentration of the peroxide and duration of application. For example, Sulieman et al.⁸³ compared the *in vitro* tooth bleaching efficacy of gels containing 5-35% hydrogen peroxide and found that the higher the concentration, the lower the number of gel applications required to produce uniform bleaching. Similar results were found by Leonard et al.⁴⁵ who compared the *in vitro* tooth bleaching efficacy of 5%, 10% and 16% carbamide peroxide gels and found the whitening was initially faster for the 16% and 10% than the 5% concentration. However, the efficacy of the 5% approached the higher concentrations when the treatment time was extended. In a clinical study using custom made bleaching trays, Kihn et al.⁴⁴ showed that a 15% carbamide peroxide gel gave significantly more tooth whitening than a 10% carbamide gel after 2 weeks use. This result was confirmed in another clinical study reported by Matis et al.⁸⁴ However, in this latter study, by extending treatment time to 6 weeks, the differences in tooth lightness were no longer of statistical significance. The initial faster rate of bleaching for higher concentrations of carbamide peroxide has also been observed when bleaching tetracycline stained teeth *in vivo* over a 6 months period.⁸⁵

In this case, the most rapid whitening occurred in the first month with 20% carbamide peroxide compared to 15% and 10% carbamide peroxide. In addition, clinical studies with hydrogen peroxide strip based products have shown similar concentration and time effects for tooth whitening efficacy.^{86,87}

4.3. Heat and light

The rate of chemical reactions can be increased by increasing the temperature, where a 10 °C rise can double the rate of reaction.¹⁵ The use of high-intensity light, for raising the temperature of the hydrogen peroxide and accelerating the rate of chemical bleaching of teeth was reported in 1918 by Abbot.¹⁶ Other approaches for heating the peroxide have historically been described to accelerate tooth bleaching, such as heated dental instruments.¹⁶ However, excessive heating can cause irreversible damage to the dental pulp.⁸⁸ Contemporary approaches and literature has focussed on accelerating peroxide bleaching with simultaneous illumination of the anterior teeth with various sources having a range of wavelengths and spectral power, for examples, halogen curing lights, plasma arc lamps, lasers and light-emitting diodes.^{21,66} For some light sources, significant increases in pulpal temperatures have been measured using *in vitro* models during tooth bleaching.^{89,90} The light source can activate peroxide to accelerate the chemical redox reactions of the bleaching process.⁹¹ In addition, it has been speculated that the light source can energise the tooth stain to aid the overall acceleration of the bleaching process.⁹² Some products that are used in light activated bleaching procedures contain ingredients that claim to aid the energy transfer from the light to the peroxide gel and are often coloured materials, for examples, carotene and manganese sulphate.^{21,66,93-96}

Case studies have demonstrated the efficacy of light activated peroxide tooth bleaching systems.^{16,92,93,97-99} However, the literature evidence from *in vitro* and clinical studies for the actual effect of light on tooth bleaching versus a suitable non-light control is limited and controversial. An *in vitro* study using naturally coloured extracted human teeth showed that the application of various light sources significantly improved the whitening efficacy of some bleach materials, but not for others.⁹⁴ Other *in vitro* studies have clearly shown significant tooth whitening benefits for peroxide plus light versus suitable control conditions.^{66,100} However, these studies artificially stained the tooth specimens with, for examples, black tea, coffee, tobacco and red wine, i.e. ingredients commonly found to promote extrinsic stains. These chromophores are likely to be different to that which may be found naturally inside the tooth.

Tavares et al.¹⁰¹ conducted a tooth whitening clinical study to compare 15% hydrogen peroxide gel illuminated with a gas plasma light source versus 15% peroxide alone versus placebo gel plus light, all treatments lasting 1 h. The change in Vita shade from baseline for peroxide plus light, peroxide alone and placebo plus light were 8.35, 5.88 and 4.93, respectively, with peroxide plus light being significantly different to the other two groups. In contrast, Hein et al.⁹⁵ demonstrated no additional effect of any of the three light sources tested over the bleaching gel alone for three commercial products in a

split mouth clinical design. Thus, further work is clearly required in order to unequivocally demonstrate the additional efficacy benefit of light activated tooth whitening systems versus their non-light activated controls.

