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CLINICAL RESEARCH

Assessment of masticatory performance by geometric measurement of the mixing ability with 2-color chewing gum

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ABSTRACT

Statement of problem. The 2-color mixing ability test has been recently introduced for objective assessment of masticatory performance. However, the ideal bicolor specimens have not yet been identified, and the color analysis of digital images requires improvement.

Purpose. The purpose of this clinical study was to formulate a custom-made, 2-color chewing gum for the mixing ability test and to develop an image-processing method for color mixing analysis.

Material and methods. Specimens of red-green (RG) chewing gum were prepared as a test food. Twenty dentate participants (10 men, 10 women; mean age 21 years) took part in this study. Each participant masticated 1 piece of RG gum for 3, 6, 9, 15, and 25 cycles, and this task was repeated 3 times consecutively (total n=15 for each participant). The boluses were retrieved and flattened to 1-mm-thick wafers and scanned with a flatbed scanner. The digital images were analyzed using ImageJ software equipped with a custom-built plug-in to measure the geometric dispersion (GD) of baseline red segment. The predictive criterion validity of this method was determined by correlating GD to the number of mastication cycles. The hardness and mass of RG chewing gum were measured before and after mastication. Hardness loss (%) and mass loss (%) were then calculated and compared with those of a commercially available chewing gum.

Results. The 2-way repeated-measures ANOVA with post hoc Bonferroni test showed that GD was able to discriminate among the groups of different numbers of mastication cycles ($P<.001$). Pearson correlation coefficient confirmed the significant correlation between GD and the number of mastication cycles ($r=0.90$, $P<.001$). The hardness loss and mass loss of RG chewing gum were significantly lower than those of commercial chewing gum ($P<.001$).

Conclusions. The newly formulated chewing gum provides an appropriate test food material for masticatory performance assessment. The new image-processing method discriminated among the different levels of color mixture and quantified the mixing ability. (J Prosthet Dent 2019;121:916-21)

Rehabilitation of masticatory function is a primary goal of prosthodontics. Therefore, an objective method for quantifying this function and monitoring dental treatment outcomes might be useful for dentists in both clinical and research arenas. Masticatory performance (MP) has been defined in The Glossary of Prosthodontic Terms as "a measure of the comminution of food attainable under standardized testing conditions."[1] Various natural foods (peanuts, hazelnuts, almonds, carrots, and apples) and artificial substances (silicone, gelatin, and alginate) have been used for evaluating an individual's ability to grind and pulverize food.[2] The particle size distribution of the resulting boluses has been measured using fractional sieving analysis and considered as the gold standard of MP assessment.[3] Nevertheless, comminution tests have some intrinsic practical inconveniences.

Alternative convenient methods were introduced to determine the ability of an individual to mix and knead a cohesive food bolus.[4-8] Validity and reliability studies have demonstrated a high correlation between comminution ability and mixing ability methods.[9-11] Furthermore, the mixing ability was especially recommended for patients with a masticatory handicap or mental disorders for whom fragmentation tests are inapplicable.[12-14]

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Clinical Implications

The mixing ability test provides an objective assessment of masticatory performance and may be performed conveniently in a dental office. The proposed test food material and image-processing method seems beneficial in this regard.

Previous researchers have used bicolor combinations of commercially available chewing gum to perform the mixing ability test and introduced computer-aided methods to evaluate the color mixture of the bolus's digital images.[12,15-22] However, optimal test specimens have not yet been identified. Furthermore, most proposed image-processing methods focused just on the heterogeneity of color value, regardless of the spatial positioning of the pixels. However, the spatial distribution of the pixels can be a fundamental parameter of the mixing characteristics.

The purpose of this study was to formulate a custom-made, 2-color chewing gum for evaluating food mixing ability and to determine the validity of a new image-processing method for the spatial analysis of the 2-color mixture. The research hypothesis was that the proposed parameter of color mixing would be able to discriminate among the groups of different numbers of mastication cycles, and a significant correlation would exist between the color mixing and the mastication cycle numbers.

