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The Determination of the Tooth Colors

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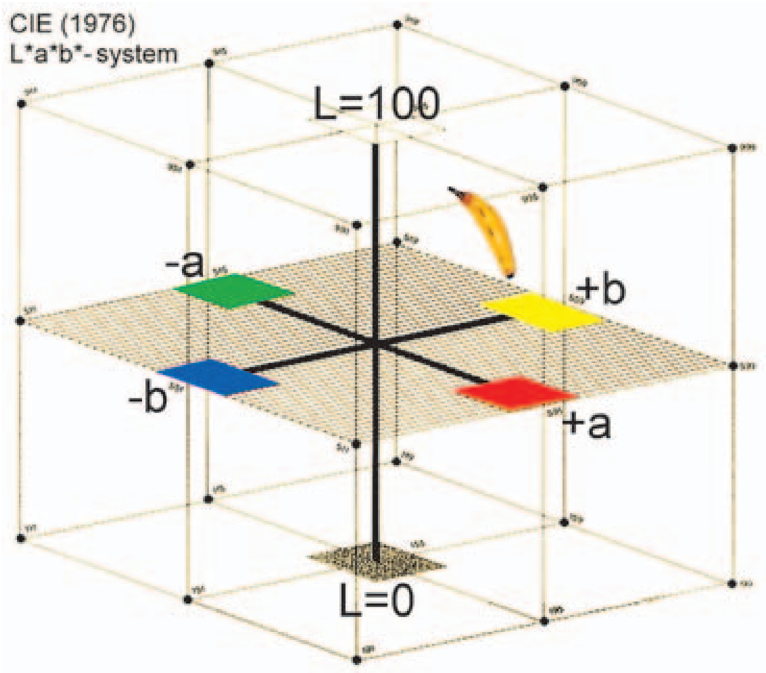

Summary

The VITA SYSTEM 3D-MASTER® was developed to achieve systemization and a higher number of accurate matches when determining the colors of teeth. It is based on the consequent adoption of modern color theory. A look at the development of a color space in which color differences are determined numerically, simplifies the understanding of the color space in which all tooth colors occurring in nature are found. In the VITA SYSTEM 3D-MASTER®, this tooth color space is divided into five lightness groups. When determining the color, the correct lightness group is selected; then the remaining color characteristics are matched from this group.

Terminology

CEREC, CAD/CAM, VITA SYSTEM 3D-MASTER®, tooth colors, color theory

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Introduction

Hardly anybody will have problems to solve our puzzle in fig. 1: You can see four colored arrows on a vertical post and a banana. The construction can be compared to a signpost. Let us look at the illustration of the signpost for a moment. The arrows have been attached to the center of a post, which becomes lighter towards the upper area, and point to different color directions. The banana is at a height at which the post is already quite light and is located towards the direction of yellow and red. If a person approaches the banana from the signpost, he will arrive in the zone in which mainly colors between light-red and light-yellow are found.

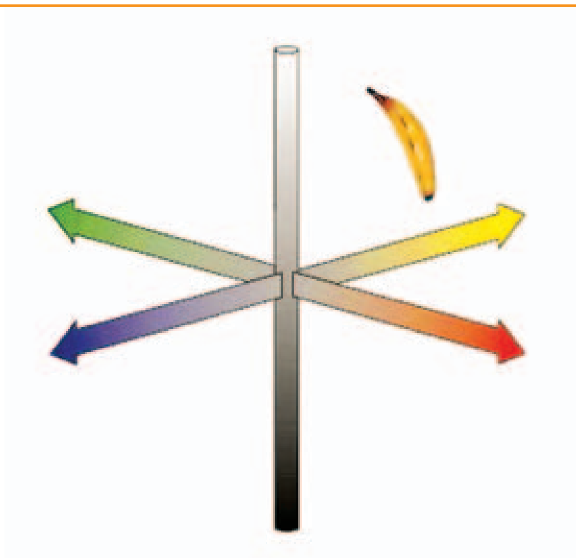


Fig. 1 Color signpost: on a post which becomes lighter towards the upper area, four arrows in the colors blue, red, yellow and blue point towards the four directions. The banana is in the light area of the vertical post between red and yellow and symbolizes the color space which includes all tooth colors occuring in natural teeth.

The shade system L*a*b* resp. L*C*h*

Fig. 2 *(opposite page)*
L*a*b color space with the vertical lightness axis L (value) and the horizontal color axes a and b which define the color plane in which the intensity (chroma) increases radially from the central achromatism ("huelessness") towards the outer region. The colors (hue) on the color plane are situated around the colorless (achromatic) central axis as mixed colors from blue to red up to yellow and green. In upper color planes the colors appear lighter, in lower ones darker. The banana marks the position and shape of the color space of natural teeth.

Those who work with colors every day, such as dental technicians and dentists, will see some connections in the drawing of the signpost and the banana. They will recognize the four color directions and the lightness which is increasing towards the upper area and decreasing towards the lower as an abstract variation of the three-dimensional color space, which is referred to as L*a*b system in color metrics (fig. 2).

All colors that can be perceived with the human eye are situated in this space. At middle height – in relation to the vertical, central black-white axis – a grey, horizontal color plane can be recognized, on which the green-red (a-axis) and blue-yellow (b-axis) colors which point towards the four main directions are found. On this color plane the colors – starting from the central, colorless black-white axis – expand to the outer area and become more intensive. The higher the position of the black-white axis on the color plane, the lighter are the colors; the lower the position, the darker are the colors.

The banana represents each sector in the color space in which the natural tooth shades are found. The banana shape symbolizes the natural conditions. The various tooth colors mainly differ in their lightness; that is why the tooth color space is vertical to the lightness axis and expands similar to a banana. The lighter teeth are in the upper area and the darker ones in the lower area. The more intensive tooth colors are situated at the outer curve of the banana which is further away from the colorless (achromatic) central axis L; teeth with a reddish shade are facing the a-axis while those with a yellowish shade are facing the b-axis.

The interesting history of the L*a*b color system is part of the cultural history of Europe. Some may feel tempted to delve into the physical, neurophysiological and psychological aspects of color theories and color systems. *Goethe's* brusque rejection of the physical findings *Newton* had presented 50 years ago and were accepted in scientific circles remains unforgotten. The famous poet refused the theory of the visionary physicist in one of his poets: "Wer aber das Licht will spalten/Den mußt du für einen Affen halten (Those who intend to divide light must be considered foolish)". Over a period of 200 years physicists, physiologists and philosophers wrote at least one essay or a speech about Goethe's unintelligible polemics against *Isaac Newton*. Only the results of modern research put an end to this neverending scientific discussion. 200 years later Goethe would have hardly been involved in such a controversy with the field of optics. The current results ended the controversy between physics and color perception theories. Things are much more closely related than people knew at the time of *Goethe*.

