Experimental Birefringence Photography in Dentistry: Unlocking Infinite Creative Possibilities

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During the late 1980s, Sieber[1,2] published a series of articles that included impressive birefringence images of extracted, sliced teeth. While these images were both spectacular and new to the field of dental technology, the optical properties of teeth were already long known. In 1861, Valentin[3] described the negative birefringence of enamel using a polarized light microscope. In 1903, Kirk[4] observed ground tooth sections in polarized light. Today, such images have become a fashionable feature of many publications, especially those discussing esthetic veneering techniques. However, the precise conditions and methods to achieve images of polarized tooth sections have remained a well-kept secret. This article aims to shed light on the exact techniques and circumstances necessary to produce stunning polarized images of sliced teeth.

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BASIC PRINCIPLES

The optical properties of human enamel are based on double refraction, or birefringence. When light that passes through an object is polarized, the light is decomposed into two rays of distinct wavelengths. This phenomenon is commonly used to study the stress of a given material, ie, the photoelasticity. However, it can also be used to study the optical characteristics of different materials.

Birefringence in tooth slices is a result not of stress but of the many different refractive indexes of the crystallite organizations within enamel rods, collagen, and water. The rainbow of colors that can be observed is a result of the light decreasing speed when passing through different arrangements of organic and inorganic structures. This effect can only occur if the structure of a specimen is anisotropic (directional dependent).[5]

Fig 1 The freshly extracted teeth are stored in moist conditions, such as in 0.9% thymol solution.

Fig 2 One side of the tooth is trimmed flat using a model trimmer.

Fig 3 Slice thickness can be controlled by adjusting the micrometer of the support arm of the milling machine.

TOOTH PREPARATION

To produce high quality images, the teeth must be freshly extracted and stored in moist conditions, such as in 0.9 % thymol solution, which completely preserves the color, or simply alcohol (Fig 1). Teeth that have been heat sterilized are not suitable. Once delivered to the dental laboratory, the teeth are cleaned with pumice, obeying the usual health and safety precautions when dealing with biologic hazardous materials. The cleaned teeth are then stored in immersion oil for at least 4 weeks.[6] Immersion oil is used in microscopy because it has a very high refractive index. It seals the extracted teeth during storage, thus preventing dehydration, and is also believed to increase the refractiveness of the tooth slices.

TOOTH SECTIONING

To produce adequate birefringence, the tooth slices must be very thin (100 to 200 µm). In fact, the thinner the slab the better. Slicing is carried out with precision low-speed saws (Isomet, Buehler, Lake Bluff, Illinois, or PM 5, Logitech, Glasgow, Scotland). The tooth is mounted on a specimen holder and sectioned with a diamond disk (10 to 900 rpm). There is no need for the tooth to be embedded in epoxy resin to obtain slices of 70 to 100 µm. However, to produce thinner sections of 10 to 15 µm, embedding is highly recommended.

Once the slices have been produced, they are lapped to the final desired thickness using a lap polisher.[7] If the dental laboratory does not carry such specialized equipment, adequate tooth slices can be achieved with a model trimmer. This requires some care, however, and usually results in a 99.9% waste of tooth substance for just one slice. A more efficient way to generate up to four 300-µm-thick slices per tooth is by using a standard milling machine for precision attachments (F3, Degussa, Hanau, Germany). For this procedure, one side of the tooth is trimmed flat using a model trimmer (Fig 2). The tooth is then adhesively bonded to a polymethyl methacrylate block for slicing. The thickness can be controlled by adjusting the micrometer of the support arm, which precisely lowers or raises the micromotor (Fig 3). Cutting can be performed using a standard diamond disk with a thickness of 0.5 mm (Fig 4). Very fine sandpaper (1000 grit) is placed on a glass plate for evenness, and the tooth section is then carefully polished to the desired final thickness using water as a coolant (Fig 5). The thickness is constantly checked with a standard dial caliper for accuracy. After sectioning is finished, it is imperative that the tooth slices are stored in immersion oil to prevent dehydration (Fig 6).

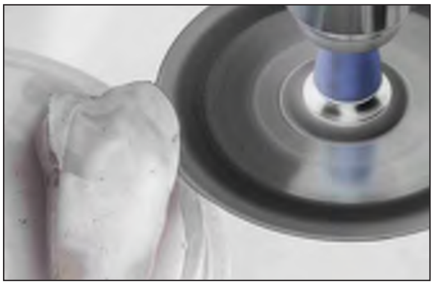


Fig 4 Sectioning can be performed using a standard diamond disk with a thickness of 0.5 mm.