MATERIAL AND METHODS

Twenty volunteers, 10 men and 10 women, with an average age of 20.9 ±3.3 years (range: 18 to 31 years) took part in this study. They were recruited from the dental students and staff of the University of Malaya. The inclusion criteria comprised a complete natural dentition except third molars, Angle class I normal occlusion, age between 18 and 40 years, and good general health. Exclusion criteria were orofacial pain, temporomandibular joint disorders, a decayed, missing, and filled teeth score higher than 4, severe tooth wear, periodontal disease, and orthodontic appliances. The Medical Ethics Committee of the University of Malaya reviewed and approved this clinical trial DF-RD1612/0045(P), and the participants signed written informed consents.

A formulation of chewing gum was developed and used to prepare 2-color test food specimens. This custom-made, red-green (RG) gum was made of 4 ingredients: gum base, softener, powder filler, and water-insoluble dyes. Pellets of gum base (Glee Gum; Verve Inc) were melted in a water bath at 100 °C for 20 minutes. Then, vegetable margarine (Daisy; Lam Soon Edible Oils Sdn, Bhd), food grade talcum powder (Microtalc FC8; Mondo Minerals BV), and lake pigments (Idacol; ROHA Dyechem Pvt Ltd) were added and mixed thoroughly using a handheld electric mixer. Subsequently, the gum dough was flattened to a thickness of 2 mm with a rolling pin and cut in dimensions of 25×10×2 mm. Two pieces of opposite colors were stuck together and wrapped in wax paper. Table 1 lists the ingredients of the RG chewing gum.

Table 1. Ingredients of RG chewing gum and their ratios

Material	Manufacturer	Description	Weight (g)	wt.%
Glee Gum	Verve Inc	Natural rubber gum base	100	71
Daisy margarine	Lam Soon Edible Oils Sdn, Bhd	Palm oil-based margarine	20	14
Microtalc FC8	Mondo Minerals B.V.	Food grade talcum powder	20	14
Idacol L17 Lake Allura Red	ROHA Dyechem Pvt Ltd	Food grade water-insoluble pigment	1	<1
Idacol L13 Lake Pea Green	ROHA Dyechem Pvt Ltd	Food grade water-insoluble pigment	0.4	<1

RG, red-green chewing gum.

Each participant was asked to sit in a chair with his/her head in a normal position and to masticate 15 specimens of RG chewing gum naturally on his/her preferred side for 3, 6, 9, 15, and 25 successive cycles; this sequence was repeated 3 times. Rest intervals of approximately 1 minute were imposed between the different trials to avoid fatigue. After mastication, the boluses were retrieved, rinsed in water, placed between 2 clear stationery laminating pouches, and flattened to 1-mm-thick wafers with 2 glass plates. Subsequently, both faces of the wafers were scanned using a flatbed scanner (CanoScan 4400F; Canon Inc) with 500 dpi resolution, saved in tagged image file format, and labeled with reference numbers for later analysis. White paperboard was placed over the specimens, and the scanner lid was closed during scanning.

A scientific image analysis program (ImageJ 1.51m; US National Institutes of Health) was used because of its availability and programmability. Images had a light background because of the white lid of the scanner, whereas the chewing gum wafer was darker. This contrast allowed segmentation of the background and foreground based on the lightness values of pixels. The International Commission on Illumination CIELab color space was used for the color measurements. The images of 2 opposite sides of the wafer were combined using the ImageJ combining tool (Fig. 1A). Then, the segment of the baseline red color was selected using the color thresholding tool with the settings: CIELab color space, ranges of normalized color values L*=[0,140], a*=[128,255], and b*=[0,255], which corresponded to real values L*=[0,55], a*=[0,+127], and b*=[−128,+127]. The perimeter (*P*) and the area (*A*) of the selected red segment were measured (Fig. 1B), and the geometric