During the first decades of the 20th century the wish to find an objective method for the determination of colors was growing stronger. There was a quest for a color system which on the one hand was based on the ability of the human eye to determine matching colors and – on the other hand – represented a mathematical construct which allowed to calculate the position of the color to be determined in relation to each primary color. Scientists were anxious to have a color system which did not need any samples since the comparison of a color sample with a standard sample will always remain a subjective process.

Moreover comparative samples may fade which renders them unreliable. The CIE (Commission Internationale d'Eclairage) was authorized to develop a mathematically defined standard color table which should fulfill the wish for precision and objectiveness.

The development of such a standard color table as a mathematical construct is based

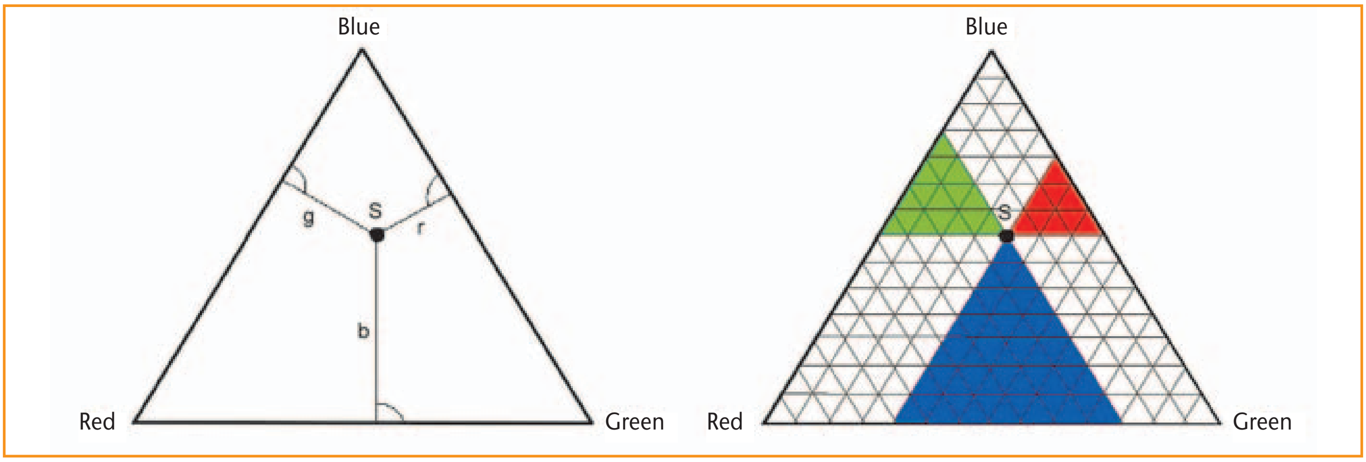


Fig. 3 Left: Maxwell's red-green-blue (RGB) triangle: every mixed color is in the center of the line which links the components to be mixed. Right: visual presentation of quantitative mixing of the red-green-blue proportions for the mixed color S.

on the color triangle of the physicist *James C. Maxwell*. In 1859 the Scottish physicist introduced his theory of color vision which is considered the beginning of quantitative color measurement (colorimetry). In his theory he demonstrated that all colors are obtained by mixing the three spectral colors red, green and blue. He placed the three primary colors red (R), green (G) and blue (B) at the angular points of an equilateral triangle and showed that any mixed color lies on the line linking the separate components (fig. 3, left). The quantitative proportion of each individual primary color corresponds to the area of the equilateral triangle which is defined by the point of the mixed color (S in fig. 3) in the total triangle and the colored side of the total triangle. Using a triangle grid of the total triangle, the conditions can be explained more clearly (fig. 3, right): the red proportion for the mixed color S in Maxwell's triangle is defined with 9, the green proportion with 16 and the blue proportion with 49 partial triangles. If, for example, the point S in Maxwell's triangle is at the top in the "blue" corner, pure blue would be obtained as the mixed color since there are no more proportions of red and green.

The geometrical relations and distances between the colors in Maxwell's RGB triangle have a precise significance and are based on the following psycho-physical measurements: using standardized illuminants, the test persons prepare various mixtures of red, green and blue until the color impression matches the sample. Accordingly, three factors are obtained for color perception:

- The observer (defined as a person with standard vision)[1]
- The illuminant (defined by the color temperature in °Kelvin)[2]
- The object (defined by its inherent color information. Any reflection by additional illuminants [glare] is eliminated)[3]

The respective mixture can be determined by the three values R, G and B, known as tristimulus values. Accordingly, three variables are available for the characterization of a

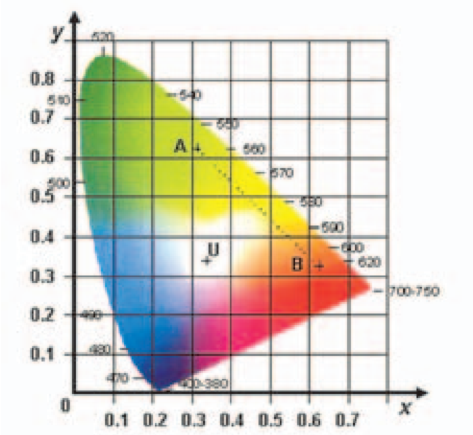


Fig. 4 Standard Color Table (CIE 1931): The colors of the spectrum are situated horseshoe-like around the absolute white point, the so-called achromatic point. Towards the outer region the degree of saturation resp. the intensity of the color (chroma) increases. Each point inside the horseshoe represents a type of color. If a straight line is drawn from color type A to color type B, additive mixing of colors allows to obtain only those colors which are on the straight line. For instance, no yellow light can be mixed from blue-green and red light.

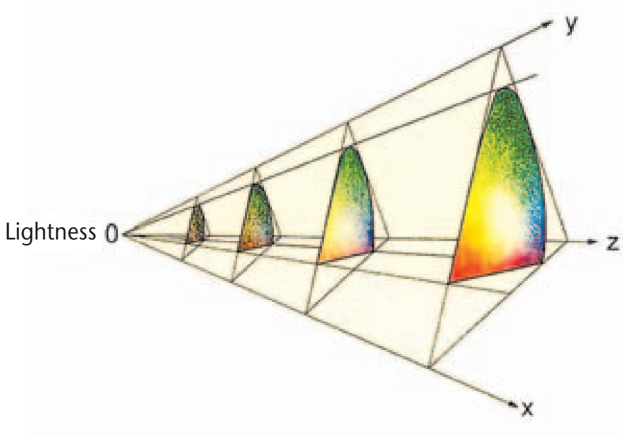


Fig. 5 Standard color tables representing the planes with decreasing lightness. The diagrams show how colors look like if there is less light. This color space is referred to as CIE-1931 system or simply "color bag".

color: hue, chroma (color saturation) and value (lightness). If the experimental results are entered into the triangle, the three colors red, green and blue will be found in the corners of the triangle and any variations of mixed colors are located inside the triangle. Towards the center of the triangle these colors are added up to pure white.

