Do you know your ceramics? Part 1: classification

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Key points

- Highlights the various ceramic classification systems.
- Explains the various ceramic processing techniques.
- Compares the differences between the different processing techniques.

Abstract

This is the first part of a six-part series exploring the main ceramic materials used for the fabrication of all-ceramic, indirect restorations to aid clinicians in their selection. We have detailed the history of how dental ceramics were introduced and how they have been revolutionised with the help of improvements within technology and understanding of the material. Dental ceramics can be classified in a few ways. One way is according to their ratio of glass to crystalline content and the other is how it is processed. Having a good in-depth understanding of this will allow clinicians to make the best decision for their patients who require ceramic restorations. This article aims to explore all the above to aid clinicians in making that decision.

Introduction

The four main groups of materials used in dentistry to reconstruct or replace teeth include ceramics, composites, metals and polymers. Ceramics have been defined as an inorganic, non-metallic material, comprising of compounds formed between metallic and non-metallic elements by sintering to high temperatures. Ceramic microstructure may be glassy, crystalline or a mixture of both. Porcelain materials are a subgroup of ceramics that have common constituents which include quarts, feldspar and kaolin.[1,2]

Porcelain was first introduced into Europe in the thirteenth century. An apothecary, Alexis Duchateau, with the assistance of a Parisian dentist, Nicholas Dubois de Chèmant, succeeded in the creation of a complete set of porcelain dentures for Alexis in 1774.[1,3,4] Previously, dentures had been made from human or animal teeth and hence were porous, leading to their degradation in the wearer's mouth. The use of porcelain meant a long-term outcome could be achieved, as well as improved personal hygiene.[4]

In 1889, Charles Land successfully patented the first version of the modern dental crown – the all-porcelain jacket (PJC) crown. The procedure involved reconstructing a broken tooth with a porcelain covering to make it appear new again, but despite its widespread use until the 1950s it was found that the strength was flawed due to internal microcracking.[3] This shortcoming was ingeniously reduced during the cooling phase of fabrication by Abraham Weinsten, who designed the porcelain-fused-to-metal (PFM) crown.[3] While PFM crowns undoubtedly decreased porcelain failures, aesthetics were severely compromised due to the addition of a metal block-out opaque layer.

John McLean and T.H. Hughes pioneered the comeback of an all-ceramic restoration around 1965, where industrial aluminous porcelain was added to feldspathic porcelain. This created a newer PJC with strength twofold of its traditional counterpart; yet, it could only be used anteriorly in the mouth due to its weakness.[3]

Moving forward, modern day dental ceramics come in a variety of different materials and processing methods. The different nuances of dental ceramics can easily overwhelm the young practitioner. Now more than ever, as demand for aesthetic dentistry has increased exponentially, it is crucial for dental practitioners to know the material's ins and outs for successful selection. This article is the first of a six-part series exploring the main dental ceramic types available on the market, including: feldspathic porcelains; leucites; lithium disilicates; alumina; and zirconia. This first article will focus on gaining an overall picture of ceramics based on the classification system and the different processing methods.

Classification system

Classification systems are useful in helping to understand ceramics, particularly aiding the comparison of different materials. Therefore, clinicians can make an informed decision on the most clinically-appropriate material for the patient and the cementation protocol required to ensure maximal success. Ideal classification systems should have clear groupings, where new materials that are continuously being developed can easily be added.