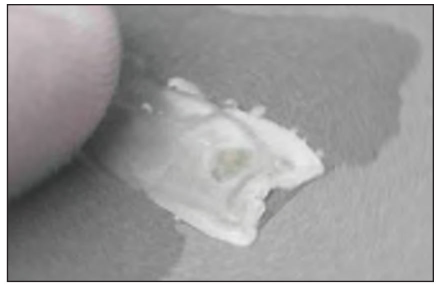
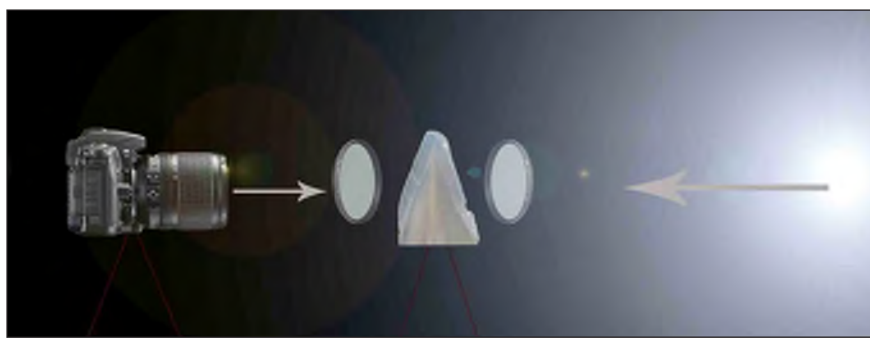


Fig 5 Very fine sandpaper (1000 grit) is placed on a glass plate for evenness, and the tooth section is carefully polished to the desired final thickness using water as a coolant.

Fig 6 The slices should be stored in immersion oil to prevent dehydration.

Fig 7 The first polarizing filter is placed in front of the light source and the second is mounted to the camera lens, with the ground section placed between them.



Figs 8 and 9 If the polarizing axes of the two filters are perpendicular to each other, all light is cut off. However, the direction of the oscillation of the light passing through the object is altered and thus not blocked by the polarizing filter on the camera lens. The result is that the object appears in its natural colors in front of a white, gray, or black background, depending on how the analyzer is rotated.

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POLARISCOPE

A polariscope or strain viewer is a device used to observe objects under polarized light. It consists of two or more polarizing filters. The first polarizing filter is fixed and is known as the "polarizer." The second, or rotating, polarizing filter is known as the "analyzer." The first polarizing filter is placed in front of the light source, whereas the second is mounted to the camera lens (Fig 7). If the polarizing axes of the two filters are perpendicular to each other, all light is cut off. However, the direction of the oscillation of the light passing through the object is altered and thus not blocked by the polarizing filter on the camera lens. The result is that the object appears in its natural colors in front of a white, gray, or black background, depending on how the analyzer is rotated (Figs 8 and 9). Either continuous light or strobe light can be used.

Fig 10 The camera of choice is a DSLR camera equipped with an exchangeable 50- to 105-mm macro prime lens.

Fig 11 The shooting mode should be set to Aperture Value.

Fig 12 The aperture value should be set to *f* 20. The exposure time will be adjusted automatically when in AV mode.

Fig 13 Another useful tool to make focusing easier at large magnification is a macro slide rail.

SHOOTING ESSENTIALS

The camera of choice is a digital single-lens reflex (DSLR) camera equipped with an interchangeable 50- to 105-mm macro prime lens (Fig 10). When looking through the viewfinder, the birefringence of the specimen is immediately evident. Capturing this effect successfully is dependent on correct light metering, which is especially important when a constant light source is used. All modern DSLR cameras are equipped with through-the-lens (TTL) metering. The metering mode should be set to Center Weighted, while the shooting mode should be set to Aperture Value (AV) (Fig 11). Upon pressing the shutter release button half way, the TTL system will offer an exposure reading at the bottom of the viewfinder. The aperture value should be set to *f* 20. The exposure time will be adjusted automatically in AV mode (Fig 12).

When a steady light source is used, it is often necessary to mount the camera on a tripod to prevent image shake due to the prolonged exposure time. This is the case when a shutter speed of less than 1/80 of a second is used with a focal length of 100 to 105 mm, which is typical for macro lenses. If the image is too dark, the shutter speed should be reduced. If the image is too bright, the shutter speed should be increased. Exposure issues can also be resolved by adjusting the ISO setting of the camera. An increase of ISO will make the image brighter, but also affect image quality (graininess). For best results, the camera ISO is usually set to low (100 or less). Using a strobe flash is more convenient because the light intensity can be easily adjusted to any shutter speed or aperture combination, making the use of a tripod or ISO adjustment obsolete. Another useful tool to make focusing easier at large magnification is a macro slide rail (Fig 13).

Fig 14 Photoelastic image shot in RAW format, displaying medium values, before postproduction in Adobe Lightroom.

Fig 15 The same image after adjustment of hue/saturation, vibrancy, sharpness, and curves.