Starting from this basic concept, CIE developed the color chart (Standard Color Table, Standard Valency System). Maxwell's traditional, trichromatic values RGB were converted into the three new tristimulus values x, y and z. The new formula is described shortly in the appendix[4]. In the resulting color chart, the value x represents the horizontal axis and the value y the vertical axis (fig. 4).

On the z-axis this x-y chart is only a plane in the color space which represents the perception of light. Planes situated on the z-axis towards the zero point represent colors with decreasing lightness, i.e. the corresponding charts show how the colors look if there is less light. In the otherwise quite prosaic scientific terminology the term "color bag" is used for this color space (CIE 1931 system) (fig. 5).

For industrial use not only the measurement of colors is relevant. The accurate determination of color differences is particularly important. The reason is quite obvious: A customer who places an order with a producer to supply a desired object (for example a car) in the desired color (for example ice-green) expects the ordered object to be delivered in a color which matches a second one (which already exists); however, a small tolerance will obviously be admitted.

Unfortunately, colorimetry's famous color bag cannot be used for determining color differences as simple gradations on a chart. Indeed, this drawback, which is evident in the

[1]Superscripts refer to the corresponding number in the appendix, p. 739 and 740.

excessive representation of green and the bunching of red, violet and blue hues into the corners, has always been the subject of criticism.

Since the sixties technical literature has repeatedly proposed usable formulae for the calculation of colour differences although such formulae have met with varying degrees of acceptance and application. In 1976 a new system emerged, recommended by the CIE and named CIE L*a*b*. This has been widely used for non-self-luminous objects such as textiles, paints and plastic objects. Converting is described in short in the appendix[5]. The CIE L*a*b* system appears to be suitable to fulfill the industrial requirements mentioned. This color system has already been shown in fig. 2.

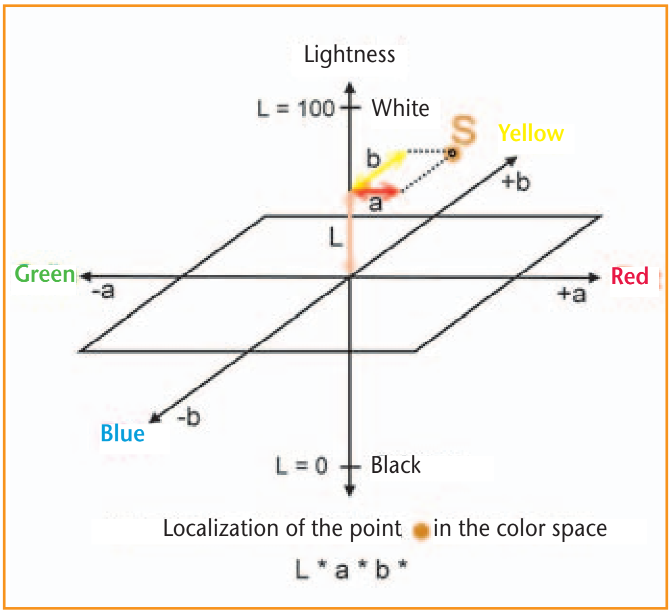
Another illustration of the CIE L*a*b system can be easily achieved using the so-called L*C*h parameters. With this method the distribution of the colors of the L*a*b color space remains unchanged; only the location of the color in the color space is calculated in a different way. In the L*a*b system a color location is defined by the distances on the coordinates L, a and b. In the L*C*h system a color location is defined by the distance on the coordinate L (lightness, value, height of the color location in relation to the L-coordinate), with the degree C (color intensity, chroma, distance from the L-coordinate to the color point) and the angle h (color, hue, angle from the axis +a to the color location). A comparison of both systems can be found in figures 6 and 7. On the left side the L*a*b parameters and on the right side the L*C*h parameters have been drawn in for the same color point S. Conversion between L*a*b and L*C*h is done according to the following formula and illustrated in figure 8:

Conversion of L*a*b into L*C*h (in the quadrant, +a / +b')[6]

L*C*h* | L (Value) remains L | C (Chroma) = $\sqrt{a^2 + b^2}$ | h (hue) = sin(h) = $b/\sqrt{a^2 + b^2}$

When determining the tooth colors, the main focus is on the evaluation of the interaction of the parameters of value (L), color intensity (chroma) (C) and color shift (hue).

For the definition of the color in practical use it is simpler to use the L*C*h values since they directly refer to relevant color characteristics of lightness (L), chroma (C) and hue (h). The chroma value C is expressed with the parameter C and does not need to be calculated using the formula mentioned above. The hue value, that is the shift from red (+A) towards yellow (+b), is also expressed more easily with the angle parameter h.



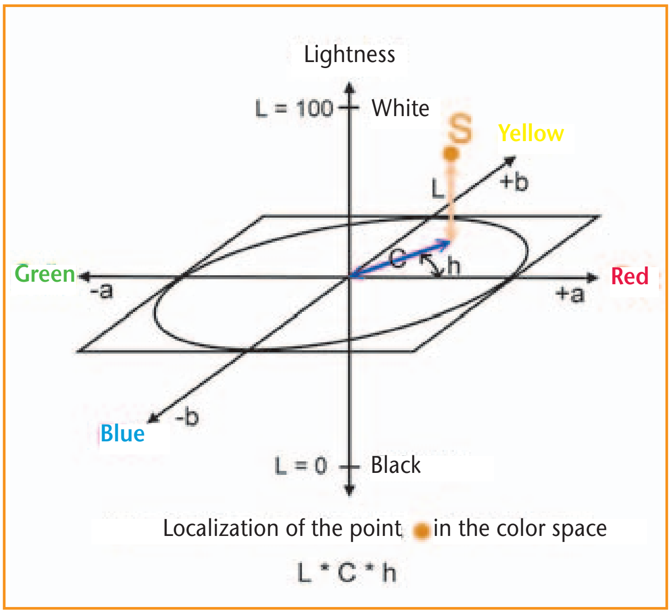


Fig. 6 and 7 The L*a*b color space and the L*C*h color space are identical with regard to the distribution of colors. Only the localization of the color points has been calculated differently.

