NATURA MAGICA: THE MAGIC OF NATURE

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The primary purpose of traditional dental technology is to manufacture functional and esthetic dental prostheses for patients with missing natural teeth. However, cultural changes in modern society over the past two decades have led to an increase in cosmetic and esthetic demands in restorative dentistry. The desire of many patients to improve their oral appearance gave rise to a new industry, which has now grown to a considerable size. These new esthetic demands often involve the use of multiunit restorations, frequently made with all-ceramic materials, to correct misalignment of natural teeth and other naturally occurring deficiencies. Therefore, cosmetic restorations focus mainly on morphologic issues, in accordance with an even shade of high value.[1]

On the other hand, dental technicians are still often required to manufacture single-unit restorations in the esthetic zone to replace a lost anterior tooth. This type of restoration is widely recognized to be the most challenging, because success is dependent on a complex combination of factors, including perfect imitation of morphology, shade, and surface texture as well as soft tissue management.[2–4] This article aims to illuminate the reasons for the frequent occurrence of failed optical reproduction of natural dentition in fixed dental prostheses and to offer some practical advice in the daily quest to "get the color right."

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Figs 1 and 2 A prism breaks a beam of light into a rainbow of colors spread across the entire visible spectrum.

Fig 3 Goethe argued that color is "a degree of darkness allied to light and shadow."

Figs 4 and 5 The greatest amount of iridescence is found at the incisal edges of the teeth, ie, the boundary between light and shadow.

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THE DISCOVERY OF COLOR

One of the minor skirmishes in science in the early nineteenth century was a difference of opinion between Newton's followers in England and Goethe in Germany over the nature of color. The touchstone of Newton's theory was his famous experiment with a prism (Figs 1 and 2). A prism breaks a beam of light into a rainbow of colors spread across the entire visible spectrum, and Newton realized that those pure colors must be the elementary components that combine to produce white. To Newtonian physics, Goethe's ideas were nothing more than pseudoscientific meandering. Goethe refused to view color as a static quantity that could be measured in a spectrometer and pinned down like a butterfly to cardboard. Color, Goethe argued, is "a degree of darkness allied to light and shadow" (Figs 3 to 5). In other words, color comes from boundary conditions and singularities. What is red? To a physicist, it is light radiating in waves between 620 and 800 billionths of a meter long.[5] In the world of physics, color does not exist. It consists of matter and energy, both of which are colorless. Color is not a material property, and rays of light have no color. Color is a purely human notion, generated in the brain in conjunction with the body's own receptive system, ie, the eyes and the sensory nervous system. Objectively, the sensation of color is triggered by the wavelength of light; however, the physiologic notion of color is subjective, making it difficult to measure or describe.[6] In other words, color is a matter of human perception and will differ from viewer to viewer. Newton's optics proved itself a thousand times over, while Goethe's treatise on color faded mercifully into obscurity. Where Newton was reductionist, Goethe was holistic. Newton broke light apart and found the most basic physical explanation for color. Goethe walked through flower gardens and studied paintings, looking for a grand, all-encompassing explanation. Newton made his theory of color fit a mathematical scheme for all of physics. Goethe, for better or worse, abhorred mathematics.

SHADE REPRODUCTION: A MATTER OF LUCK?

Several studies have recently been published on shade reproduction in dentistry.[7–15] Many of these contributions are academic in nature, often resorting to the Munsel system, which divides color into three aspects: hue, chroma, and value. Due to its rational foundation, this concept is fairly easy to understand and hence its widespread use in color studies. Recently, a number of new innovations, such as digital shade-taking aids and shade guide systems, have been introduced.[16–20] Although these new guides are widely considered to be an improvement, they don't appear to hold the ultimate answer to shade determination and subsequent shade reproduction of natural dentition. The reasons for this may be explained by four important issues:

1. The dimensions of hue, chroma, and value coexist simultaneously. It is difficult for the human eye to view and judge them separately.
2. Determining the exact hue, chroma, and value together may not be as important as previously thought.
3. With increased age, natural teeth will show more iridescence and a greater ability to display changing optical appearances, depending on the light conditions under which they are examined.[21,22]
4. Due to the physical differences between natural dentition and dental ceramic, the effect of metamerism is generally unavoidable.[23]

It appears that trying to judge the optical appearance of natural teeth based on the concept of hue, chroma, and value alone is a flat, two-dimensional approach. Instead, we must examine other important phenomena that may explain the three-dimensional optical appearance of natural teeth but which have been widely overlooked by the scientific community.