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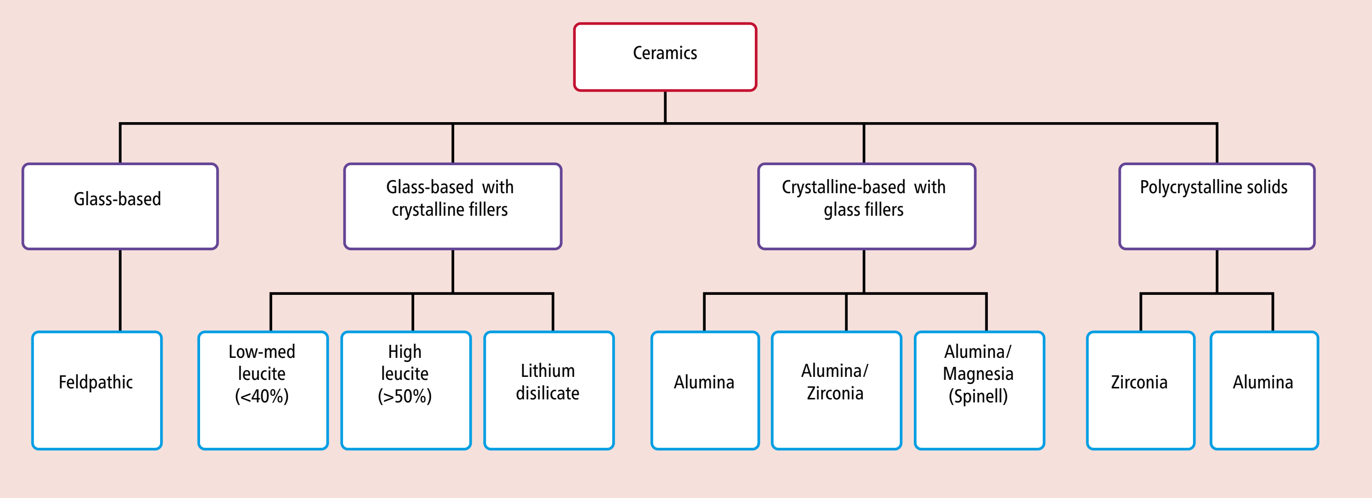
Fig. 1 Flowchart showing the microstructural classification of ceramics



Various classification systems have been formulated to group ceramics based on the following:

- Indications
- Composition
- Processing method
- Firing temperature
- Microstructure
- Translucency
- Fracture resistance
- Flexural strength
- Abrasiveness.[5]

The classification based on microstructure is commonly used (see Figure 1). Ceramics are categorised on the basis of the glass to crystalline content ratio:

- Category 1: glass-based/silica-based
- Category 2: glass-based with crystalline fillers
- Category 3: crystalline-based with glass fillers
- Category 4: polycrystalline solids.

The microstructure component ratio has a huge influence on the material properties, affecting strength and optical properties. In general, a ceramic with a higher glassy matrix content has higher translucency but will have lower strength. However, other factors also influence ceramic translucency, such as the porosity of the material, the refractive index, particle size and particle density.[6,7]

A similar, more straight-forward classification system is based on chemical composition:

- Category 1: glass ceramics
- Category 1a
  - Porcelain-based
  - Feldspathic porcelain
  - Leucite-reinforced porcelain
- Category 1b
  - Not porcelain-based
  - Fluoromica glass
  - Lithium ceramics.

Glass is an amorphous solid where the molecules within are not organised; therefore, no definitive lattice pattern is present. This group of ceramics is often referred to as silica-based ceramics. Silica is a chemical compound formed of silicon and oxygen. Glass is formed by heating solid precursors until they become viscous. The cooling of a formed liquid phase creates a metastable glass, which can be heat treated to stimulate the nucleation and growth of internal crystals. The duration and temperature of the heat treatment impacts the growth rate and size of the crystals formed.[8] Quick cooling of the liquid avoids crystalline formation, enabling the molecules to remain in a disordered state that is similar to liquids, thus forming glass. Over time, glass has the ability to transform into a crystalline structure; a metastable characteristic of the material. However, for this to occur naturally it would take a very long time. This process where a glass is transformed to a partially crystalline glass is referred to as ceraming or controlled crystallisation. Fillers and/or crystals may be added to this to enhance the properties.

- Category 2: oxide ceramics
- Category 2a
  - Alumina/alumina oxide
  - Glass-infiltrated alumina
  - Densely-sintered alumina
- Category 2b
  - Zirconia/zirconia oxide
  - Glass-infiltrated zirconia
  - Densely-sintered zirconia.

Oxide ceramics are primarily crystalline based structures with a minimal glassy phase.[7,9] The crystalline phase forms 85% of the total volume.

These ceramics are formed by:

1. The creation of a porous matrix form of the primary crystalline phase
2. The second phase material, lanthanum aluminosilicate glass, is melted and is used to fill the pores of the matrix. The drawing of the molten glass into the pores occurs via a capillary action. The end product is a dense interpenetrating material.[7,10]

Polycrystalline ceramics are also included in this category. Zirconia or alumina crystals are directly sintered together to form an air-free, dense, glass-free, 100% polycrystalline structure.[7,8,10] The resulting ceramic has incredible fracture toughness; however, unlike other ceramics, it is not etchable due to the absence of a glassy matrix.[7,10,11] These ceramics have replaced metal as core substructures of indirect restorations. The strength of this material hugely affects the processing time, requiring hours to mill a fully dense block compared to half an hour for partially sintered or a block in the green state which can be sintered to full density afterwards.[11]