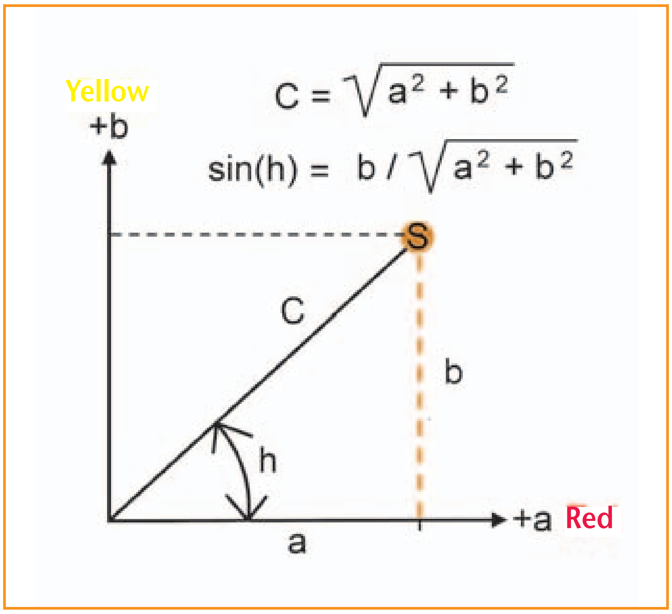
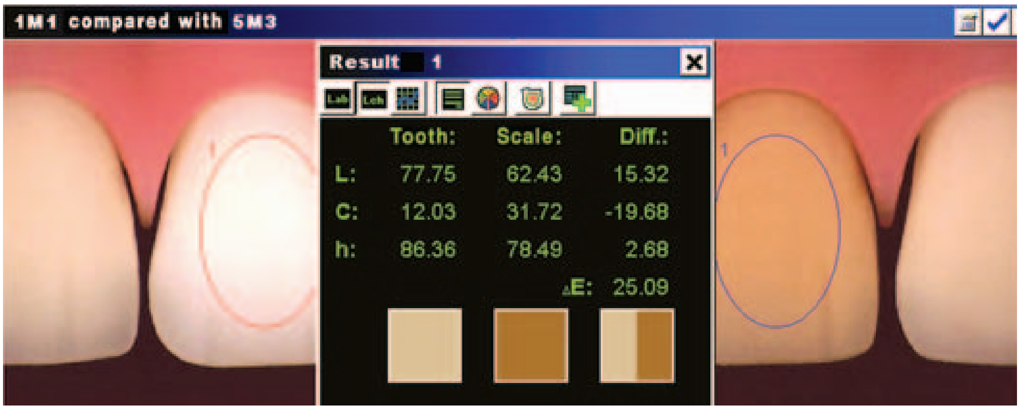


Fig. 8 Localization of the point S (color mixture red-yellow) in the color plane: in the L*a*b system it is defined through a (horizontal) and b (vertical). In the L*C*h system it is defined through C and the angle h.

The position of the tooth color space in the L*a*b resp. L*C*h color space

The area of the natural tooth colors has been described as a banana-shaped color space in the L*a*b resp. L*C*h system. This tooth color space is situated between light-red and light-yellow and is stretched slightly along the lightness axis. If the color values (that is the locations or points in the color space) of the lightest natural tooth are compared with those of the darkest ones, they will have the values 78/1/12 and 62/6/31 in the L*a*b system (fig. 10) and the values 78/12/86 resp. 62/33/78 in the L*C*h system (fig. 9).



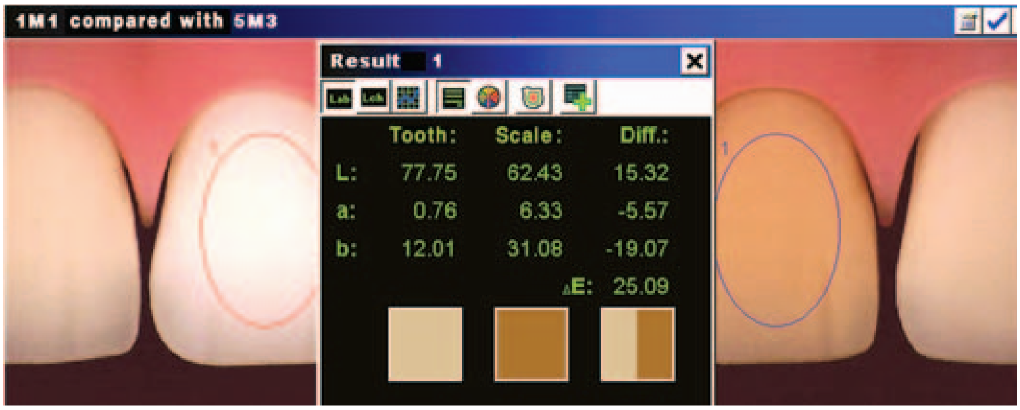


Fig. 9 and 10 L*C*h values resp. L*a*b values of the lightest natural tooth in comparison with the darkest natural tooth. The differences of the L*a*b-values produce the values ΔL = 15.32, Δa = –5.75 and Δb = 19.07. The term ΔE describes the perceived color difference between the two color samples and corresponds to the distance between the two color positions in the color space.

The position of the tooth color space (banana) becomes evident after the integration of the L*C*h values into the graphic representation of the color space (fig. 11).

The light tip of the banana lies at a height of lightness L = 78 (value), reveals a low intensity of C = 12 (chroma) and – with an angle of h = 86 (hue) - is far away from the red axis +a, almost on the yellow axis +b. The dark end of the banana is further below at a height (level) of lightness of L = 62 (value), its intensity is three times higher at C = 33 (chroma) and is closer to the red axis +a with the angle h = 78 (hue). Accordingly, in the color space as shown in figure 11, the banana-shaped tooth color space reveals double inclination at a height of lightness between 78 and 62. In relation to the vertical axis, the upper end of the longitudinal axis is inclined towards the lightness axis while the lower end is inclined towards the yellow axis.

Based on the position of the tooth color space in the psychometric color space, colorimetry can also be used to determine what dental technicians and dentists have known for quite some time:

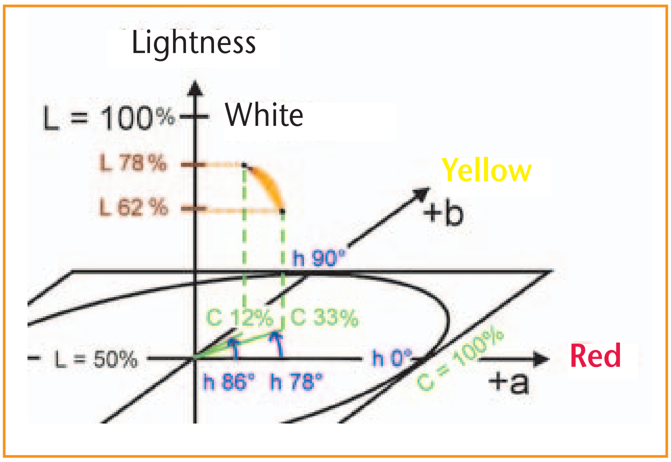


Fig. 11 The position of the tooth color space in the L*a*b color space.