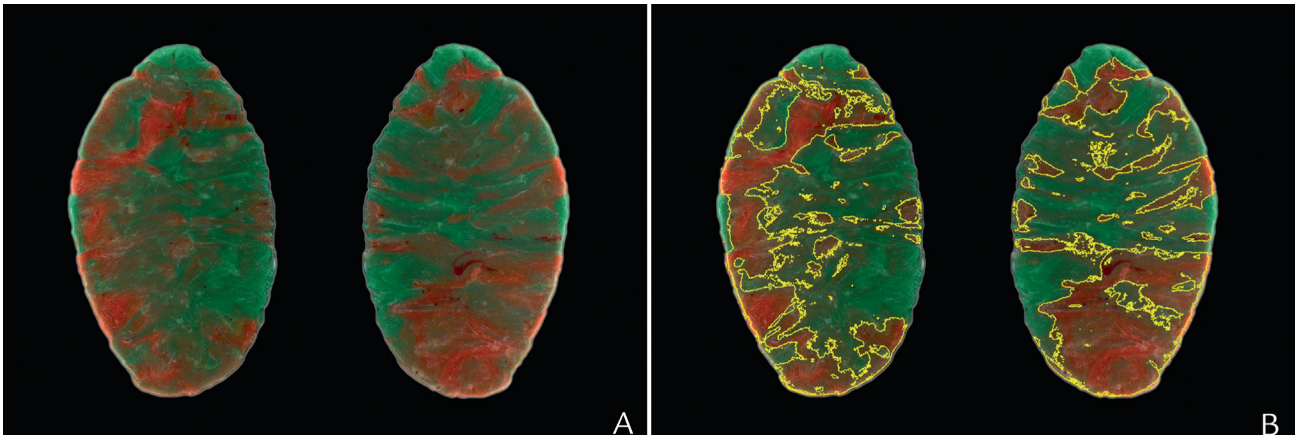

Figure 1. A, Example of RG chewing gum wafer. Two faces of specimen masticated for 9 cycles. B, Boundary of red segment drawn using ImageJ color thresholding tool. Selected region has area of 768 mm^2, perimeter of 1938 mm, and geometric dispersion of 19.73. RG, red-green chewing gum.

dispersion (GD) of this 2-dimensional shape was calculated using the following formula:

$$GD=\frac{P}{2\sqrt{\pi A}},$$

where *GD* is the geometric dispersion, *P* is the perimeter, and *A* is the area. GD is a dimensionless measure that relates the perimeter of a 2D-shape to that of a circle with the same area (isoareal quotient).[23] The GD value is 1 for the most compact 2D shape (circle), and much more for scattered and irregular objects. GD indicates the diffusion and spatial dispersion of the selected baseline color (red in the present case). A custom-built macro was used to measure the dispersion of 2-dimensional objects *Help> Examples>Macro>Custom Measurement*. ImageJ batch processing tool was used for the automated analysis of the digital images. Therefore, blinding for analyst and image label concealment was unnecessary.

The hardness of the chewing gum was determined by penetration with a 6-mm-diameter cylinder probe using a texture analyzer (TA-XT Plus; Stable Micro Systems). The specimen was placed on the platform, and the probe was moved downward with a pretest speed of 1 mm/s, test speed of 10 mm/s, posttest speed of 10 mm/s, trigger force of 0.05 N, and distance of 3 mm. The highest peak force (N) of the resulting force−time curve was considered the hardness value.[7] Five specimens were measured at a room temperature of 23 °C. Then, the average was calculated. To evaluate the hardness changes throughout mastication, 1 participant masticated 5 specimens of chewing gum for 15, 25, and 100 successive cycles. The hardness was then determined by following the same preceding procedures. Hardness loss was calculated using the following formula:

$$Hardness\ loss(\%)=\frac{H_i-H_f}{H_i}\times 100,$$

where H_i is the initial hardness of the unmasticated specimen and H_f is the final hardness of the masticated specimen. For comparison, sticks of commercially available chewing gum (Wrigley's Spearmint; Wrigley Inc) were folded into 4-mm-thick specimens, and the hardness was measured by following the same preceding procedures.

One participant masticated 5 preweighed specimens of each brand of chewing gum for 15, 25, and 100 successive cycles with a 1-minute rest period in between. The retrieved boluses were then washed with running tap water to remove saliva, dried at 37°C for 2 weeks and weighed with an electronic scale of 0.1 mg accuracy (Sartorius BP221S; Sartorius AG). Then, the mean values were calculated. The percentage mass loss of chewing gum after mastication was calculated from the following equation[4]:

$$Mass\ loss(\%)=\left(\frac{M_i-M_f}{M_i}-\frac{m_i-m_f}{m_i}\right)\times 100,$$

where M_i is the initial mass of specimen, M_f is the final dried mass of masticated specimen, m_i is the initial mass of control unmasticated gum specimen, and m_f is the final dried mass of control unmasticated gum specimen. Similarly, the mass loss of the commercially available chewing gum (Wrigley's Spearmint; Wrigley Inc) was measured by following the same procedures.