The polycrystalline structure also impacts the material opacity and so current developments have provided more translucent versions of ceramics within this category.[6,7]

The International Organisation for Standardisation (ISO), is an independent international body that formulates standards to establish consistency in the safety, quality and efficiency for a huge range of activities. ISO 6872 is the standard that deals with dental ceramic materials which is reviewed every

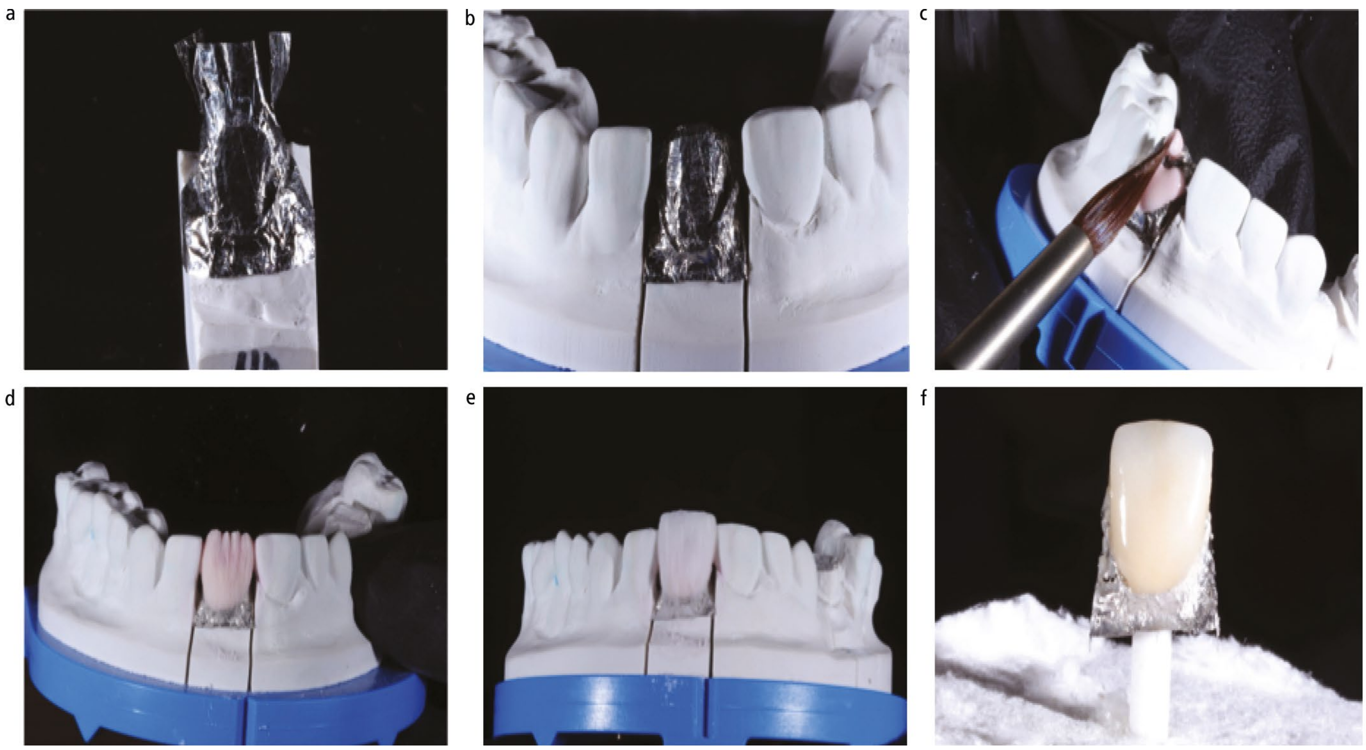


Fig. 2 Condensation. a) Placement of foil onto dye. b) Foiled dye. c, d) Layering of feldspathic porcelain. e) Final layered porcelain ready for firing. f) Final restoration

five years. Also provided is a classification based on the ceramic's flexural strength and chemical solubility to classify them according to recommended clinical indications.[12]