Iridescence

Iridescence is an optical phenomenon characterized as the property of surfaces in which hue changes, according to the angle from which the surface is viewed. Iridescence is caused by multiple reflections from multilayered, semitransparent surfaces in which phase shift and interference of the reflections modulate the incident light by amplifying or attenuating some frequencies more than others (Figs 6 to 17).[24]

Many plastics, acrylics, and composites, including those used to fabricate chairside provisional restorations, show a high degree of iridescence (Figs 18 to 20). This property, in conjunction with a relatively high degree of translucency and the absence of a supporting framework, offers a simple explanation of why it is often so difficult to match the shade of the provisional restoration with the ceramic restoration, despite the fact that the first makes no use of any polychromatic layering techniques.


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Figs 6 to 8 The effect of iridescence can be seen in a variety of everyday objects, such as the security features on modern bank notes, the tiny depressions of varying depth on a CD, and a soap bubble.


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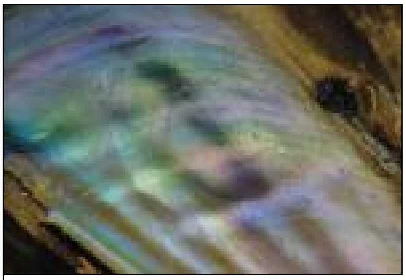
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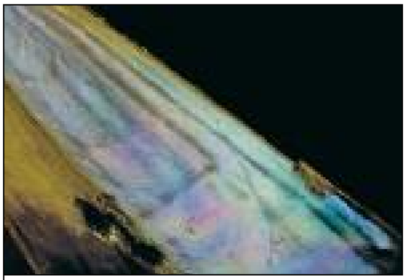
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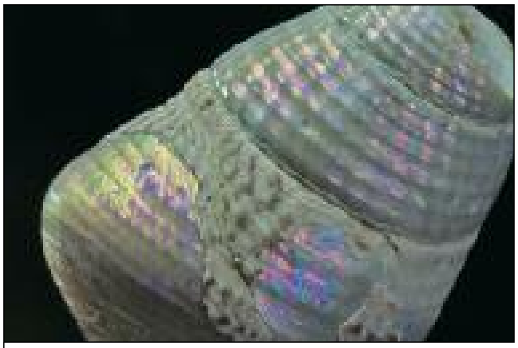
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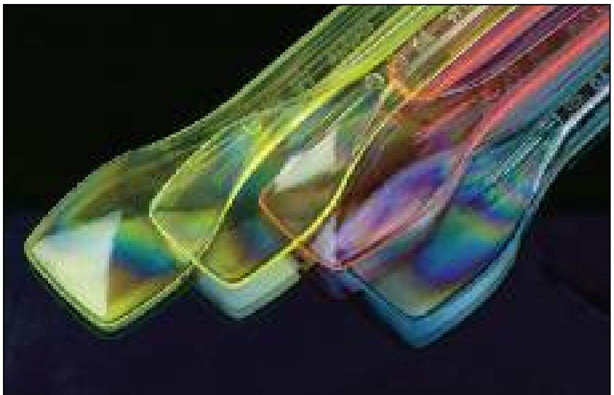
Figs 9 to 15 Mother of pearl on an oyster and seashells is the most common type of anisotropic iridescence.



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Figs 16 and 17 Certain types of light refraction can be achieved structurally, as can be seen with these ice spoons. Due to the transparency of the material, a certain highlight effect becomes visible on the edge of the spoons, varying in intensity depending on the angle of the light. Note also the subtle iridescence of the plastic, which was also photographed under polarized light.

