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Enamel Surface Changes After Exposure to Bleaching Gels Containing Carbamide Peroxide or Hydrogen Peroxide

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Clinical Relevance

Bleaching gels with a relatively high concentration of peroxide and shorter application time might be less harmful to enamel. A clinically significant whitening effect can be obtained after a few bleaching treatments.

SUMMARY

Objective: This study evaluated the differences in enamel color change, surface hardness, elastic modulus, and surface roughness between treatments with four bleaching gels containing carbamide peroxide (two at 10% and one each at 35%, and 45%) and two bleaching gels containing hydrogen peroxide (two at 40%).

Methods: Enamel specimens were bleached and color changes were measured. Color change was calculated using either ΔE or the Bleaching Index (BI). Then, surface hardness, elastic modulus, and surface roughness of the enamel specimens were evaluated. All measurements were performed at baseline and directly after the first bleaching treatment for all carbamide peroxide– and hydrogen peroxide–containing bleaching gels. In addition, final measurements were made 24 hours after each of a total of 10 bleaching treatments for carbamide peroxide bleaching gels, and 1 week after each of a total of three bleaching treatments for hydrogen peroxide bleaching gels.

Results: After the last bleaching treatment, respective ΔE scores were 17.6 and 8.2 for the two 10% carbamide peroxide gels, 12.9 and 5.6 for the 45% and 35% carbamide peroxide gels,

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and 9.6 and 13.9 for the two 40% hydrogen peroxide gels. The respective BI scores were −2.0 and −2.0 for the two 10% carbamide peroxide gels, −3.5 and −1.5 for the 45% and 35% carbamide peroxide gels, and −2.0 and −3.0 for the two 40% hydrogen peroxide gels. Each bleaching gel treatment resulted in significant whitening; however, no significant difference was found among the gels after the last bleaching. Whitening occurred within the first bleaching treatments and did not increase significantly during the remaining treatments. Surface hardness significantly decreased after the last bleaching treatment, when 10% carbamide peroxide was used. Furthermore, significant changes in the elastic modulus or surface roughness occurred only after treatment with 10% carbamide peroxide.

Conclusion: All six bleaching gels effectively bleached the enamel specimens independent of their concentration of peroxide. Gels with low peroxide concentration and longer contact time negatively affected the enamel surface.

INTRODUCTION

Modern dentistry focuses not only on the treatment of dental diseases but also deals increasingly with the esthetic demands of patients. Whitened teeth lead people to have a better assessment of a person's social competence, intellectual ability, psychological adjustment, and relationship satisfaction.[1] Remarkably, more than one-third of people in the United States and about every fifth person in the United Kingdom are dissatisfied with the color of their teeth, which explains the widespread use of tooth whitening products.[2,3] Tooth whitening products usually contain carbamide peroxide or hydrogen peroxide in different concentrations, carbamide peroxide releasing about 33% of its content as hydrogen peroxide (the active bleaching agent).[4] During ionization of hydrogen peroxide, free oxygen ions are released and cause oxidation of discolored organic pigments in dental hard tissues, thereby resulting in whitening of teeth.[5,6] The efficacy of different tooth whitening products is mostly affected by the final peroxide concentration and the contact time of the bleaching agent with the dental hard tissue.[6]

Three types of bleaching products exist, according to the concentration of peroxide in the tooth whitening product: over-the-counter home-use bleaching gels with a concentration of up to 10% carbamide peroxide, dentist-dispensed home-use bleaching gels with a concentration of up to 20% carbamide peroxide, and professional in-office bleaching gels with a concentration of up to 45% carbamide peroxide or 40% hydrogen peroxide.[6,7] Home-use bleaching gels have the advantages of being self-administered; requiring no, or only short, chair-side time; and being cheaper than an in-office bleaching treatment.[5,8] In-office bleaching treatments, on the other hand, have the advantages of being performed under the dentist's control, requiring less total bleaching time, and avoiding soft tissue exposure and risk of material ingestion.[9,10]

Efficacy of tooth whitening products can be verified visually by a dental shade guide or quantitatively by a spectrophotometer. Spectrophotometers allow for an objective assessment of tooth color and thus provide data that can be used in statistical calculations. The measured colors of a given dental shade are presented by CIELAB values according to the Commission Internationale de l'Eclairage (International Commission on Illumination). Color differences can be calculated using the formula $\Delta E = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]/2$, where ΔL, Δa, and Δb are differences in lightness (L, achromatic coordinate), green-red coordinate (a), and blue-yellow coordinate (b), respectively.[11,12] For a tooth color change to be clinically visible, ΔE has to be higher than 3.7, with the prerequisite of a positive shift in the lightness coordinate and a shift in the blue-yellow coordinate.[13,14] To facilitate communication with the patient, a recently marketed spectrophotometer with a simplified color index (Bleaching Index [BI]; VITA Zahnfabrik, Bad Säckingen, Germany) has been designed, which indicates whitening of teeth in an easy way using decreasing numbers.