- Class 1
  - Class 1a: monolithic ceramic for single-unit anterior prostheses, veneers, inlays or onlays adhesively cemented
  - Class 1b: ceramic for coverage of a metal framework or a ceramic substructure
- Class 2
  - Class 2a: monolithic ceramic for single-unit anterior or posterior prostheses adhesively cemented
  - Class 2b: partially or fully covered substructure ceramic for single-unit anterior or posterior prostheses adhesively cemented
- Class 3
  - Class 3a: monolithic ceramic for single-unit anterior or posterior prostheses and for three-unit prostheses not involving molar restoration, adhesively or non-adhesively cemented
  - Class 3b: partially or fully covered substructure for single-unit anterior or posterior prostheses and for three-unit prostheses not involving molar restoration, adhesively or non-adhesively cemented
- Class 4
  - Class 4a: monolithic ceramic for three-unit prostheses involving molar restoration
  - Class 4b: partially or fully covered substructure for three-unit prostheses involving molar restoration
- Class 5
  - Monolithic ceramic for prostheses involving partially or fully covered substructure for four or more units or fully covered substructure for prostheses involving four or more units.[12]

This classification would be incredibly useful for clinicians when choosing the ceramic for indirect restorations; furthermore, it aids clinicians by also classifying whether they can or cannot be adhesively cemented. In the future the packaging of ceramic materials could be coded with their class, corresponding to their indication.

Processing techniques

Condensation

This method is typically used to produce all-ceramics and metal framework veneers as they are inherently weaker. The ceramic used may be solely glass-based or may contain a crystal component – feldspathic porcelain is commonly used. Fundamentally, the chosen ceramic powder and liquid are hand-mixed creating a slurry. The liquid can either be deionised water or a manufacturer-supplied special modelling liquid. The condensation method is then used by building up the restoration free-hand (see Figure 2) and vibrating the ceramic slurry to allow excess liquid to rise to the surface which can then be blotted away, preventing any voids that further weaken the restoration.[13] To remove the residual moisture and continue condensing, the build-up is then fired in a vacuum at a selected temperature. This is known as sintering and it is, at this stage, the fusion of particles occurring at their point of contact, resulting in a denser material with enhanced aesthetics. Commonly, restorations processed this way are overcontoured from the desired dimension by 25% to allow for the 40% shrinkage during the firing cycle.[13] Albeit the technique is very simple but it is heavily dependent on the artistic skill of the ceramicist, hence there is a large variation in predictability of results using this method. The variables that contribute to the unpredictability of the final outcome of the ceramic can be attributed to the environmental conditions, technician skill and experience and the firing cycle.