- Lighter teeth have a less intensive color and reveal larger proportions of yellow.
- The darker the teeth, the higher the intensity and the larger the proportions of red.

The ΔE-value

The perceivable difference between the lightest and darkest natural tooth color (L*a*b* 78/1/12 compared to L*a*b* 62/6/31) becomes visible as distance between the two color locations in the color space and is described using the term ΔE. The "Δ" symbol represents the difference and "E" is the initial of "Empfindung" (German for sensation/perception). ΔE is calculated according to the formula of Pythagoras for the space diagonal:

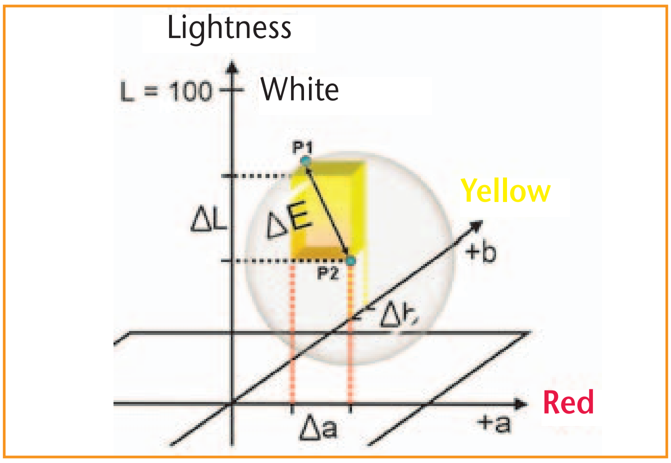


Fig. 12 The space diagonal between the points P2 and P1 corresponds to the color distance and is expressed with ΔE. ΔE represents the difference between the colors of the points P1 and P2 perceived by the human eye. It is difficult for the human eye to recognize ΔE-values below 2 as color difference. The highest color difference in the L*a*b color space is ΔE = 387.

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$$

This calculation method of ΔE is illustrated in figure 12.

The calculation formula of the ΔE value indicates that ΔE refers to the color distance (difference) between the reference and the test color. There is no information on the direction of the difference of the test color. The ΔE value does not provide any information whether the test color differs from the reference color e.g. by its lower lightness and higher intensity. This is illustrated graphically in figure 12. There is an infinite number of test colors featuring the same ΔE difference around the reference color P2. They are all on the surface of the sphere with P2 as the center and ΔE as the radius. This is very important in the area of tooth colors where ΔE values are relatively low. Frequently, in a certain light (operation lamp at the dental chair) the human eye "determines" that the shades of two teeth match each other although one of the teeth is darker and – in exchange – less color-intensive (lower chroma). Outside the office you may sometimes feel disappointed about the result. Those who would like to avoid such an experience may want to use a digital shade measurement device which does not only capture the approximate ΔE values but also the exact differences in the lightness, chroma and hue values.[7] A report on the functional principle of such systems and their meaningful use as a complementary tool for the visual determination of tooth shades will be published in the next issue of Quintessenz Zahntechnik.

The determination of the color (shade) of a tooth

The correct localization of the tooth in the banana-shaped tooth color space is essential to avoid problems in the determination of the color of a tooth. For this purpose samples of a tooth shade guide are compared with the reference tooth in the mouth. In this shade matching process the color of the reference tooth is defined with the code of the shade guide. The dilemma of this method of color matching is the number of color samples available in the shade guide. If a shade guide includes more samples, the number of comparisons increases until they are no longer practicable since the human eye tires quickly during such activities and does not produce any reliable results any longer.

If the number of samples in a shade guide is small, random factors influence shade

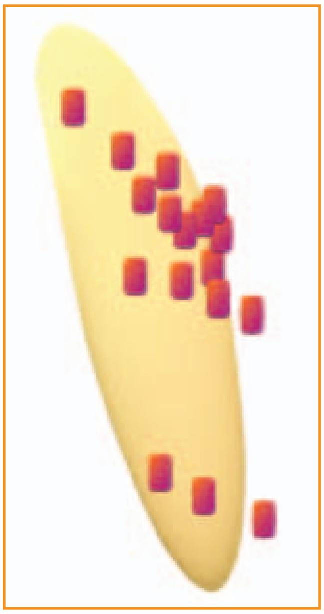


Fig. 13 Conventional shade guides mostly exhibit non-uniform distribution of the individual shade samples in the tooth color space. This results in concentration of colors with small distances to each other and zones including samples which are not useful. Some samples are even situated outside the color space of natural teeth.

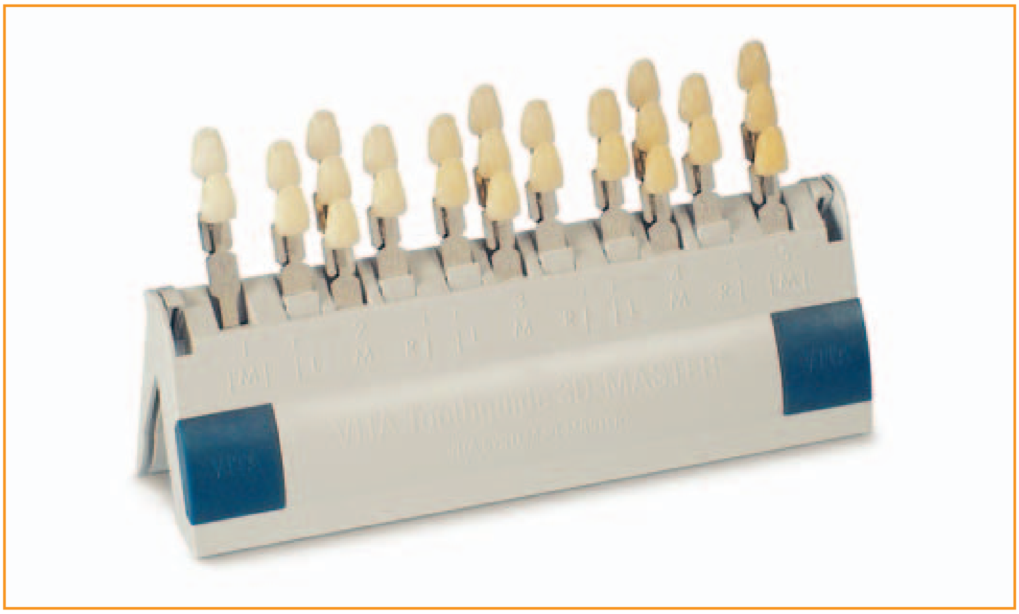


Fig. 14 VITA SYSTEM 3D-MASTER®: The toothguide is divided into five lightness groups. Each lightness group includes a central tooth with six teeth around it for the determination of differences in intensity (chroma) and hue.

matching since there are considerable differences between a limited number of color samples (color distances in the color space). Additionally, almost all shade guides feature arbitrary distribution of the color samples in the color space which results in unnecessary concentrations and very large color distances. Numerous shade guides also offer samples which are even outside the tooth color space and make shade matching unnecessarily difficult (fig. 13).