4.4. Other factors

The type of intrinsic stain and the initial tooth colour can play a significant part in the ultimate outcome of tooth bleaching. Mild to moderate tetracycline staining tends to respond to extended bleaching regimes of 2–6 months.^{102,103} However, it is documented that severe tetracycline staining is more difficult to bleach¹⁰² with the darker the teeth at baseline, the longer it can take to lighten them.⁷³ In addition, it is reported that when the tetracycline discolouration is located in the neck of the tooth, the prognosis for bleaching is the poorest; when it is dark gray or blue, the prognosis also is poor.¹⁰⁴

For non-tetracycline stained teeth, a meta analysis of placebo controlled, patient applied tooth whitening clinical studies using 10% carbamide peroxide found that 93% of people who used the peroxide product and 20% who used the placebo exhibited a change of two shade guide units. In addition, 20% of subjects who used the peroxide product achieved a mean change of five shade guide units.¹⁰⁵ Ishikawa-Nagai et al.¹⁰⁶ evaluated the tooth colour change of 80 subjects after using 10% carbamide peroxide in a gum shield over 14 days and found a strong correlation between total colour change and b^* values, demonstrating that bleaching works efficiently for teeth with a yellow hue. Further, an analysis of the clinical results with over 600 subjects undergoing tooth bleaching, indicate that the yellower the teeth at baseline, the greater the magnitude of the whitening response.¹⁰⁷ This analysis demonstrated a significant relationship between subject age and the magnitude of whitening response, with younger subjects experiencing greater tooth whitening.¹⁰⁷ Further, there was a relationship between subject age and the initial colour and the magnitude of whitening response. Older subjects with less yellow initial tooth colour exhibited the smallest mean colour change post bleaching, whereas younger subjects with more yellow initial tooth colour exhibited the greatest mean colour change post bleaching.¹⁰⁷ In addition, neither gender nor coffee/tea consumption had any significant affect on the tooth whitening response.¹⁰⁷

The presence on the tooth surface of pellicle and plaque has the theoretical potential to reduce the activity of peroxide by acting as a substrate for peroxide bleaching and/or degrading peroxide. Wattanapayungkul et al.¹⁰⁸ has shown that the rate of peroxide degradation did not increase with the presence of pellicle on tooth surfaces in vivo over 1 h indicating that pellicle does not have a significant effect on the stability of peroxide. In addition, a clinical study by Gerlach et al.,⁸⁶ comparing the effect of immediate prebrushing with a toothpaste versus no prebrushing prior to tooth bleaching with 6.5% hydrogen peroxide over a 14-day period, suggested that toothbrushing immediately before bleaching has only a modest positive impact on overall efficacy. Thus, the modifying role of pellicle on peroxide delivery and whitening efficacy appears to be overall small.

5. Concluding remarks

The importance of tooth whitening for patients and consumers has seen a dramatic rise in the number of tooth whitening products and procedures. Concomitantly, there has been a rapid increase of published in vivo and in vitro tooth whitening studies. Indeed, it is clearly evident that there is an extensive literature describing their efficacy and safety. However, some of this literature is conflicting, and these topics warrant further careful evaluation as they were outside the scope of the current review. A number of approaches to measuring tooth colour changes following tooth whitening exist, each with their own advantages and disadvantages, and this topic is likely to be an area commanding further research in the future. With the continued interest in tooth whitening amongst basic and clinical researchers, the further mechanistic understanding and optimisation of the factors controlling the tooth whitening process will continue to expand. This will give further improvements to the tooth whitening products and procedures, and give significant benefits to the field of aesthetic dentistry. This will ultimately lead to the enhancement of patient compliance and satisfaction with the whitening outcome.

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