POSTPRODUCTION

There is a limit to how many tones or values a digital sensor can record. This limit is described as the sensor's dynamic range. The dynamic range is measured in terms of stops or exposure values (EVs). Typically, the human eye has an estimated dynamic range of 10 to 14 stops, while the DSLR sensor has a dynamic range of 5 to 7 stops.[9] This discrepancy explains why the color range and intensity of a polarized tooth section appear much stronger when viewed with the eye through the view finder than when captured by the camera. To convey an adequate impression of the photoelasticity as seen by the eye, or even to enhance that effect, digital postproduction is commonly used. Images should be shot in RAW format, in which the collected data are preserved without compression, unlike in the JEPG format. The most commonly used software for postproduction include Adobe Photoshop and Lightroom (Adobe, San Jose, CA, USA) and Color Efex Pro (NIK Software, San Diego, CA, USA). These programs offer infinite artistic possibilities. The most common adjustments include an increase of hue/saturation and vibrancy and adjustment of sharpness and curves (Figs 14 and 15).

TIPS AND TRICKS

The essentials of polarized birefringence photography as explained above are fairly simple. Creating truly interesting and unique images, however, requires some creativity and experimentation. Once you have mastered the basics, here are some ideas to take your creative ambitions to the next level.

Alternative Tooth Preparation Techniques

Along with the commonly used longitudinal sections, teeth can also be sliced vertically or simply carved out (Fig 16). Vertical slicing is easily achieved with a diamond disk and hand piece (Fig 17). Carved tooth sections can result in impressive images, but they are more difficult to make. When enamel is ground thinly it becomes extraordinarily brittle, which can quickly result in chip-offs and fractures. Hence, this process is best done with a lot of care and patience, using a microscope (Figs 18 and 19). In theory, erosion by etching can work as well; however, this process lacks control.

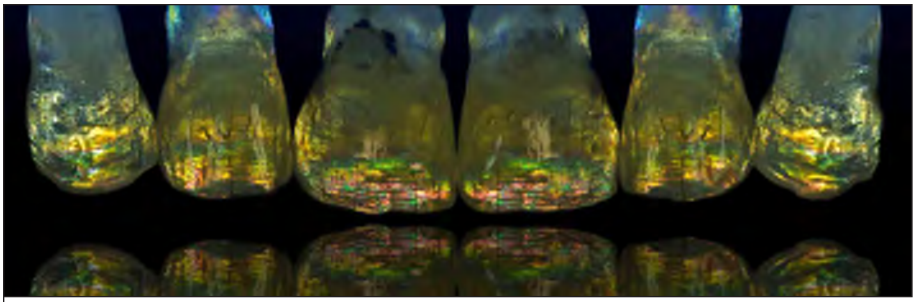

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Fig 16 Along with longitudinal sections, teeth can also be sliced vertically or simply carved out.

Fig 17 Vertical slicing is easily achieved with a diamond disk and hand piece.

Figs 18 and 19 Carved tooth sections can result in impressive shots, but are more difficult to make.

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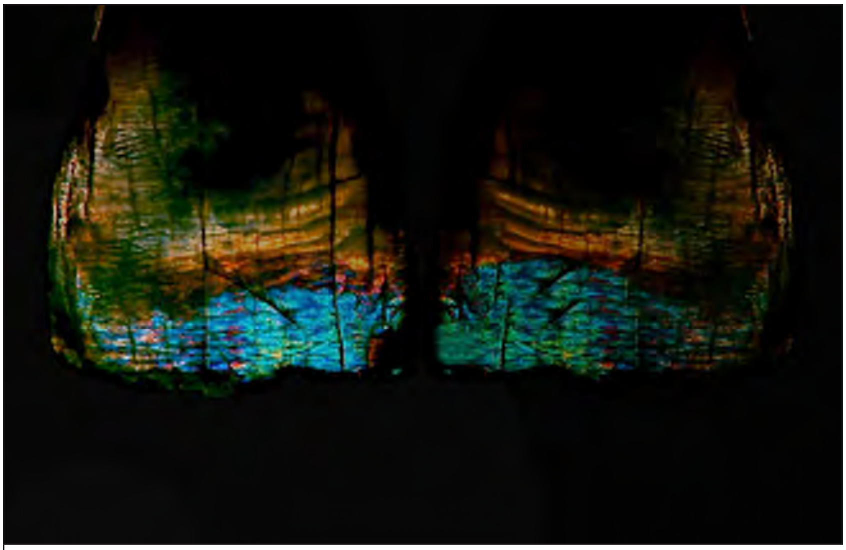