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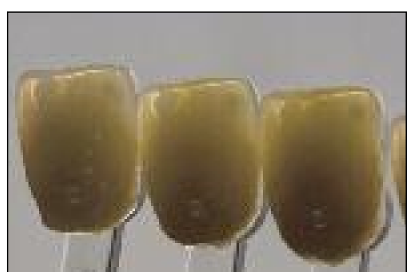

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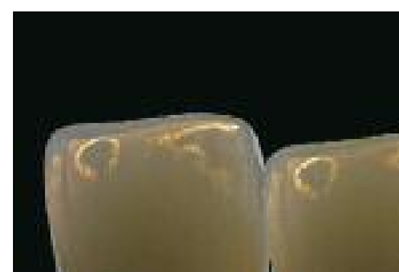

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Figs 18 to 20 Many acrylic resins naturally possess iridescent properties that are very close to natural teeth. Modern dental composite materials often make use of organic pigments, which cannot be used in dental ceramics due to the necessary heat involved to fuse the glass. Most modern composites are superior to ceramic in terms of optical adaptation but are still less durable and more prone to discoloration.

Anisotropy and Isotropy

Anisotropy is the property of being directionally dependent, as opposed to isotropy, which means homogeneity in all directions. It can be defined as a difference in a physical property (absorbance, refractive index, density, etc) of a material when measured along different axes. Anisotropy is a typical characteristic of minerals or any other naturally grown material such as wood, tissue, or teeth. Minerals such as crystals are especially strong examples of anisotropic materials that typically display a high degree of iridescence and therefore the ability to change color depending on the penetration angle of incidental light.[25,26] Human enamel, with its directional arrangement of prism rods, prism sheets, and


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Figs 21 to 23 Crystalline materials may have different indices of refraction associated with different crystallographic directions. A common situation with mineral crystals is that there are two distinct indices of refraction. Such materials are called birefringent, which refers to the resolution or splitting of a light wave into two unequally reflected or transmitted waves by an optically anisotropic medium, in this case by the hydroxyapatite crystals of the enamel. This effect is also called double refraction.


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Fig 24 The origin of the two-phased leucite-reinforced dental ceramic lies in the technology of fusing metal jackets to light bulbs. When fusing ceramic to metal, the coefficient of thermal expansion of silicate glass must be adjusted to prevent cracking during cooling. This is achieved through feldspar-induced leucite crystal growth. A similar technology is used when light bulbs are manufactured in order to maintain the necessary vacuum under which the filament operates.


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Figs 25 to 27 Sample of an extracted human central sliced to a thickens of 0.2 mm in comparison to a sample made of polychromatically layered dental ceramic of the same thickness. Both were photographed under polarized light, clearly showing the almost complete lack of iridescence of the amorphous porcelain in comparison to the anisotropic natural image.

hydroxyapatite crystals, also falls into this category (Figs 21 to 23). In contrast, neither the two-phased leucite-reinforced dental ceramic based on the Weinstein patent from 1962, which is still used for veneering ceramometal restorations today, nor the more modern glass ceramics used for veneering zirconium and alumina restorations are anisotropic (Fig 24). Instead, they are of an opposite isotropic or amorphous constitution. This major discrepancy exemplifies the biggest deficiency of any dental ceramic today (Figs 25 to 27).[27] However, dental ceramic's well-documented clinical longevity, biocompatibility, and acceptable esthetics still make it the primary choice in restorative dentistry.

Figs 28 and 29 Maxillary full-arch case consisting of a number of single zirconia crowns, veneers, and posterior zirconia prostheses. It is important to remember that colors that match under one light source will often appear different under another.


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Figs 30 to 32 The effect of metamerism is usually less evident with multiple restorations, since there is no natural dentition left with which to directly compare the prostheses.


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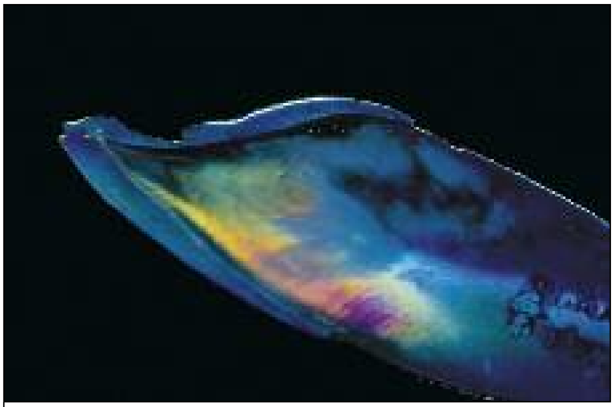
Metamerism