Data were explored for normality using the Shapiro-Wilk test. The ability of the spatial color mixing indicator (GD) to distinguish the specimens of different numbers of mastication cycles was investigated by means of 2-way repeated-measures ANOVA with post hoc Bonferroni test for pairwise multiple comparisons. The relationship between GD and the number of mastication cycles was examined with the Pearson correlation coefficient. The independent samples *t* test was used to compare the 2 brands of chewing gum in terms of

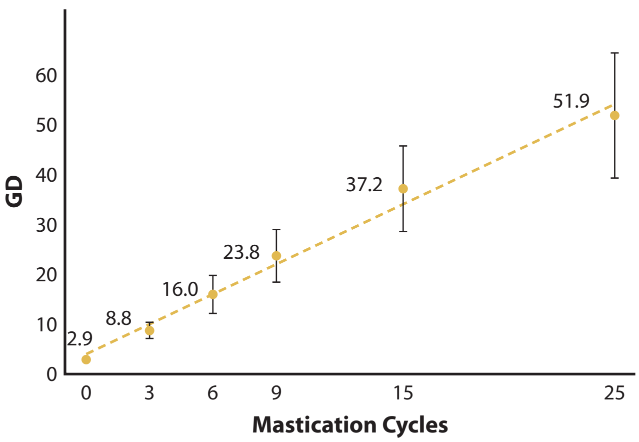

Figure 2. GD (mean ±SD) of 2-color chewing gum specimens for successive numbers of mastication cycles. Pairwise multiple comparison revealed significant differences between each pair of groups (*P*<.001). Pearson correlation test showed high positive relationship between GD and the number of mastication cycles (r=0.90, *P*<.001). GD, geometric dispersion; SD, standard deviation.

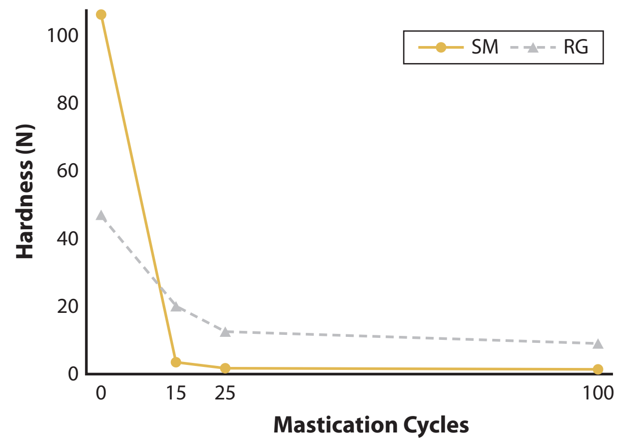

Figure 3. Hardness loss of RG chewing gum throughout different numbers of mastication cycles in comparison with commercially available chewing gum. Specimens tested using Texture Analyzer and highest peak force (N) of resulting force–time curve considered hardness value. RG, red-green newly formulated chewing gum, SM, Wrigley's Spearmint chewing gum.

Table 2. Hardness and hardness loss (mean ±SD) of RG chewing gum in comparison with commercially available chewing gum at different numbers of mastication cycles

	Hardness (N)			Hardness Loss (%)		
Cycles	RG	SM	*P**	RG	SM	*P**
0	47.20 ±2.51	106.34 ±1.70	<.001	0	0	–
15	20.10 ±2.57	3.51 ±0.74	<.001	57.31 ±0.06	96.70 ±0.01	<.001
25	12.55 ±1.13	1.78 ±0.26	<.001	73.42 ±0.02	98.32 ±0.01	<.001
100	8.99 ±1.04	1.45 ±0.25	<.001	80.88 ±0.03	98.63 ±0.01	<.001

N, Newtons; RG, red-green chewing gum; SD, standard deviation; SM, Wrigley's Spearmint gum. *Independent samples *t* test. Sample size: 5.

hardness, hardness loss, and mass loss. All the analyses were performed using statistical software (IBM SPSS Statistics, v23; IBM Corp) (α=.05).