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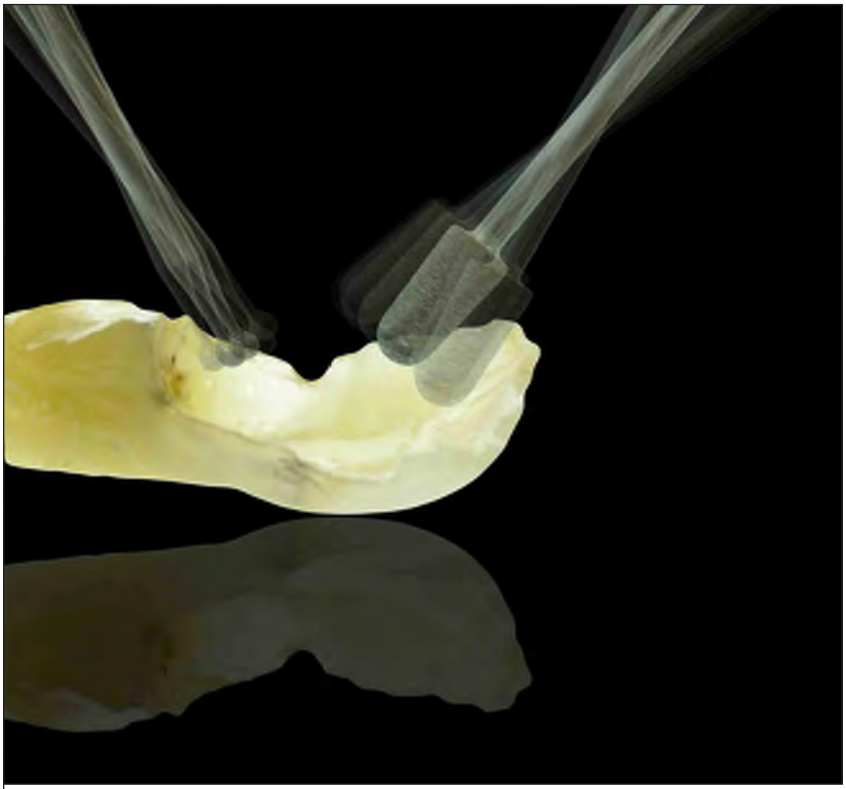

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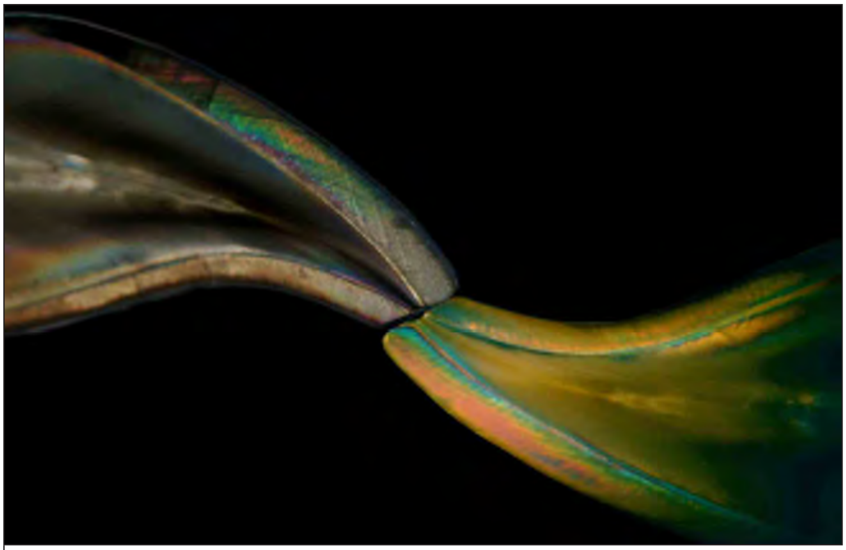