The phrase *illuminant metameric failure* is sometimes used to describe situations where two samples match when viewed under one light source but not when viewed under another. Most types of fluorescent lights produce an irregular or peaky spectral emittance curve; therefore, two materials may not match under fluorescent light even if they are a metameric match under an incandescent "white" light source with a nearly flat or smooth emittance curve. Geometric metameric failure can occur when two samples match when viewed from one angle, but then fail to match when viewed from a different angle.[28] This phenomenon is always present in any dental restoration due to the differences of physical and chemical constitution between teeth and restorative materials.[6] However, the degree of metamerism can be controlled through the amount of invasiveness of a restoration. The less invasive the treatment, the more natural tooth substance is left, and therefore the less metamerism will occur. For example, achieving a color match with a minimally invasive veneer is much likelier than with a complete crown (Figs 28 to 32).



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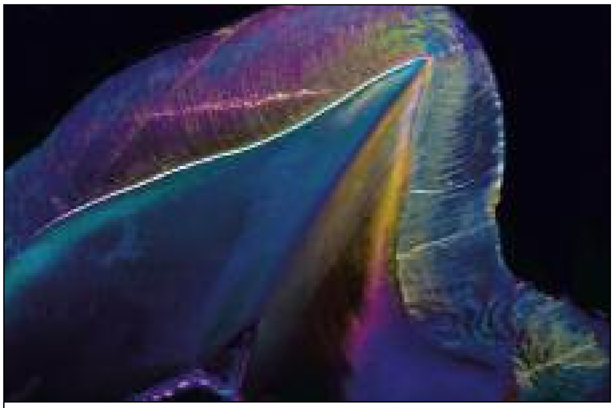
Figs 33 to 35 Photoelastic images of sectioned human teeth. The DEJ is mainly responsible for the increase or decrease of value of natural teeth depending on the surrounding light conditions.



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The Dentoenamel Junction

The dentoenamel junction (DEJ) unites hard, brittle enamel and tough, flexible dentin.[29] The estimated refractive index of collagen fibrils, one of the main ingredients of the DEJ, is 1.49. The refractive index of air is 1, which means that light will travel at almost the same speed through the DEJ as it does through air. This explains the fiberoptic property of the natural tooth.[30] It is this specific optical property of the DEJ that allows the tooth to increase or decrease in value depending on the illumination or light conditions (Figs 33 to 35).

Value, Opacity, and Translucency

Along with the purely morphologic requirements that must be fulfilled by an adequate restoration, a single restoration in the esthetic zone must be harmonious with the natural dentition in terms of value, opacity, and translucency (Figs 36 to 41).[31–35] These three aspects are invariably linked. Failing to address any one of them is often considered the most common reason for inadequate color matching. For instance, if a crown is too opaque, it will often be too high in value and lack translucency/depth as well. Achieving accurate reproduction of the exact hue and chroma is often impossible, but luckily, it is also of secondary importance. Almost every clinical case presented in this article has failed to accurately match hue and chroma of the natural dentition; however, the value has been at least fairly well matched, and the necessary amounts of opacity and translucency have been provided.

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Fig 36 Preoperative image of a missing maxillary central incisor. A zirconia crown was planned.

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Fig 37 One simple but effective way to judge the shape of a restoration is by viewing it in front of a mirror. This has a camera obscura effect that converts a three-dimensional object into a two-dimensional one. This way, slight disproportions or errors in the design of the line angles can be immediately detected.

Figs 38 and 39 Imbrication lines (growth bands) are a common surface feature of teeth. They can be quickly and accurately imitated using the modified non-edge technique. A coarse diamond bur is used to cut off the tip of an old diamond flame-shaped bur. It is then run across the labial surface of the tooth at medium speed from left to right, with the radius increasing toward the cervical aspect.

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Figs 40 and 41 Direct zirconia crown 2 months after insertion. The key in this case is the balance between opacity and translucency, which makes control of the value very difficult. If too much transpa powder is used to dilute the dentin, the higher the likelihood that the color will become too gray. On the other hand, a lack of translucency will quickly result in an overly opaque appearance with too high a value.