RESULTS

A total of 600 images corresponding to both sides of 300 wafers were recovered. An example of a chewing gum wafer is presented in Figure 1A. The boundary line of the red segment was determined using the color threshold tool to evaluate its GD (Fig. 1B). The values of GD (mean ±standard deviation) for each step of the mastication cycles are given in Figure 2. The Shapiro-Wilk test detected signs of nonnormality at 6 mastication cycles, but the data of the remaining cycles were normally distributed. Two-way repeated-measures ANOVA with Bonferroni test confirmed the ability of GD to discriminate among the groups of different numbers of mastication cycles (*P*<.001). Pairwise multiple comparisons revealed significant differences between each pair of the groups (*P*<.001). The GD increased significantly with an increasing number of mastication cycles, and the Pearson correlation coefficient test showed a high positive correlation between the 2 variables (r=0.90, *P*<.001).

The initial hardness of RG chewing gum was significantly lower than the hardness of commercial chewing gum (Wrigley's Spearmint chewing gum [SM]) (*P*<.001). However, the SM showed a steeper drop in hardness as mastication progressed (97% hardness loss after 15 cycles) compared with its RG counterpart (57% hardness loss after 15 cycles) (Table 2, Fig. 3). Throughout the mastication process, a significant mass loss of SM was observed (48% mass loss after 100 cycles) (Table 3, Fig. 4), whereas RG chewing gum displayed a trivial mass loss (mass loss within 1%) under the presented testing conditions (Fig. 4).

DISCUSSION

The data support accepting the research hypothesis, as the GD was able to discriminate among the groups of different numbers of mastication cycles, and a significant correlation was observed between the 2 variables. The 20 participants in this cross-sectional validation study had a complete natural dentition, normal occlusion, and a healthy masticatory system. The small interindividual variability of GD in each step of the mastication cycles confirms the participants as "healthy chewers." However, the higher variability in 25 cycles could be explained by the difficult recognition of baseline color at that stage of mixture. GD variation was correlated to the different numbers of mastication cycles to determine the predictive criterion validity of the new method (Fig. 2). The regression function of presented data would, therefore, predict the equivalent number of mastication cycles for healthy chewers. These reference data might be valuable for quantifying the masticatory handicap of a specified

Table 3. Mass and mass loss (mean ±SD) of RG chewing gum in comparison with commercially available chewing gum at different numbers of mastication cycles

	Mass (g)			Mass Loss (%)		
Cycles	RG	SM	P*	RG	SM	P*
0	1.35 ±0.10	2.74 ±0.02	<.001	0	0	–
15	1.34 ±0.10	2.45 ±0.02	<.001	0.14 ±0.03	08.18 ±0.51	<.001
25	1.34 ±0.11	2.33 ±0.04	<.001	0.14 ±0.05	12.56 ±1.25	<.001
100	1.33 ±0.12	1.35 ±0.05	.783	0.88 ±0.08	48.33 ±1.89	<.001

RG, red-green chewing gum; SD, standard deviation; SM, Wrigley's Spearmint gum.
*Independent samples *t* test. Sample size: 5.

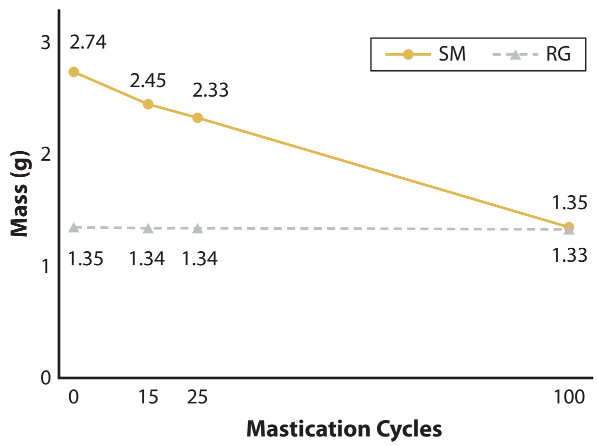

Figure 4. Mass loss of RG chewing gum throughout different numbers of mastication cycles in comparison with commercially available chewing gum. RG, red-green newly formulated chewing gum, SM, Wrigley's Spearmint chewing gum.

patient in relation to the healthy population.[18] The mastication cycle numbers (0, 3, 6, 9, 15, and 25) were chosen to cover the complete range of possible degrees of spatial color mixing. Beyond 25 cycles, GD outcomes had low repeatability in a pilot study, possibly due to vanishing of the baseline colors.