Despite the widespread success of tooth whitening products regarding their efficacy in whitening teeth, there is no general consensus about possible negative effects on enamel. On the contrary, it is controversial in the literature whether bleaching gels adversely affect enamel. Several studies using carbamide peroxide with concentrations from 10% to 35% showed a decrease in surface hardness,[15,16] demineralization of enamel,[17] alterations in the surface roughness,[7,18] and even damage to the enamel surface.[19] Other studies using the same concentrations of carbamide peroxide and hydrogen peroxide, however, showed no impact on enamel[20] with respect to microhardness,[21] surface roughness,[5,22] or other deleterious effects on enamel.[23]

Discrepancies in the literature may be due to different study designs, for example, differences in peroxide concentrations, contact time, and tooth

color analyses. Furthermore, most studies usually consider single factors that could be affected by bleaching and are mostly focused on either home-use bleaching gels or in-office bleaching gels. The aim of the present study was to evaluate the change in tooth color (ΔE) and bleaching efficacy (using the BI) of six home-use and in-office bleaching gels as well as their impact on surface microhardness, elastic modulus (EM), and surface roughness of enamel. Furthermore, the recently introduced BI was compared with the CIELAB system in order to investigate its usefulness.

METHODS AND MATERIALS

Preparation of Enamel Specimens

Ninety-six extracted human incisors without caries, erosion, cracks, cavities, or restorations were selected, cleaned, and stored in 1% chloramine T trihydrate solution. Before the extraction, the patients were informed about the possibility that their teeth would be used for research purposes and consent was obtained. Before preparation of enamel specimens, the teeth were rinsed thoroughly under running tap water. The crowns of the incisors were separated from their roots using a diamond blade saw (IsoMet Low Speed Saw, Buehler, Lake Bluff, IL, USA) and embedded in acrylic resin as previously described.[24] The embedded crowns underwent a standardized grinding and polishing procedure on a polishing machine (LabPol 21, Struers, Ballerup, Denmark) with silicon carbide paper discs of grain size 18, 8, and 5 μm (Struers) for 60 seconds each and a Struers polishing cloth with a 3-μm diamond abrasive (LaboPol-6, DP-Mol Polishing, DP-Stick HQ, Struers). All grinding and polishing procedures were carried out under water cooling with ultrasonication for 1 minute in tap water between every grinding and polishing step. Enamel specimens were assigned to one of the six bleaching gels (n = 16) according to their baseline color in order to provide identical initial conditions in all groups. For storage before and between experimental procedures, a mineral solution (1.5 mmol/L $CaCl_2$, 1.0 mmol/L KH_2PO_4, and 50 mmol/L NaCl, pH = 7.0)[25] was used to simulate the oral environment.

Experimental Procedures

The carbamide peroxide–containing gels designed for home-use bleaching that were tested in the present study were Opalescence PF 10% and Home Whitening 10%, and those designed for in-office bleaching were Opalescence Quick 45% and Home Whitening 35%. The hydrogen peroxide–containing gels designed for in-office bleaching that were tested in the present study were Opalescence Boost PF 40% and Power Whitening YF 40%. The manufacturer of the Opalescence bleaching gels was Ultradent Products Inc. (South Jordan, UT, USA), and the manufacturer of the Home Whitening and Power Whitening bleaching gels was WHITEsmile (Birkenau, Germany). Determination of color values (ΔE), bleaching efficacy (with the BI), surface hardness (measured as the Vickers hardness number [VHN]), EM, and surface roughness were carried out at baseline (m_0), that is, before the bleaching treatments and directly after the first bleaching treatment (m_1) for all bleaching gels. Measurements were also obtained 24 hours after each of a total of 10 bleaching treatments for carbamide peroxide–containing bleaching gels (m_2–m_11), and 1 week after each of a total of three bleaching treatments for hydrogen peroxide–containing gels (m_2–m_4). A flowchart of the experimental procedures is given in Figure 1.

Bleaching Procedures

Enamel specimens were bleached according to manufacturers' instructions. Before bleaching treatments, specimens were rinsed thoroughly with tap water and dried with oil-free air. Enamel specimens were covered with a 1-mm layer of the bleaching gel according to the group: 1) for 8 hours 10 times with Opalescence PF 10%, 2) for 4 hours 10 times with Home Whitening 10%, 3) for 30 minutes 10 times with Opalescence Quick PF 45%, 4) for 30 minutes 10 times with Home Whitening 35%, 5) for three sessions of 20 minutes each, repeated three times, with Opalescence Boost PF 40%, and finally 6) for three sessions of 15 minutes each, repeated three times, with Power Whitening YF 40%. After application, the 1-mm layer of bleaching gel was evenly distributed on the enamel surface using plastic paraffin film (Parafilm M, Neenah, WI, USA), and the specimens were kept at 37°C and 100% humidity for the required bleaching time. After each bleaching treatment, the bleaching gel was removed and the specimens were washed thoroughly with tap water and dried with oil-free air. During the time when specimens were not treated or measured, they were stored in the aforementioned mineral solution.