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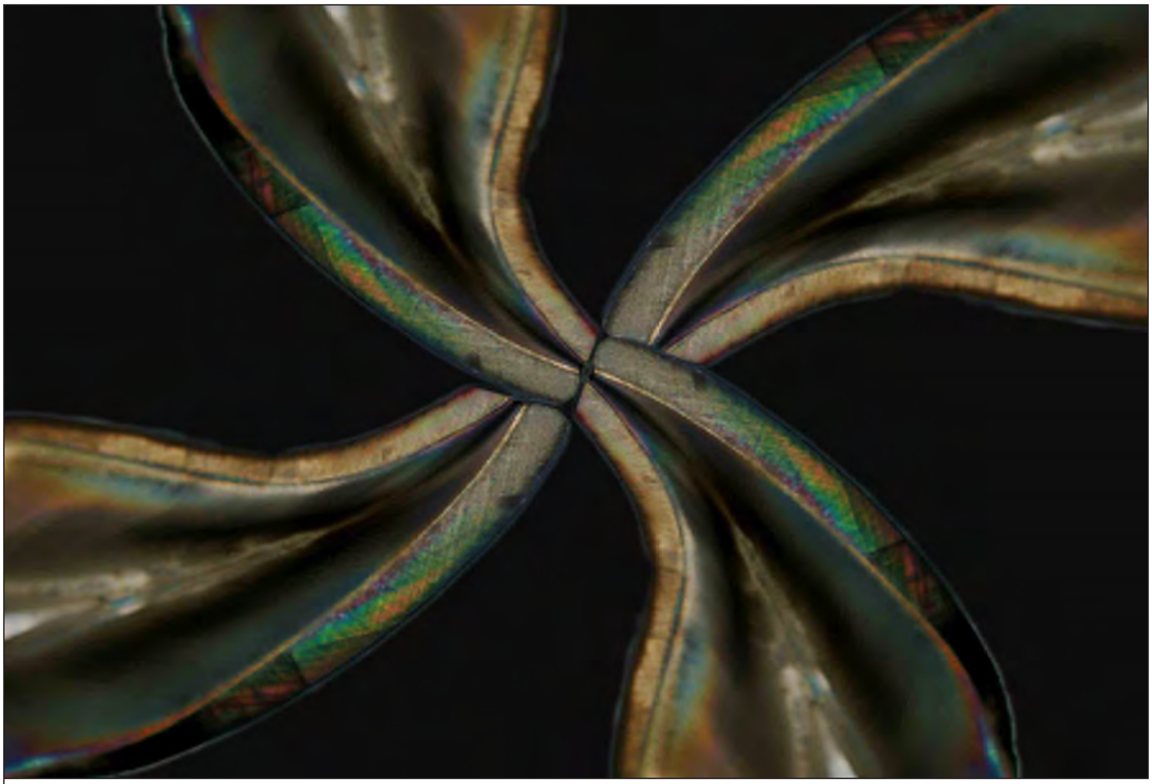

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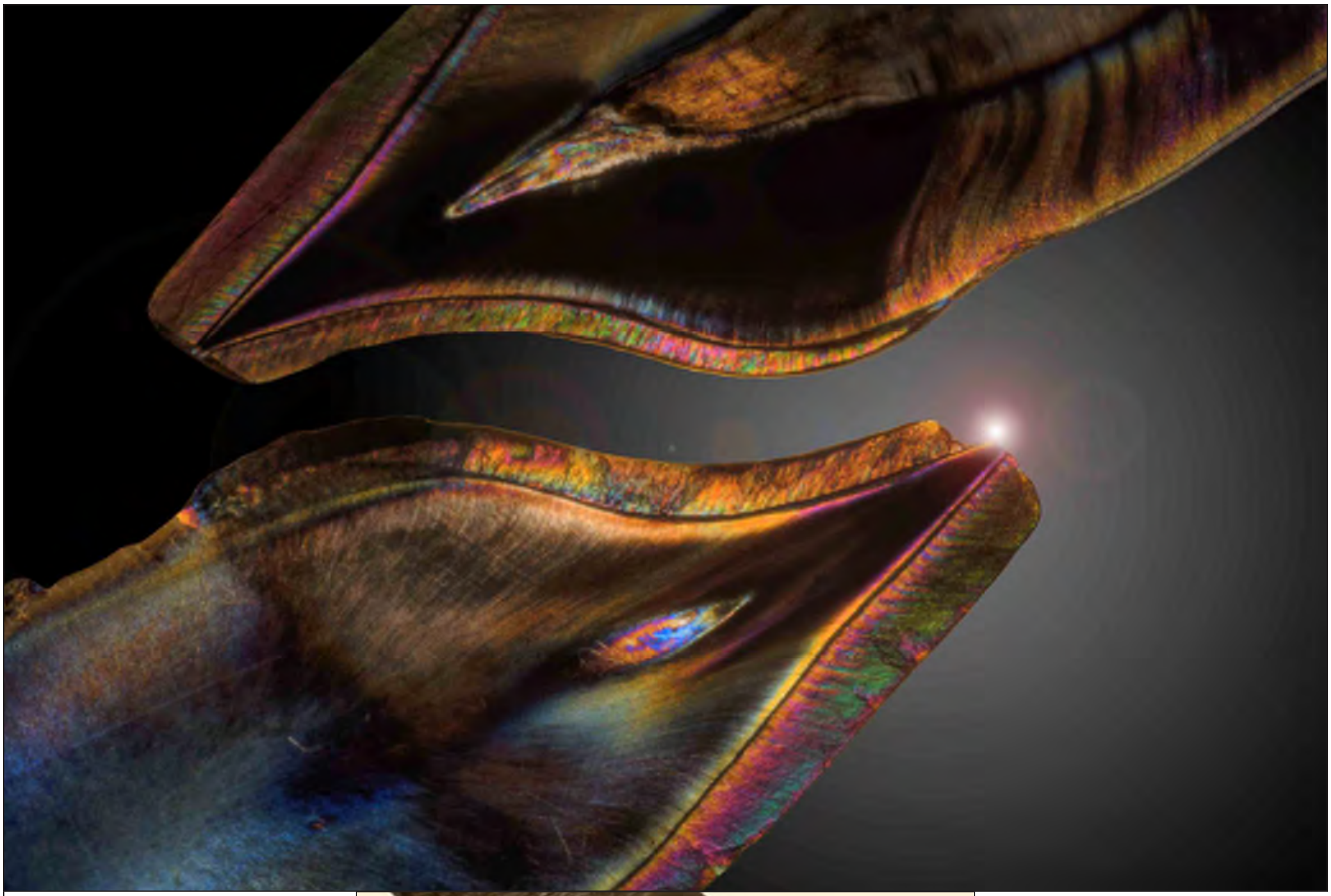
Figs 20 and 21 Image composition is largely an intuitive process. However, figure-ground theory states that the empty space resulting from placing figures in a given arrangement should be considered as carefully as the figures themselves.