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Figs 42 to 44 Lateral views showing the effect of DEJ-induced fiber-optic illumination. The same tooth was sequentially photographed with a steady decrease of light intensity, while the shutter speed and aperture remained unchanged. The less light that is used, the more value is lost. Natural iridescence also has an effect on the visibility and intensity of many internal characteristics, such as imbrication bands, mamelons, and incisal translucency, which appear much clearer and more intense when less light is used.

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PRACTICAL IMPLEMENTATION

Lighting Conditions

Since most dental restorations tend to be too high in value, it is advisable to select the shade under relatively bright lighting conditions (no less than 6,500 K) (Figs 42 to 44).[6,36] If a restoration does not immediately appear to be too light compared with the adjacent natural tooth when first tried-in under such bright conditions, its value will usually be accurate when viewed under a variety of normal lighting conditions. This approach is somewhat risky, since most ceramists will prefer an outcome that is too light, because a restoration can easily be stained darker. However, superficially applied stains will often interfere with the natural surface luster of the adjacent natural dentition. A modern, high-resolution digital image will always expose a stained surface.

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Fig 45 Every attempt at shade taking is merely a snapshot of a dynamic situation. It records a specific moment of time; as such, it can be very deceiving. Is the platform diver rising or falling?

Fig 46 In most cases it is necessary to use a mixture of effect powders and modifiers to adjust the details. However, this method will also compromise the predictability of the outcome, since the combination of those intricate mixtures is based on clinical experience, instinct, and last but not least, imagination. Before any unknown mixture is used in the definitive buildup, it should be quickly tested using a shortened firing cycle.

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Figs 47 and 48 True opalescence cannot be achieved artificially in dental ceramic. A pseudo-opalescent effect is achieved through pigmentation using ingredients of varying degrees of fluorescence. In direct comparison with a real opal, every opalescence powder is basically white, changing from blue to orange. These images exemplify the current possibilities a modern ceramic system can offer.

Shade Guide Systems

Despite the introduction of various new shade-taking products, the old standard 16-color Vita Classical shade guide (Vita Zahnfabrik, Bad Säckingen, Germany) is still adequate in most cases. However, it is advisable to rearrange the shade tabs with respect to the value progression of each shade (B1, A1, B2, D2, A2, C1, C2, D4, A3, D3, B3, A3.5, B4, C3, C4).[37] Digital shade-taking devices appear to be of limited value, since the only reliable information they convey is the very basic shade, eg, A3 or B2. Such systems do not usually account for the concepts of depth or translucency, nor are they able to interpret certain biocharacteristics such as mamelons or imbrication lines. A two-dimensional digital shade map is also of little value to the dental ceramist, who can achieve a natural appearance only by stacking many intricate layers of ceramic with varying degrees of translucency and by being completely familiar with the effect powders and modifiers offered by the ceramic system used (Figs 45 to 48).[38–40]


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Fig 49 This case included a number of faint, lightly colored imbrication lines. The credible imitation of this unique feature was vital to the successful outcome. A fashioned diamond-infiltrated carborundum bur was used to cut the wavy lines, which are somewhat reminiscent of ripples of sand dunes in shape and orientation.

Figs 50 and 51 A previously tested mixture of PS-0, OD 43, and Crack Liner White (Creation, Klema, Meiningen, Austria) was thickly mixed, washed in, and fired.


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Fig 52 The result is tried-in at the bisque-bake stage. It helps to mark the line angles on both the crown and natural tooth to check the symmetry and proportions.


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Fig 53 Screw-retained zirconia crown 6 weeks after placement.

Fig 54 Zirconia is an ideal choice for single-implant restorations due to its excellent biologic properties. The likelihood of soft tissue integration with zirconia is of great benefit to the tissue architecture, thus ensuring healthy gums.


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Fig 55 Preoperative situation of a case involving a four-unit maxillary restoration.

Figs 56 and 57 The treatment proposal included three pressable crowns and one feldspathic veneer on platinum foil, veneered with Creation Classic.


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Fig 58 Bonded restoration 3 months after placement. Pressable feldspathic materials possess the highest degree of translucency of any all-ceramic material available in dentistry today. Some natural iridescence is preserved due to the vital teeth underneath, thus minimizing the effect of metamerism.