Shade matching with the VITA SYSTEM 3D-MASTER®

Such problems have been minimized in the VITA SYSTEM 3D-MASTER® toothguide. The color samples feature equidistant distribution in the color space in accordance with scientific principles, which adds superior precision to shade matching if proper handling is ensured. Knowledge of the L*a*b* resp. L*C*h* color space is quite useful in this context. The VITA SYSTEM 3D-MASTER® toothguide includes five lightness groups with equal distances ($\Delta L = 4$) within the tooth color space. The sample teeth (tabs) of the individual lightness groups reveal the same lightness (L) but differ in their intensity (chroma) (C) and hue (h) (fig. 14).

This arrangement in the tooth color space provides the basis for the procedure of tooth color determination.

Fig. 15 The comparison with the average value M2 of the five lightness groups is perfectly suitable for accurate determination of the lightness value of a tooth.

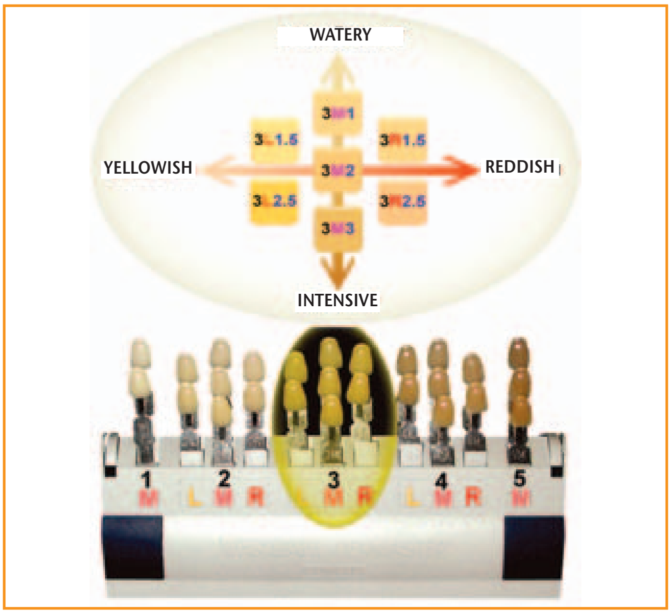


Fig. 16 Arrangement of the VITA SYSTEM 3D-MASTER®: first the lightness group (1 to 5) is determined. Then the intensity (chroma) is checked (pale to intensive); finally the hue is determined (tendency to yellow or red).

Determination of the lightness (L)

First the correct lightness group is selected. Each lightness group includes a central sample tooth M2. If the five M2 teeth are placed against the natural tooth in an order with decreasing lightness and compared one after the other with the reference tooth in a swift manner, incorrect determination of the lightness can almost be excluded (for practical reasons VITA recommends to determine the lightness with the M1 teeth (tabs)[8]). When determining the lightness, the precision can be improved if the five central M2 teeth are spread out like a fan (without adjacent teeth) (fig. 15) and – lying next to each other – are used for comparison with the reference tooth in the mouth. Use the middle sample 3M2 to start the comparison. The decision whether the reference tooth is darker or lighter is easier than the decision whether the tooth is darker or even more darker. The fact that eyes tire within just a few moments should be considered; that is why decisions have to be made quickly and any distractive factors should be eliminated.

If a lightness group has been selected, it is advisable to cover the other lightness groups or to remove them from the toothguide (shade guide). Experience shows that uncertainty frequently arises when continuing to select the corrrect intensity, which reminds that is was quite common to move the entire shade guide sideways in front of the reference tooth. In this case shade matching itself can rather be compared with the random position of the pointer when the wheel of fortune stops spinning.

Determination of the intensity (C)

Further decisions should then be made within the selected lightness group (fig. 16).

First the reference tooth is compared with the central sample M2 of the selected lightness group. It must be decided whether a more intensive resp. saturated or a paler color is present.

In the first case the three samples of the lower semi-circle are eliminated; in the second case the three samples of the upper semi-circle are eliminated.

Determination of the hue (h)

The third and final decision is exclusively made using the remaining four samples: three upper samples (intensity levels 1 and 1.5) or three lower samples (intensity levels 2.5 and 3) and the central sample (intensity level 2). The color matching process is completed after determining the hue. It must be determined whether the reference tooth has a tendency towards yellow (hue L, left) or towards red (hue R, right). If no tendency is found, the hue M is used (middle) (fig. 17).

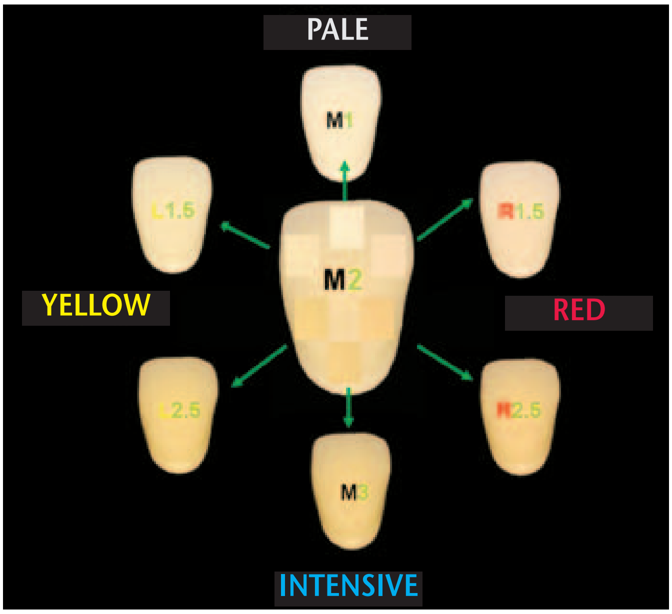


Fig. 17 The hexagon around the average value M2: compared to the average value M2 the three upper samples are paler than the three lower ones. The samples on the right side of the average value M2 are more reddish and those on the left side of the color-neutral average value M2 are more yellowish.