Image Composition

Once useful samples have been produced, they must be arranged for shooting. This is largely an intuitive process. However, certain guidelines derived from other artistic fields can be useful. For example, figure-ground theory states that the empty space resulting from placing figures in a given arrangement should be considered as carefully as the figures themselves (Figs 20 and 21).[10] This concept ties in with the Law of Prägnanz, which describes the mind's tendency to interpret ambiguous images as simple and complete, versus complex and incomplete.[11] The vertical slices in Fig 16, for example, were arranged to take on the ap-



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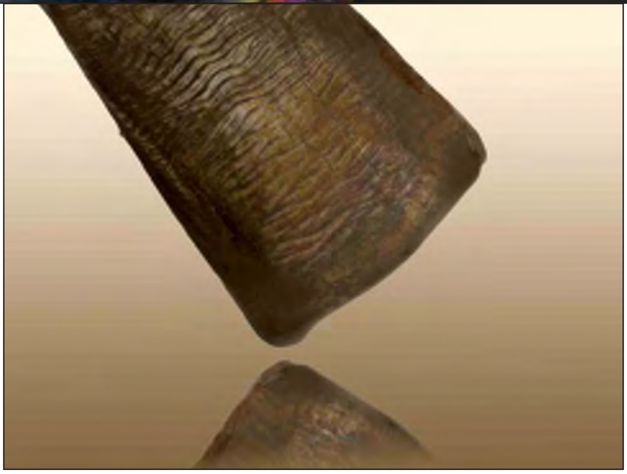
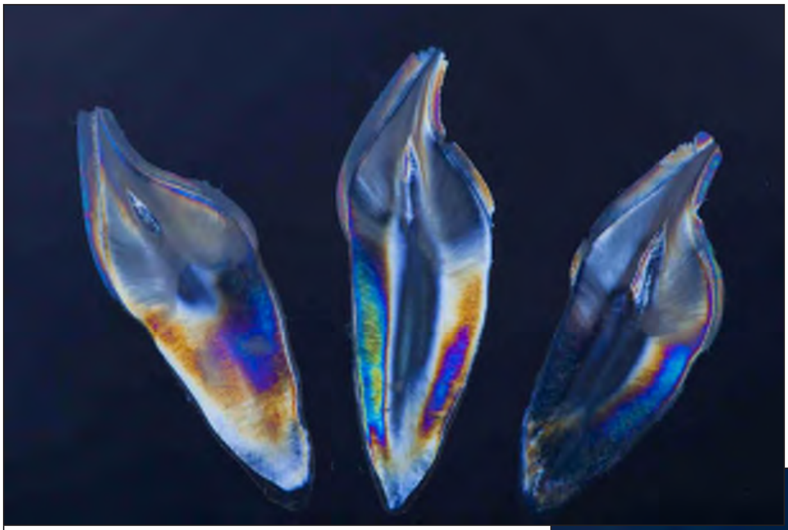


Fig 22 and 23 Objects can be separated from the original background using the quick selection tool in Photoshop. This allows for infinite arrangement possibilities.

pearance of tree trunks (Fig 16) **[Au: Fig 15 meant?]**. Kandinsky[12] advised that once a number of good images have been gathered, an object can be separated from the original background using the quick selection tool in Photoshop **[Au: Kandinsky died in the 1940s. Please revise sentence.]**. This allows for infinite arrangement possibilities. The most commonly applied methods include use of graduated backgrounds, lens flare, reflections, and opacity (Figs 22 and 23).