Measurement of Color Values

Enamel specimens were evaluated with a spectrophotometer (VITA Easyshade Advance 4.0, VITA Zahnfabrik, Bad Säckingen, Germany) at each time point (m_0–m_11, respectively). The spectrophotom-

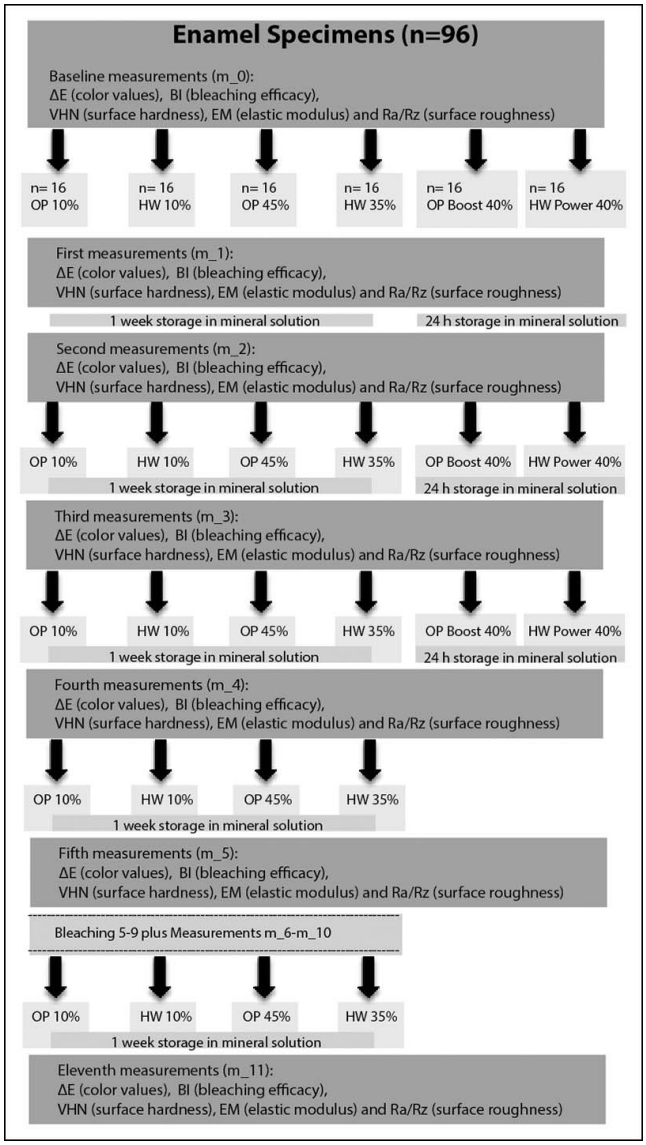

Figure 1. *Flowchart of the experimental procedures.*

eter was always placed at the center of the enamel specimen to ensure reproducibility. For each enamel specimen, the spectrophotometer generated a BI value as well as CIELAB values according to the Commission Internationale de l'Eclairage (CIE), where L represents the lightness in a specimen, a represents the saturation of green and red, and b represents the saturation of blue and yellow.[11,12] ΔE was then calculated using the formula $\Delta E = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]/2$.

Measurement of Surface Hardness and Elastic Modulus

Surface hardness (VHN) and elastic modulus (EM; gigapascals) of the enamel specimens were measured with a hardness indentation device at a force of 50 mN with an indentation time of 30 seconds (Fischerscope HM2000, Helmut Fischer GmbH, Sindelfingen, Germany). Four indentations were made on each specimen, and the mean value of the four VHN and four EM values per specimen were then calculated for each time point (m_0–m_11) for statistical analysis.

Measurement of Surface Roughness

Surface roughness (the average surface roughness [Ra; μm] and the arithmetic mean height of the surface profile [Rz; μm]) of the enamel specimens was profilometrically determined using a surface roughness meter (Perthometer S2, Mahr GmbH, Göttingen, Germany). Three measurements were performed per specimen over a transverse length of Lt = 1.750 mm, with a cutoff value of 0.250 mm and a stylus speed of 0.1 mm/s. The specimen was turned 45° for each of the three measurements to ensure that a representative area of the specimen was investigated; this resulted in three Ra and Rz values per specimen at each time point (m_0–m_11). Using the three Ra and Rz values, a mean value per specimen was calculated for each time point (m_0–m_11) for statistical analysis.