Various commercial brands of chewing gum have been used for the 2-color mixing ability test. Unfortunately, finding specimens with optimal color combinations was not straightforward, as most manufacturers no longer add artificial colorings to their gums.[19] Some investigators have used custom-made wax specimens.[7,8] However, people might prefer gum instead of wax because they are accustomed to its taste and texture. Therefore, RG bicolor chewing gum was formulated and validated.

According to color theory, red and green are a pair of opposite colors.[24] The high contrast of this combination enables color recognition both visually and digitally. Furthermore, mixing red and green pigments produces brown, which is an intermediate color located in mid-spectrum between the 2 baseline colors. Saliva might be a confounding factor in the color change. The composition of saliva and its flow rate differs among people. Therefore, water-insoluble dyes were used to color the RG chewing gum.

The test food specimen should have a suitable texture and should be easy to masticate by individuals with compromised oral function. In food science, Texture Analyzer has been widely used to assess food texture by examining force-deformation/time curves.[7] Clearly, the mixing ability score depends on the texture of the chewing gum. The hardness behavior of RG chewing gum demonstrates that it has better hardness stability throughout the duration of mastication compared with the SM commercial gum (Fig. 3). The steep drop in the hardness of the latter could be attributed to the gum base characteristics and the plasticizing effect of sugar-saliva content. The sugar might be harmful to patients with diabetes, and the release of sugar into saliva causes undesirable mass loss of the gum. Thus, a sugar-free chewing gum was recommended.

The commercially available chewing gum lost up to 13% of its weight after only 25 mastication cycles, which is consistent with the findings of a previous study.[4] By contrast, RG chewing gum showed a minimal mass loss over 100 cycles (Fig. 4). The volume of the chewing gum is directly proportional to the surface area of the wafer. In other words, the longer the duration of mastication, the more the lost pixels on the digital image. Therefore, mass stability is considered a favorable characteristic of RG chewing gum. Some research groups have produced custom-made chewing gum,[15] but the recipe and method of preparation remain exclusive to the manufacturing company. The ingredients of RG chewing gum are available (Table 1), and its preparation is relatively straightforward.

In Euclidean geometry, the circularity (isoperimetric quotient) has been frequently used to measure the compactness of 2-dimensional objects.[23] However, circularity outcomes of the present data were limited to a tiny span [0 to 0.05]. Therefore, a new measure of an object's anticompactness "geometric dispersion" was derived from an isoareal quotient formula and used in this study. The isoareal quotient is a dimensionless measure that relates the perimeter of a shape P_s to that of a circle P_c with the same area (A_s=A_c). The radius $r=\sqrt{\frac{A_c}{\pi}}$, and the perimeter of this circle is $P_c=2\pi r$. Then, the isoareal quotient is $Q_a=\frac{P_s}{P_c}=\frac{P_s}{2\sqrt{\pi A_s}}$. The isoareal quotient for a circle is 1 and increases for more scattered and irregular objects.

In CIELab color space, the pixel of a 2-dimensional image is typically digitized by 2 sets of data: 3 color values (L*, a*, b*) and 2 Cartesian coordinates (x, y) of spatial position. Both the contrast of color values and the spatial polarization of pixels can be considered the main characteristics of color heterogeneity. The former feature has been extensively studied.[12,16,19] However, it might be useful to investigate the image from a spatial point of view and then evaluate the color mixture using a holistic spatial value approach.

Color thresholding based on the cutoff point a*=0 splits the baseline colors (red versus green) into 2 mutually exclusive segments. Each red and green segment has almost the same number of pixels (surface area), regardless of the degree of mixture, whereas spatial distribution of pixels defines the resulted shape perimeter. In the early stage of mastication, reddish pixels—for instance—are concentrated and compacted in just a few wide areas. As kneading advances, the GD increases because of fragmentation and diffusion.

The present method of image analysis showed a significant correlation between GD and the number of mastication cycles of the healthy participants in this study. Thus, the method appears valid for assessing the MP of different dental conditions when a fixed number of mastication cycles are applied. Future studies are required to investigate the reliability and concurrent validity of this approach.

CONCLUSIONS

Based on the results of this clinical study, the following conclusions were drawn:

1. The newly developed chewing gum has favorable structural and colorimetrical characteristics for the assessment of masticatory function.
2. The new image-processing method is valid and precise for quantifying spatial mixing ability.

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