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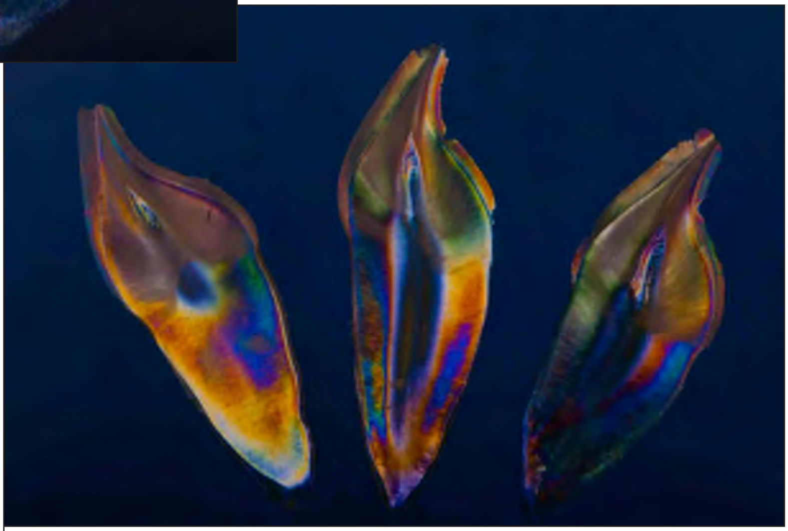

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Figs 24 and 25 Birefringence of the tooth section can be shifted by adding a second circular polarizing filter to both ends of the polariscope. This results in a color shift by one order (eg, from blue primary to red primary).

Altering the birefringence

A circular polarizing filter consists of the linear polarizer and a quarter wave plate. The latter is cemented to the back of the linear polarizer with a one-fourth orientation so that the light emerging from the quarter wave plate is circularly polarized. Birefringence of the tooth section can be altered by adding more circular polarizing filters at both ends of the polariscope. This results in two side effects: a color shift by one order (eg, from blue primary to red primary) and a much darker image. However, this added darkness can be easily compensated for through appropriate aperture and shutter speed settings or an increase of ISO (Figs 24 and 25).

High dynamic range

As mentioned previously, a standard, small-format DSLR sensor does not yield enough dynamic range to truly capture an image as it is perceived by the human eye. However, there are two ways of overcoming this limitation. The first is by shifting from a standard DSLR to a medium-format camera (eg, Phase One, Melville, New York, USA), which is equipped with a much larger charge-coupled device image sensor (53.9 × 40.4 mm) that can yield a dynamic range close to that of the human eye as well as a high resolution (60.5 MP). This results in stunning image clarity and noticeably increased contrast range. Unfortunately, such camera systems are extremely expensive. A much more affordable way to achieve similar results is by using high dynamic range (HDR) technology, which offers a wide range of brightness values. HDR photography is the process of taking several pictures of a subject at various exposure levels, then merging the images into one file to maximize the dynamic range of the captured object. Each image that contributes to the final HDR

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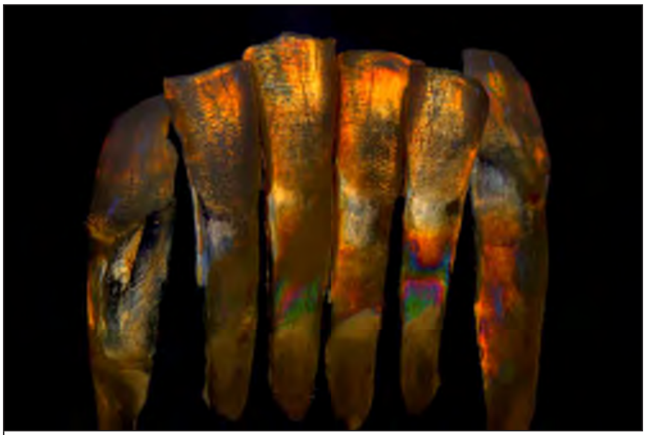

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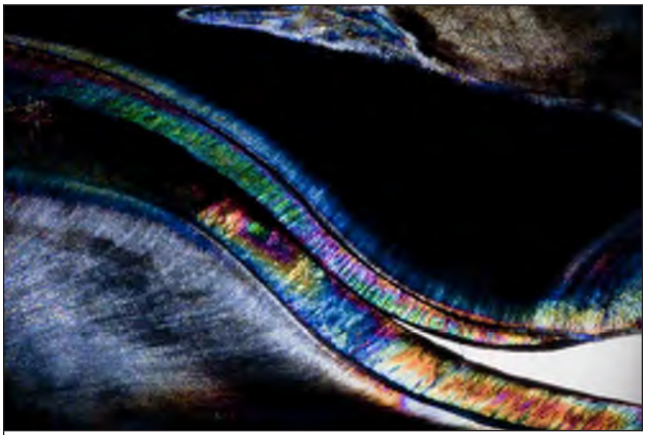