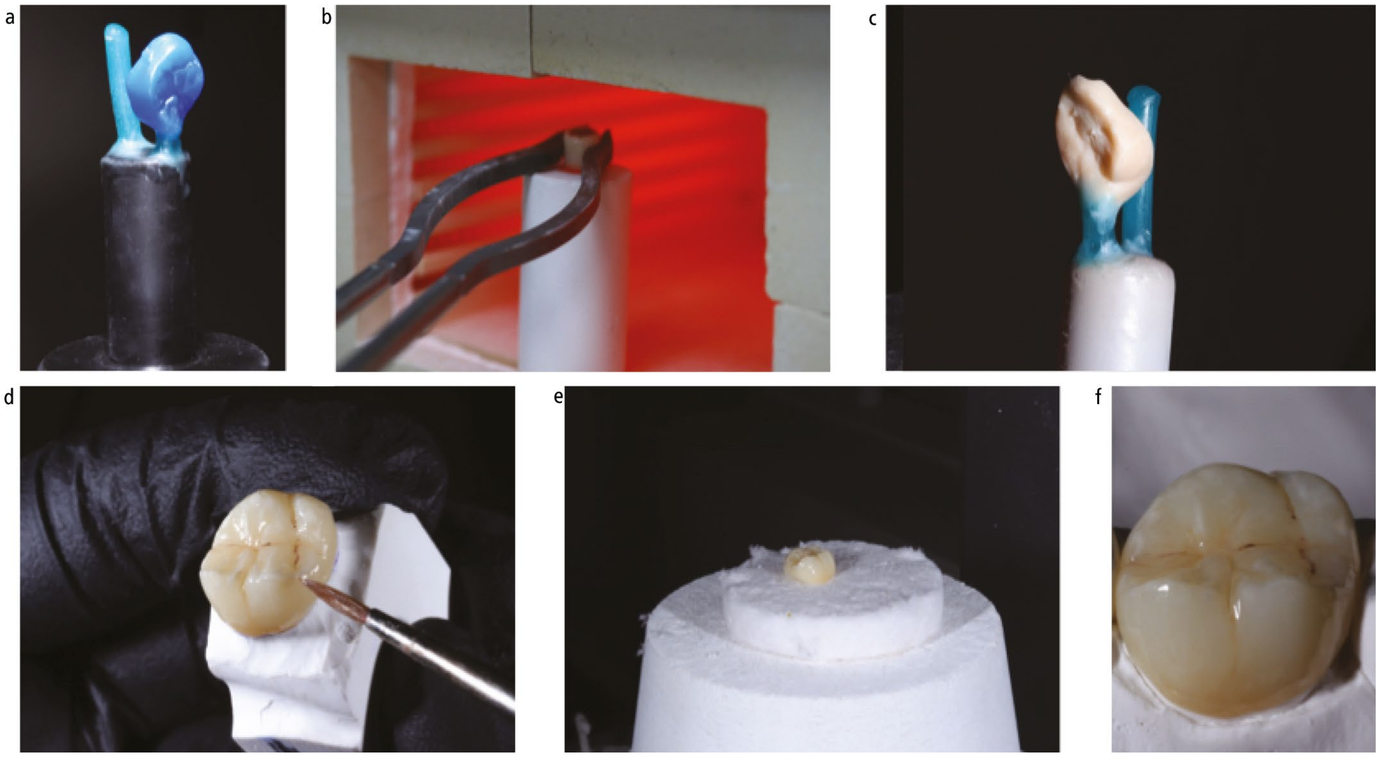


Fig. 3 a) Hot isostatic pressing: wax-up. b) Ingot placement into investment. c) Lithium disilicate pressed restorations. d) Staining and characterisation. e) Sintering. f) Final restoration

Hot isostatic pressing

With the latest press technology, the fabrication of all-ceramic restorations is relatively straightforward with better predictability; allowing any laboratory to produce a consistent and high-quality all-ceramic product.

Pressable ceramic systems may be used for inlays, onlays, veneers and crowns. Generally, heat-pressing involves the simultaneous application of high heat to a prefabricated ingot as to allow it to flow under external pressure into a mould to shape the ceramic restoration.[14] It fundamentally uses a similar approach to injection moulding and lost wax technique. In more detail, the first step is to construct a precisely-designed wax model of the restoration (see Figure 3a), which is closely followed by the placement of the wax model in a phosphate-bonded refractory dye.[11,14] After burning off the wax model, an empty mould is formed which is then used to have the glass-ceramic or ceramic ingot pressed into it. The softening point of the ceramic material used is chosen as the heat-pressing temperature with a pressure of 0.3–0.4 MPa applied to the plasticised ingot block under vacuum to press it into the created mold.[14]

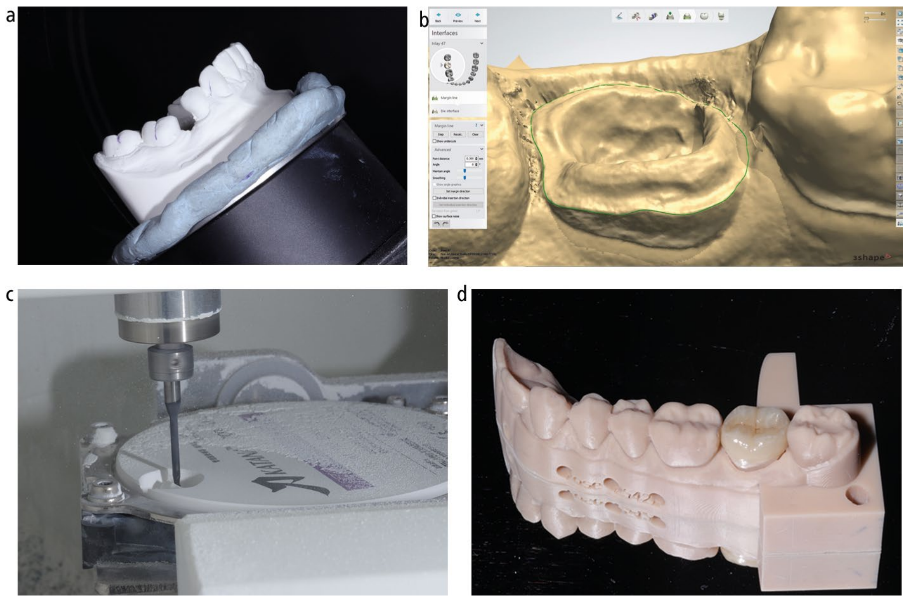


Fig. 4 CADCAM. a) Scanning of model. b) Design of restoration. c) Dry milling of zirconium. d) Final restoration