Statistical Analysis

Power analysis and sample-size calculation were performed at alpha = 5% and beta = 20% with a power of 80% using NCSS PASS (Power Analysis and Sample Size Software; NCSS, LLC. Kaysville, UT, USA). Statistical analysis was performed using SPSS version 21.0 (SPSS Inc, Chicago, IL, USA). The nonparametric Mann-Whitney U test for paired samples was used to test for differences in ΔE, BI, VHN, EM, and Ra/Rz between the bleaching gels after the last bleaching treatment only, and for each bleaching gel after each bleaching treatment (with Bonferroni correction for multiple comparisons).

RESULTS

Measurement of Color Values

The mean CIELAB values for lightness, saturation of green-red and saturation of blue-yellow at baseline and after the last bleaching treatment, as well as color change and BI value after the last bleaching treatment are given in Table 1. All six bleaching gels resulted in an increase in lightness (higher L), a reduction in yellowness (lower b), and clinically significant changes in ΔE and BI. When comparing the ΔE and the BI value of the six bleaching gels

Table 1: *Mean CIELAB Values (Minimum; Maximum) According to the Commission Internationale de l'Eclairage International Commission on Illumination for Lightness (L), Saturation of Green/Red (a), and Saturation of Blue/Yellow (b) at Baseline and After the Last Bleaching Treatment As Well As the Color Change (ΔE) and the Bleaching Index (BI) During the Whole Bleaching Procedure of Enamel Specimens Using Six Different Bleaching Gels*

	Baseline			After the Last Bleaching Treatment			ΔE	BI
	L (Lightness)	a (Green-Red)	b (Blue-Yellow)	L (Lightness)	a (Green-Red)	b (Blue-Yellow)		
Carbamide peroxide–containing gel								
OP 10%[a]	74 (67;81)	–2 (–4;1)	18 (13;25)	78 (68;90)	–4 (–4;1)	15 (10;22)	17.6	–2.0
HW 10%[a]	72 (64;87)	–2 (–3;0)	20 (14;33)	75 (64;92)	–2 (–4;–1)	18 (12;24)	8.2	–2.0
OP 45%[b]	71 (60;76)	–2 (–4;4)	19 (13;28)	75 (63;83)	–2 (–4;0)	16 (9;25)	12.9	–3.5
HW 35%[b]	71 (64;82)	–2 (–3;–2)	18 (13;26)	74 (67;80)	–3 (–3;–1)	17 (12;21)	5.6	–1.5
Hydrogen peroxide–containing gel								
OP Boost 40%[b]	74 (69;80)	–3 (–3;–1)	18 (11;26)	76 (67;84)	–3 (–4;–2)	14 (9;20)	9.6	–2
PW Power 40% [b]	76 (66;87)	–2 (–4;0)	20 (12;32)	76 (66;84)	–3 (–4;–2)	16 (9;29)	13.9	–3

Abbreviations: HW 10%, Home Whitening 10%; HW 35%, Home Whitening 35%; OP 10%, Opalescence PF 10%; OP 45%, Opalescence Quick 45%; OP Boost 40%, Opalescence Boost PF 40%; PW Power 40%, Power Whitening YF 40%.
[a] Home-use bleaching.
[b] In-office bleaching.

after the last bleaching treatment, no statistically significant differences were found between the gels ($p = 0.145$ and $p = 0.433$, respectively).

When comparing the color changes between baseline and every single bleaching treatment, there was a statistically significant difference over the bleaching procedure for each of the six bleaching gels. Opalescence PF 10% and Home Whitening 10% each resulted in a statistically significant increase in ΔE between baseline and after each of the 10 bleaching treatments ($p<0.001$); however, after the first bleaching treatment, no statistically significant differences occurred up to the tenth bleaching treatment. When evaluating the BI, statistically significant whitening occurred between baseline (m_0) and after the third bleaching treatment (m_4; $p=0.003$) for Opalescence PF 10% and between baseline (m_0) and the second bleaching treatment (m_3; $p=0.001$) for Home Whitening 10%. However, no further statistically significant whitening effect occurred up to the tenth bleaching treatment.

Treatment with Opalescence Quick PF 45% and Home Whitening 35% also resulted in statistically significant increases in ΔE between baseline and after each of the 10 bleaching treatments ($p<0.001$), however after the first bleaching treatment, no statistically significant differences occurred up to the tenth bleaching treatment. When evaluating the BI, statistically significant whitening occurred between baseline (m_0) and after the second bleaching treatment (m_3; $p<0.001$) for Opalescence Quick PF 45%, and between baseline (m_0) and the fourth bleaching treatment (m_5; $p=0.001$) for Home Whitening 35%. However, no further statistically significant whitening effect occurred up to the tenth bleaching treatment.

Treatment with Opalescence Boost PF 40% and Power Whitening YF 40% resulted in statistically significant increases in ΔE between baseline and after each of the three bleaching treatments ($p<0.001$); however, after the first bleaching treatment, no statistically significant differences occurred up to the third bleaching treatment. When evaluating the BI, statistically significant whitening occurred between baseline (m_0) and directly after the first bleaching treatment (m_1; $p<0.001$) for Opalescence Boost PF 40%, and between baseline (m_0) and 1 week after the first bleaching treatment (m_2; $p<0.001$) for Power Whitening YF 40%. However no further statistically significant whitening effect occurred up to the third bleaching treatment.