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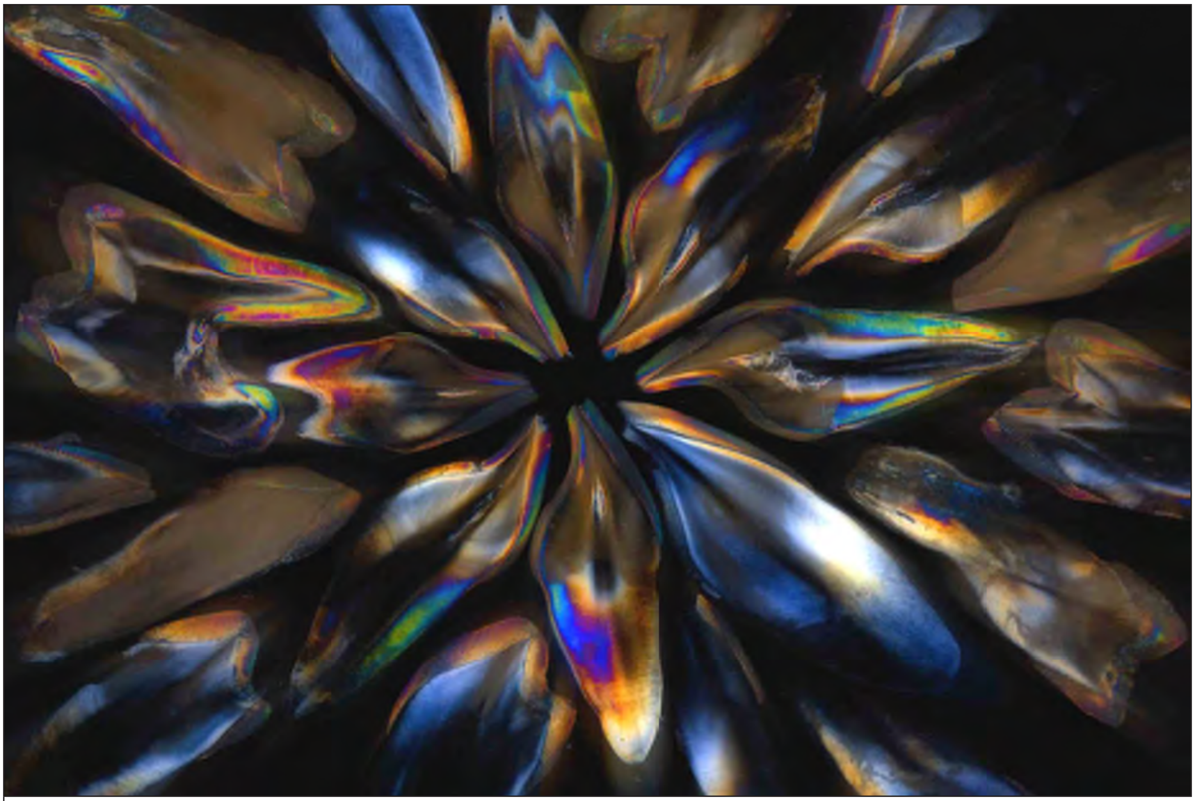
Figs 26 and 27 HDR photography is the process of taking several pictures of an object at various exposure levels, then merging the images into one file to maximize the dynamic range of the captured subject. The merging process creates a 32-bit file that is capable of holding the full dynamic range of the object.

Fig 28 Various software programs can be used for the merging and tone-mapping process. Experimenting with this technology can produce interesting results.

photograph provides important information about the subject; underexposed images capture highlight detail, and the overexposed images capture shadow detail (Fig 26). The merging process creates a 32-bit file that is capable of holding the full dynamic range of the subject (Fig 27).[13] Various software programs can be used for the merging and tone-mapping process (eg, Photomatix Pro, HDR Soft, Sarl, Montpellier, France). Experimenting with this technology can produce interesting results (Fig 28).



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Figs 29 and 30 An LCD screen can practically become a very large polarizer, making the use of two circular polarizing filters obsolete. The size of most LCD screens also allows for larger and more elaborate compositions.

LCD polarization

A liquid crystal display (LCD) screen provides a ready-made source of polarized light. The screen itself can be used as the background polarizing material. In LCD screens, the polarizing filter is the last object that the light from the back of the display must travel through.[14] The LCD screen therefore behaves as a very good source of polarized light. The first step in making the LCD screen a useful and uniform source of polarized light is to give the screen a uniform brightness or tone across its entire surface, preferably white. There are various ways to achieve this. Creating an image file that consists of nothing but white is one way, as is choosing a screensaver that consists of a light tone or white background. The LCD screen practically becomes a very large polarizing filter, allowing for larger and more elaborate compositions (Figs 29 and 30).

CONCLUSIONS

The birefringence images described in this article may be used to demonstrate the sheer difference between human teeth and dental ceramics. However, without rigorous scientific standardization and the use of a genuine polarized microscope, birefringence images of extracted/sliced teeth made in-house have limited scientific value. Nevertheless, from a purely artistic point of view, taking and collecting such images is a great source of inspiration. Using the methods described in this article, the enthusiast can flourish while exploring the beauty of the optical properties of human teeth.

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