Framework Material

Over the last few years, all-ceramic materials, particularly zirconium dioxide, have made a strong impact on the international dental market. However, the actual benefits of such restorations compared to the conservative porcelain-fused-to-metal restorations are still unclear. So far, practical experience has shown that choosing an all-ceramic framework material may not guarantee an esthetic result. In certain cases, such as with aged teeth, the opacity of a classic feldspar-based leucite-reinforced ceramic (eg, Creation Classic, Willi Geller Creation, Baar, Switzerland) is more advantageous than the glass ceramic used for veneering zirconia, which is often too translucent. However, zirconium dioxide does have certain biologic advantages, such as the possibility of soft tissue integration, which makes it particularly suitable for implant cases in the esthetic zone (Figs 49 to 54).[41,42]

Controlling Opacity and Translucency

Due to the many differences between ceramic systems, technicians should choose one system that suits their personal preferences and then stick to it. Ideally, this system should posses enough opacity to allow the ceramist to adjust the degree of translucency based on individual requirements by choosing from a broad selection of transpa powders and modifiers to mix in with the dentin and enamel powders.[43] Many new ceramic systems seem to lack this degree of opacity and often appear too dark or too gray in the mouth. If only a small amount of space is available, it is often hard to mask the framework with many of these new products (Figs 55 to 58).

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Fig 59 Standard shade-taking procedure for a single crown on a traumatized central incisor. First, a shade tab is chosen that is the closest match in terms of value. In this case, some white stains were applied to imitate the many faint lines (InNova, Creation, Klema).

Fig 60 Based on the initial shade, a number of powder mixtures are fired and compared with the natural tooth. It is necessary to adjust the degree of translucency of the dentin by adding colored transpa powders.

Fig 61 Unfortunately, the first crown revealed a classic case of metameric failure. This was partially due to oversaturation of the dentin with transpa powders, causing the crown to appear too gray. Further, the patient had used home bleaching between shade-taking and try-in.

Fig 62 The second crown was contoured and textured on the cast using silver powder.

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Figs 63 and 64 Final zirconia restoration on a nonvital and discolored tooth 3 months after cementation. A minimal amount of metamerism is still visible depending on the background color and viewing angle.

Soft Tissue Management

Many recent publications have emphasized the importance of "pink esthetics" to the point that it is now an established fact that an adequate esthetic result cannot be achieved without the presence of healthy and carefully prepared soft tissue. This can be achieved through treatment planning and communication between the clinician and dental technician.[44]

Self-Criticism and Personal Progress

Whether or not the technician is working directly with the patient, it is still possible to achieve a successful color match.[2,45] However, it is not always possible to easily apply the lessons learned from one case to the next, which can make learning difficult. Therefore, it is important to remain critical about one's own results and to use a digital single-lens reflex camera to document progress.[46–48]

If a crown does not match the expectations when it comes out of the furnace, there is no use in trying to convince oneself that the result will be adequate in the mouth. This very human behavior will often lead to a waste of valuable time for everyone involved. Stacking the actual ceramic is not nearly as time consuming as deciding on which powders to use and how to mix them based on the collected data. Since the vast majority of the process is carried out in the mind and imagination of the ceramist, it is only normal to sometimes find that one particular effect may not have worked out as intended once the crown is fired. Therefore, it pays to have a number of copings prepared to restack the porcelain and start again, until a truly promising result can be tried-in (Figs 59 to 64).

CONCLUSION

Shade determination and reproduction based solely on the Newtonian, scientific approach may not guarantee a successful outcome. Color is a matter of human perception and will differ from person to person.

Natural dentition differs substantially from any currently available ceramic system. These differences include completely different chemical and physical compositions (anisotropy versus isotropy). The main result of these differences is the unavoidable effect of metamerism. Determining and matching hue, chroma, and value is difficult, but it is also not as important as previously thought. Adequate color matching can be achieved through matching value, opacity, and translucency of the natural image, in accordance with accurate morphologic reproduction and imitation of surface texture. It has also become increasingly apparent that soft tissue management is a vital factor in achieving the perfect color match. In terms of material selection, it may be assumed that zirconia frameworks do not posses any real esthetic advantage over metal frameworks. However, due to its biologic properties, zirconia is an ideal choice for single-implant restorations in the esthetic zone. Therefore, the choice of framework material must consider the individual case requirements.

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