Determination	Select
1. Determination of the lightness (value): the reference tooth is neither lighter nor darker than the central sample (3M2) in the lightness group 3	Lightness group 3
2. Determination of the intensity (chroma): the reference tooth is slightly paler than the central sample (3M2) in the lightness group 3	Intensity 1 or 1.5
3. Determination of the color (hue) The reference tooth is slightly more reddish than the central sample (3M2) in the lightness group 3	Color (hue) R
Result: VITA SYSTEM 3D-MASTER®	**3 R 1.5**

Pattern 1 Example of color determination

Example

Accordingly, color (shade) determination with the VITA SYSTEM 3D-MASTER® could be performed as shown in pattern 1.

A more accurate and faster method of shade taking with the human eye can hardly be imagined. The modular arrangement and the selection of the correct color by means of an exclusion process allow reliable and efficient handling after a short time of practising. In extremely light or dark teeth shifts towards yellow or red are quite unlikely; that is why color determination within the lightness groups 1 and 5 will probably always end in the middle hue M.

The distribution of the tooth colors in the tooth color space

To obtain useful information, we will take a look at the frequency distribution of the tooth colors in the tooth color space. In accordance with the narrowing ends of the banana-shaped tooth color space, the color planes of the lightness groups 1 and 5 in the end positions are relatively small. Following the principle of equal color distances, there is not enough space in these color planes for all six sample teeth. Additionally, teeth of the lightness groups 1 and 5 are extremely rare. Approximately half of all natural human teeth are found in the middle of the color space, i.e. in lightness group 3. When determining the lightness group it is recommended - from a statistical point of view - to start from the middle and then to decide whether the reference tooth is lighter or darker or if it is virtually located in lightness group 3 (fig. 18)[9].

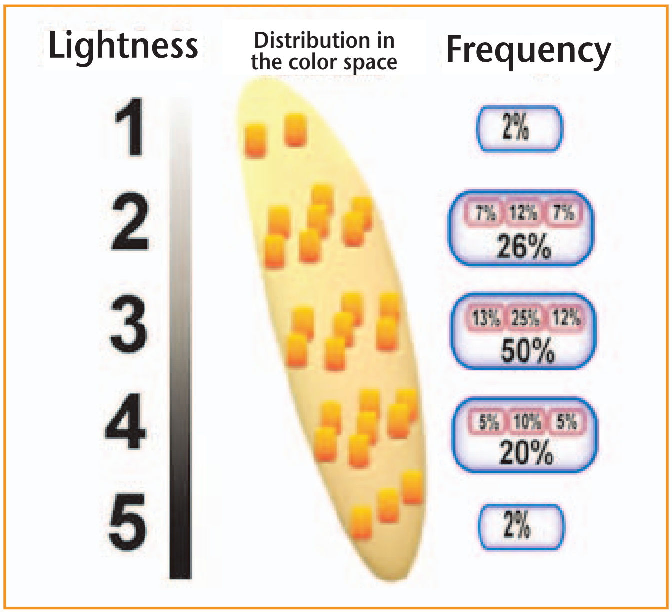


Fig. 18 The quantitative distribution of the natural tooth colors in the tooth color space. 50 % of all natural tooth colors are on the color plane of the middle lightness group 3. When determining the lightness group, it is recommended to start matching the lightness from this group.

Mixing the primary 3D-Master colors (shades)

In dental techniques all-ceramic reconstructions are on the advance. Compared to other reconstruction techniques their proportion and the aesthetic requirements are increasing rapidly. More and more value is attached to a highly natural reconstruction: the new all-ceramic and veneering systems play a key role in this development. When determining the color (shade) of a tooth, brilliance, translucency and opalescence influence the perception of color. The selection of the correct basic color, however, is always vital. Previous reconstructions with color deviations of ΔE 4 – ΔE 6 are considered to be suboptimal results today. ΔE values of 1 to 3 are being demanded which can only be achieved using

1M1	1.5M1	**2M1**	2.5M1	**3M1**	3.5M1	**4M1**	4.5M1	**5M1**
1M1.5	1.5M1.5	2M1.5	2.5M1.5	3M1.5	3.5M1.5	4M1.5	4.5M1.5	5M1.5
1M2	1.5M2	**2M2**	2.5M2	**3M2**	3.5M2	**4M2**	4.5M2	**5M2**
	1.5M2.5	2M2.5	2.5M2.5	3M2.5	3.5M2.5	4M2.5	4.5M2.5	5M2.5
		2M3	2.5M3	**3M3**	3.5M3	**4M3**	4.5M3	**5M3**
23 additional, exactly defined mixed colors can be obtained from the fourteen main M shades.								
		2R1.5	2.5R1.5	**3R1.5**	3.5R1.5	**4R1.5**		
		2.5R2	2.5R2	3R2	3.5R2	4R2		
		2R2.5	2.5R2.5	**3R2.5**	3.5R2.5	4R2.5		
Nine additional, exactly defined mixed colors can be obtained from the six main R shades.								
		2L1.5	2.5L1.5	**3L1.5**	3.5L1.5	**4L1.5**		
		2L2	2.5L2	3L2	3.5L2	4L2		
		2L2.5	2.5L2.5	**3L2.5**	3.5L2.5	**4L2.5**		
Nine additional, exactly defined mixed colors can be obtained from the six main L shades.								

Pattern 2 The 29 samples of the VITA 3D-MASTER toothguide.

all-ceramic subconstructions and require careful shade matching and good cooperation between dentists and dental technicians.

The VITA SYSTEM 3D-MASTER® provides perfect preconditions to reach this target. The exact arrangement of the toothguide, which is based on the colorimetric principle, allows mixing colors with precisely predictable results, which is not possible if e.g. A2 and C1 are mixed. According to the tables in pattern 2, all desired mixed colors can be obtained from the 29 samples of the VITA 3D-MASTER toothguide.

Moreover, an infinite number of additional mixed colors can be obtained when mixing M-colors (shades) with L-colors or R-colors. This provides unimagined possibilities for the correct selection of the basic color (shade) of a tooth. The deviations in the basic colors will be minimized and dental technicians' scope for precise characterization of the tooth by means of transparencies and effects is extended. The ΔE values are reduced to an extent close to the resolution limit of the human eye. The accompanying use of digital color measurement devices, provided that they capture the entire spectral data just like the "VITA Easyshade" system which has been launched in the market only recently, may be quite helpful. A report on this subject will be published in the next issue of Quintessenz Zahntechnik.