To summarize, each gel resulted in a statistically significant color change over the entire bleaching procedure; however, no statistically significant differences were found between the different gels after the last bleaching treatment. Color changes occurred within the first two to four bleaching treatments for carbamide peroxide–containing gels and within the first bleaching treatment for hydrogen peroxide–containing gels. No significant improvement in whitening of the enamel specimens occurred during the remaining bleaching treatments. An overview of the ΔE and BI values of the different bleaching gels is given in Figures 2a and 2b, respectively.

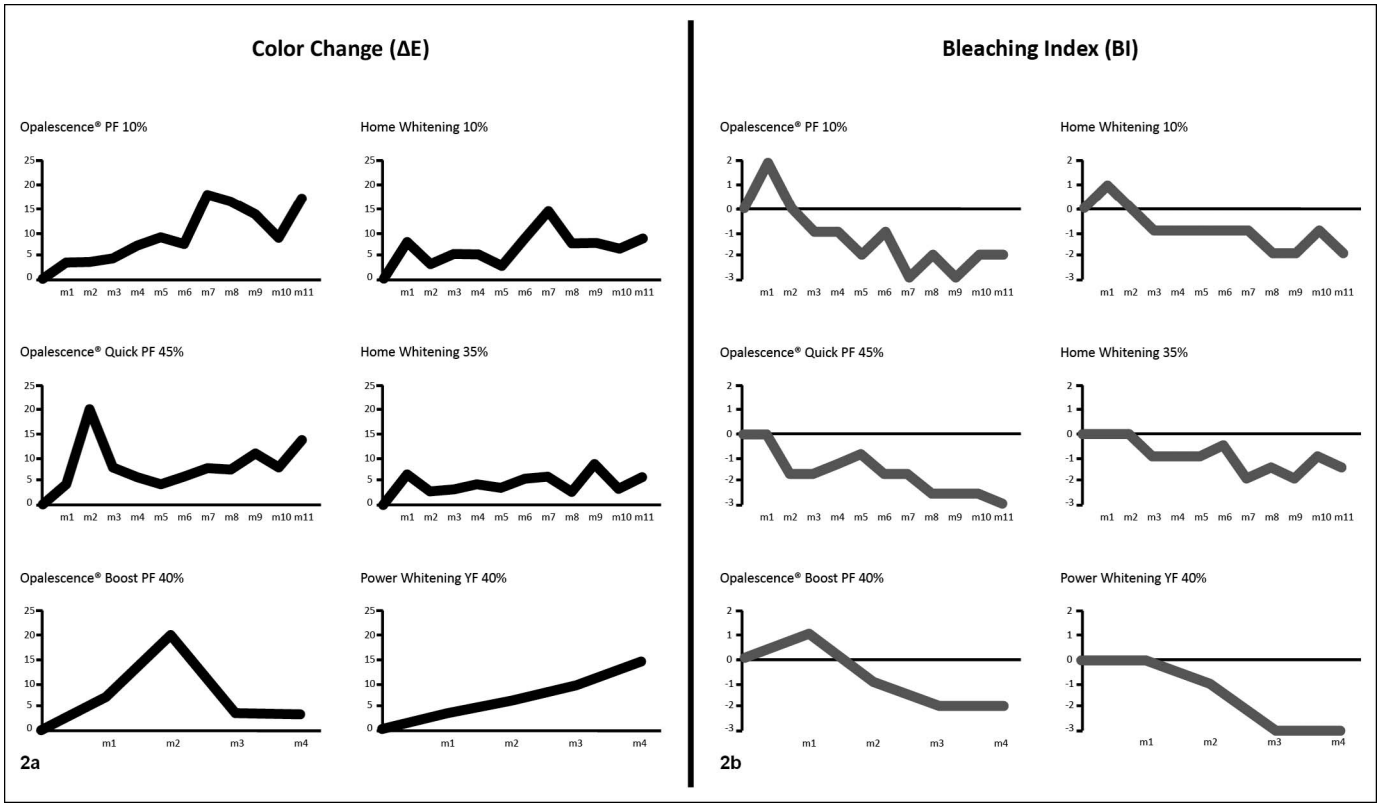

Figure 2. *(a): Color change (ΔE) and (b) bleaching efficacy (according to the BI) of enamel using six different bleaching gels.*

Measurement of Surface Hardness, EM, and Surface Roughness

Surface microhardness, elastic modulus, and surface roughness at baseline as well as the change in these parameters after the last bleaching treatment are shown in Table 2. Comparisons among the six bleaching gels after the last bleaching treatment showed statistically significant differences in ΔVHN

Table 2: Mean Baseline Surface Microhardness (Measured as VHN), Baseline Elastic Modulus (EM), Baseline Surface Roughness (Ra/Rz), and Changes in Parameters After the Last Bleaching Treatment of Enamel Specimens Using Six Different Bleaching Gels

	Baseline			Changes After the Last Bleaching Treatment		
	VHN	EM	Ra/Rz	ΔVHN	ΔEM	ΔRa/Rz
Carbamide peroxide–containing gel						
OP 10%[a]	626	98	0.002/0.120	–69	–1.8	0.001/0.026
HW 10%[a]	579	95	0.026/0.249	–35	+1.9	0.000/0.000
OP 45%[b]	602	98	0.011/0.097	–23	–1.24	0.001/0.010
HW 35%[b]	614	95	0.033/0.311	–56	+1.49	0.000/0.010
Hydrogen peroxide–containing gel						
OP Boost 40%[b]	540	97	0.029/0.175	+20	–0.91	0.001/0.026
PW Power 40% [b]	550	95	0.015/0.172	+44	–0.12	0.001/0.023

Abbreviations: HW 10%, Home Whitening 10%; HW 35%, Home Whitening 35%; OP 10%, Opalescence PF 10%; OP 45%, Opalescence Quick 45%; OP Boost 40%, Opalescence Boost PF 40%; PW Power 40%, Power Whitening YF 40%. Ra, average surface roughness; Rz, arithmetic mean height of the surface profile; VHN, Vickers hardness number
[a] Home-use bleaching.
[b] In-office bleaching

between Opalescence PF 10% and both of the hydrogen peroxide–containing gels (Opalescence Boost PF 40% and Power Whitening YF 40%, $p=0.003$). No statistically significant differences were found among the six gels with respect to ΔEM or ΔRa/Rz.

When comparing each gel over time (between baseline and after the last bleaching treatment), Opalescence PF 10% and Home Whitening 10% showed a statistically significant decrease in VHN ($p<0.001$ and $p=0.014$, respectively) whereas Power Whitening YF 40% showed a statistically significant increase in ΔVHN ($p=0.024$). Furthermore, treatment with Opalescence PF 10% resulted in a statistically significant increase in surface roughness ($p=0.041$), while Home Whitening 10% resulted in a statistically significant increase in elastic modulus ($p=0.014$). All other bleaching gels showed no statistically significant changes in ΔVHN, ΔEM, or ΔRa/Rz.

DISCUSSION

The current study investigated six bleaching gels containing different concentrations of carbamide peroxide or hydrogen peroxide and, consequently, different final concentrations of hydrogen peroxide.[4] The bleaching gels were compared with respect to their whitening efficacy and their influence on the surface of enamel specimens. Because of the different concentrations of peroxide, they also differed in recommended application time. All enamel specimens were characterized before the first bleaching treatment and after each single bleaching treatment with regard to color and surface changes (ie, surface hardness, EM, and surface roughness).

The present study showed that all bleaching gels were effective in whitening the enamel as indicated by ΔE and a decrease in the BI. No statistically significant difference in bleaching efficacy was found among the different gels, which is consistent with studies showing that the bleaching gels containing a higher concentration of hydrogen peroxide need fewer bleaching treatments to produce similar bleaching effects.[6] Nevertheless, it is interesting that a significant change in enamel color, independent of the bleaching gel, occurred after the first bleaching and showed no further significant increase, whereas more bleaching treatments were generally needed to obtain a significant change in BI. For the carbamide peroxide–containing gels (from 10% to 40%), two to four bleaching treatments were needed, whereas for the hydrogen peroxide–containing gels, only one bleaching treatment was needed to demonstrate statistically significant decreases in BI values.

These results indicate first that the number of bleaching treatments can be dramatically decreased, which is consistent with a study by Polydorou and others[21] showing that a bleaching time of approximately 24 minutes is sufficient to reach a clinically significant level of bleaching.[13] A reduced number of bleaching treatments would be beneficial for patients and dentists; treatment time and costs would be reduced, as would the danger of negative side effects resulting from fewer application times.[26,27] Second, our results show that the recently introduced BI is comparable to ΔE in the CIELAB system; both indicated a significant whitening effect. The benefit of using the BI compared with assessing changes in tooth color to investigate the efficacy in whitening teeth is that the BI distinguishes between improvements in tooth color (negative values indicating a whitening) and a worsening of tooth color (positive values indicating a darkening). The ΔE values, however, merely indicate a change in color and do not indicate whether the tooth got lighter or darker. To obtain this information, one has to analyze the single components of ΔE.[11,12] Furthermore, because patients are more interested in the whitening of their teeth than in changes in the single components, BI might be easier to use.