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Appendix

[1]Color perception of the visible light in the wavelength range of 380 nm to 720 nm is assigned to the observer with standard vision. The color receptor cells of the human eye are concentrated around the central area of the retina (fovea centralis). The size of the area around the fovea centralis (field of vision) is important for color comparison. Larger fields of vision result in different perception of colors than smaller ones. The observer's field of vision is defined by the determination of the angle capturing the field of vision (fig. 19).

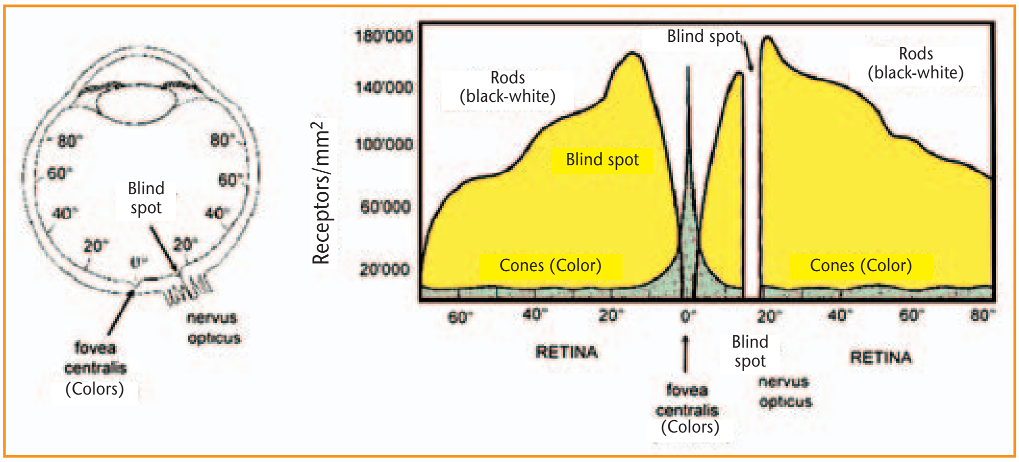

Fig. 19 Color perception on the fovea centralis: photosensitive but not color-sensitive cells are situated outside the fovea centralis and distributed across the entire retina. In 1931 CIE defined the standard observer with a viewing angle of 2° (2° observer). In 1964 the viewing angle was extended to 10° (10° observer).

[2]In accordance with a physical law, light which is emitted by a black object is linked with its temperature. If, for example, glowing coal is heated, its color will also change. Accordingly, color can also be expressed as color temperature in °Kelvin.

Illuminant, type of light	Description	Color temperature (°Kelvin)
A	Tungsten filament lamp	2'856
B	Midday sunlight	4'870
	Rising sun	1'800
D65	Standard light of the spectrophotometer VITA Easyshade or MHT SpectroShade (average daylight)	6'500

[3]Each object reveals its inherent color information to the human eye. This information can be distorted during perception if the object is exposed to an additional, reflecting source of light (illuminant). When matching colors, it is therefore always required to eliminate such "glare". Naturally, brilliance, translucency and opalescence of a tooth also influence color perception. First of all, however, the correct basic shade must be determined. Only then other factors which have an influence on the color need to be considered.

[4]In the CIE system, the traditional Mawellian trichromatic values are converted into three new tristimulus values X, Y and Z. Identical X, Y and Z values add up to white. These variables (color masses) are converted further into x, y and z by dividing each of these numbers by their total sum, i.e. $x = X/(X + Y + Z)$ and so forth. With this conversion, it is important that the sums of the colour masses add up to one ($x + y + z = 1$). Only two of the new values thus remain independent, and these can be shown on a two-dimensional chart (see fig. 4).

[5]In order to arrive at the CIE L*a*b* color space, the three colorimetric coordinates (colour-values) of X, Y and Z from the CIE Standard Color Table have been transformed into the three new reference values of L, a and b. In a not entirely simple way, X and Y become a, with b similarly obtained from Y and Z. Y on its own becomes L. L represents a type of "psychometric brightness" (or lightness). In other words, this parameter is defined by the appropriate function of a psycho-physical value (a color value) selected in such a way that uniform steps on the scale will reproduce as closely as possible the uniform differences – which are related in terms of lightness – between colours. The values of L extend between 0 for black and 100 for white.

[6] The angle h is between 0° and 90° for the colors between yellow and green. The angle h is between 90° and 180° for the colors between green and blue. The angle h is between 180° and 270° for the colors between blue and red. The angle h is between 270° and 360° for the colors between green and red. This formula for the calculation of the angle h is based on the trigonometry of the triangle with 90° angle. No rectangular triangle can be obtained any longer for colors and mixed colors outside the red side/line (+a) and the yellow side/line (+b) so that a more complex formula to calculate the angle h is used.

[7] In the calculation method of ΔE described here, the factors value, chroma and hue are weighted in a way which renders them not particularly suitable for the definition of the size of the perceived color difference. Using various changes in the calculation, improvement of the original ΔE value can be achieved. ΔE_{CMC}, ΔE_{94}, ΔE_{2000}, ΔE_{LC}, ΔE_{MHT} etc. represent complimentary corrections for the irregularity of the color difference of the L*a*b* color space. The given method for calculating ΔE is not very useful in the field of dentistry and dental techniques. The relevance of the value should be higher since it is the most significant factor in the determination of tooth shades. If the reconstruction of a tooth reveals the correct value, any color errors may be considered less significant.

[8]The determination of the lightness (value) group with the M2 teeth described in here does not follow the recommendations of VITA. In the VITA SYSTEM 3D-MASTER® the value is determined with the M1 teeth (samples). This appears to be logical since the M1 teeth are located in the upper row of the toothguide and can be placed against the tooth without the need to disassemble the toothguide. Determining the value with the M2 teeth is a different approach which is more complicated but – according to our experience – also more promising.

[9]For some years chemical brightening (bleaching) of teeth has become more and more popular – either within the "eternal quest for the fountain of youth" or as a cultural variation of the motto "citius, altius, fortius" – faster, higher, stronger. As long as such shifts in lightness lie within the natural tooth color space, this trend may be acceptable to a certain extent. Brightening (bleaching) should be rejected if the value is to extend across the lightness (value) group 1 resp. if an unnatural lightness group is intended to be reached. We are left quite helpless, however, to fashion trends and extravagant wishes. The VITA SYSTEM 3D-MASTER® has already responded to such tendencies and integrated a lightness group 0 in the toothguide. Extreme, unnatural bleaching is particularly popular in the United States. Whether this trend will cause a shift in the statistical distribution of tooth colors in the tooth color space remains to be seen.

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