Another purpose of the present study was to investigate the influence of the six bleaching gels on the enamel surface. More specifically, we examined whether the bleaching gels had a negative effect on surface hardness, EM, and surface roughness. Interestingly, the bleaching gels with a relatively high concentration of carbamide peroxide (Opalescence Quick PF 45%, and Home Whitening 35%, resulting in approximately 15% and 11% hydrogen peroxide,[4] respectively) and the bleaching gels containing 40% hydrogen peroxide (Opalescence Boost PF 40% and Power Whitening YF 40%), which were all used with a shorter application time, did not show any negative effects on these enamel characteristics. In fact, one of the 40% hydrogen bleaching gels (Power Whitening YF 40%) caused a significant increase in surface hardness, which is consistent with the study by Polydorou and others.[21] On the other hand, the bleaching gels with the lowest concentration of carbamide peroxide (Opalescence PF 10% and Home Whitening 10%), resulting in a final concentration of approximately 3% hydrogen peroxide,[4] caused a significant decrease in surface hardness after the bleaching treatments. Further-

more, treatment with Opalescence PF 10% resulted in an increase in surface roughness, and treatment with Home Whitening 10% resulted in an increase in elastic modulus. Our results with respect to microhardness partially contradict those of an in situ study in which bleaching with different concentrations of carbamide peroxide resulted in reduced enamel hardness values, suggesting demineralization.[28] The reason why the changes in the present study occurred in the low, but not the high, concentration bleaching gels might be the increased contact time of the low concentration gel. For example, the two 3% hydrogen peroxide products had to be applied for 40 hours or 80 hours, respectively, whereas the 40% hydrogen peroxide products had to be applied for 135 minutes or 180 minutes, respectively.

In the current study, the enamel specimens were stored in a mineral solution between bleaching treatments and measurements.[25] The mineral solution contained $CaCl_2$, KH_2PO_4, and NaCl in order to simulate the oral environment, and remineralization could have been the reason why four of the six bleaching gels did not exhibit decreased surface hardness. Using the bleaching gels for longer times might have disrupted the balance between demineralization caused by the bleaching gel and remineralization caused by the mineral solution to result in decreased surface hardness. This explanation, however, needs further investigation, taking into account the differences between mineral solutions and human saliva. Mineral solutions containing $CaCl_2$, KH_2PO_4, and KCl are, however, supersaturated with respect to enamel, and precipitation of mineral can occur, while human saliva contains proteins hindering this precipitation.[29] Furthermore, the interindividual differences in human saliva and the possibility that the acquired pellicle might have a protective effect on the enamel might also be relevant to investigate in future studies.

CONCLUSIONS

- Bleaching gels containing carbamide peroxide from 10% up to 40% or hydrogen peroxide at 40% effectively whitened enamel.
- A clinically significant whitening effect was obtained within the first few bleaching treatments.
- The simplified BI might be useful in communications between clinician and patient.
- Use of bleaching gels with a relatively high concentration of carbamide peroxide or hydrogen peroxide and a shorter application time might be less harmful to the enamel surface.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies of Department of Preventive, Restorative and Pediatric Dentistry, School of Dentistry, University of Bern, in Bern, Switzerland.

Conflict of Interest

The authors have no proprietary, financial, or other personal interest of any kind in any product, service, and/or company that is presented in this article.

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REFERENCES

1. Kershaw S, Newton JT, & Williams DM (2008) The influence of tooth colour on the perceptions of personal characteristics among female dental patients: Comparisons of unmodified, decayed and 'whitened' teeth *British Dental Journal* **204(5)** 256-257.
2. Alkhatib MN, Holt R, & Bedi R (2005) Age and perception of dental appearance and tooth colour *Gerodontology* **22(1)** 32-36.
3. Odioso LL, Gibb RD, & Gerlach RW (2000) Impact of demographic, behavioral, and dental care utilization parameters on tooth color and personal satisfaction *Compendium of Continuing Education in Dentistry Supplement* **(29)** S35-S41.
4. Goldberg M, Grootveld M, & Lynch E (2010) Undesirable and adverse effects of tooth-whitening products: A review *Clinical Oral Investigations* **14(1)** 1-10.
5. Ozkan P, Kansu G, Ozak ST, Kurtulmus-Yilmaz S, & Kansu P (2013) Effect of bleaching agents and whitening dentifrices on the surface roughness of human teeth enamel *Acta Odontologica Scandinavica* **71(3-4)** 488-497.
6. Joiner A (2006) The bleaching of teeth: A review of the literature *Journal of Dentistry* **34(7)** 412-419.
7. Azrak B, Callaway A, Kurth P, & Willershausen B (2010) Influence of bleaching agents on surface roughness of sound or eroded dental enamel specimens *Journal of Esthetic and Restorative Dentistry* **22(6)** 391-399.
8. Batista GR, Barcellos DC, Torres CR, Goto EH, Pucci CR, & Borges AB (2011) The influence of chemical activation on tooth bleaching using 10% carbamide peroxide *Operative Dentistry* **36(2)** 162-168.
9. Al-Harbi A, Ardu S, Bortolotto T, & Krejci I (2013) Effect of extended application time on the efficacy of an in-office hydrogen peroxide bleaching agent: An in vitro study *European Journal of Esthetic Dentistry* **8(2)** 226-236.

10. Kossatz S, Dalanhol AP, Cunha T, Loguercio A, & Reis A (2011) Effect of light activation on tooth sensitivity after in-office bleaching *Operative Dentistry* **36(3)** 251-257.
11. Luo W, Westland S, Ellwood R, Pretty I, & Cheung V (2009) Development of a whiteness index for dentistry *Journal of Dentistry* **37(Supplement 1)** e21-e26.
12. Commission Internationale de l'Eclairage (2004) CIE 15: Colorimetry, Technical Report *Vienna, Austria: Commission Internationale de l'Eclairage* **3rd edition**.
13. Paravina RD, Johnston WM, & Powers JM (2007) New shade guide for evaluation of tooth whitening—Colorimetric study *Journal of Esthetic and Restorative Dentistry* **19(5)** 276-283.
14. Johnston WM, & Kao EC (1989) Assessment of appearance match by visual observation and clinical colorimetry *Journal of Dental Research* **68(5)** 819-822.
15. da Costa JB, & Mazur RF (2007) Effects of new formulas of bleaching gel and fluoride application on enamel microhardness: An in vitro study *Operative Dentistry* **32(6)** 589-594.
16. Attin T, Vollmer D, Wiegand A, Attin R, & Betke H (2005) Subsurface microhardness of enamel and dentin after different external bleaching procedures *American Journal of Dentistry* **18(1)** 8-12.
17. Efeoglu N, Wood DJ, & Efeoglu C (2007) Thirty-five percent carbamide peroxide application causes in vitro demineralization of enamel *Dental Materials* **23(7)** 900-904.
18. Cavalli V, Arrais CA, Giannini M, & Ambrosano GM (2004) High-concentrated carbamide peroxide bleaching agents effects on enamel surface *Journal of Oral Rehabilitation* **31(2)** 155-159.
19. Grobler SR, Hayward R, Wiese S, Moola MH, & van W Kotze TJ (2010) Spectrophotometric assessment of the effectiveness of Opalescence PF 10%: A 14-month clinical study *Journal of Dentistry* **38(2)** 113-117.
20. Wang X, Mihailova B, Klocke A, Fittschen UE, Heidrich S, Hill M, Stosch R, Guttler B, Broekaert JA, & Bismayer U (2009) Side effects of a non-peroxide-based home bleaching agent on dental enamel *Journal of Biomedical Materials Research. Part A* **88(1)** 195-204.
21. Polydorou O, Hellwig E, & Hahn P (2008) The efficacy of three different in-office bleaching systems and their effect on enamel microhardness *Operative Dentistry* **33(5)** 579-586.
22. Mielczarek A, Klukowska M, Ganowicz M, Kwiatkowska A, & Kwasny M (2008) The effect of strip, tray and office peroxide bleaching systems on enamel surfaces in vitro *Dental Materials* **24(11)** 1495-1500.
23. Sulieman M, Addy M, Macdonald E, & Rees JS (2004) A safety study in vitro for the effects of an in-office bleaching system on the integrity of enamel and dentine *Journal of Dentistry* **32(7)** 581-590.
24. Lussi A, Bossen A, Hoschele C, Beyeler B, Megert B, Meier C, & Rakhmatullina E (2012) Effects of enamel abrasion, salivary pellicle, and measurement angle on the optical assessment of dental erosion *Journal of Biomedical Optics* **17(9)** 1-13.
25. Zero DT, Rahbek I, Fu J, Proskin HM, & Featherstone JD (1990) Comparison of the iodide permeability test, the surface microhardness test, and mineral dissolution of bovine enamel following acid challenge *Caries Research* **24(3)** 181-188.
26. Soares DG, Ribeiro AP, da Silveira Vargas F, Hebling J, & de Souza Costa CA (2013) Efficacy and cytotoxicity of a bleaching gel after short application times on dental enamel *Clinical Oral Investigations* **17(8)** 1901-1909.
27. Tam LE, Kuo VY, & Noroozi A (2007) Effect of prolonged direct and indirect peroxide bleaching on fracture toughness of human dentin *Journal of Esthetic and Restorative Dentistry* **19(2)** 100-109.
28. Rodrigues JA, Marchi GM, Ambrosano GM, Heymann HO, & Pimenta LA (2005) Microhardness evaluation of in situ vital bleaching on human dental enamel using a novel study design *Dental Materials* **21(11)** 1059-1067.
29. Lussi A, Lussi J, Carvalho TS, & Cvikl B (2014) Toothbrushing after an erosive attack: Will waiting avoid tooth wear? *European Journal of Oral Sciences* **122(5)** 353-359.