Computer-aided milling

The milling of ceramics involves the automated subtractive cutting of ceramic blocks/discs of the material of choice to fabricate a designed indirect restoration.[11] Milling is part of the computer aided design/computer aided manufacture (CAD/CAM) system of indirect restoration fabrication involving data acquisition, design and fabrication. It is important to remember that CAD can also be used in the production of pressed ceramics. CAD/CAM can also allow the completion of a single visit, indirect restoration at the chairside.[8]

On completion of the CAD by either the lab technician or clinician in-house, the design is sent to the milling machine which begins the restoration fabrication with the ceramic block (see Figure 4). The CAM software of the milling machine requires configuration with the specifications of the mill to formulate the most appropriate milling sequence to follow, influencing the milling time.[15]

Milling machines can be referred to as wet or dry, depending on the presence of a fluid which acts as a coolant or lubricant during the process of cutting by milling burs.[16] The fast cutting speed of the burs creates heat which can damage the ceramic, hence the need for water to cool down the block and cutting tool. Dry milling machines use vacuum or pressurised air to remove material from the cut surface with milling bits. They can be purchased as wet or dry, or a combination of either functionality. Often the dual functionality of these milling machines will not be utilised as it can increase the maintenance required.[16] Materials that can be used in wet milling machines include glass ceramics and hybrid composites. Whereas, zirconia, gypsum, composite resin, wax and glass fibre composite can be processed in dry milling machines.[17]

Milling machines may also be categorised based on the number of cutting axes; the more the axes, the increase in ability to cut undercuts in multiple directions, with three-axis mills not having any ability to.[6,7,18] The milling machine contains a spindle which encompasses the motor that spins the cutting bur and a collet which holds the cutting bur. The number of cutting burs used depends on the milling machine.

Diamond encrusted tools tend to be used for glass ceramics, whereas carbide tools are used for other materials such as zirconia. The size of the diamond particles can vary which provides different results. Coarse diamond particles allow for greater cutting efficiency of gross material; fine diamond burs allow for fine detail to be created with a smooth finish.[19] Carbide tools tend to have special coatings such as gold-coloured titanium nitride and black-coloured polycrystalline diamond. The coatings can help extend the life of the tool as they are of higher risk to corrosion and wear from the high pressure.

The spindle speed varies depending on the material to be milled and the amount of material that needs to be cut, as well as the type and size of the cutting tool. The milling procedure involves several step-over and step-down sequences. Step-over refers to the distance that the mill moves over before moving onto the next mill pass, which is usually horizontal. Step-down refers to the distance that the mill moves downwards before making the next mill pass, which is usually vertical. A smaller number of step-down and step-over sequences causes the milling to take a longer period of time to complete but provides an optimum surface finish.

The milling sequence can be described in three stages:

1. Roughing: the cutting tool with the largest diameter is used to quickly remove the bulk of the material. During this stage, the spindle and cutting travel speed are at their fastest and the step-over and step-down values are also at their highest, enabling as much material to be removed as possible
2. Finishing: a smaller cutting tool and the step-over and step-down values are reduced to enable a better surface finish. The margins and other areas are milling during this stage so the feed rate (velocity at which the cutting tool engages the material) is slower. Several step-over and step-down sequences may be programmed for the axial walls, occlusal anatomy and margins
3. Detailed sequence: finer occlusal detail is produced by the use of even smaller cutting tools. The spindle speed and feed rate are their lowest values.[15]

Partial sintered blocks may be used to reduce the milling time as they have lower toughness.[10,20] Therefore, after the milling procedure, the indirect restoration may require sintering to its full density to obtain the desired properties. They may also then require colouring by dipping into colouring solutions, staining layering with a veneering ceramic or glazing to obtain the desired aesthetics.[5]

Ceramic blocks and discs can be milled several times to produce as many indirect restorations as possible from them; however, inevitably there will always be an excess along with the build-up of milling dust. This wastage can be recycled, where it is treated and formed into new blocks/discs. The flexural strength, hardness and density of these recycled blocks/discs have been tested and displayed no significant difference.[21,22,23]

Comparison between processing methods

The benefits of milling machines has been a topic of discussion. With fewer steps and the automated milling sequence, the processing technique is far quicker. Furthermore, the milling machine can be left to work overnight, producing several indirect restorations without the need of staff; however, an error overnight can cause delays the next day. An automated process reduces human error as there is increased uniformity and reliability and as a result fewer remakes are required.[17] All of these factors improve the efficiency of the manufacture of indirect restorations so more restorations can be fabricated during a set period, indirectly increasing revenue. The cost of milling machines is very high and would require a huge investment for dental practices.[11]

Unlike ingots, there are ceramic blocks marketed that have multiple translucencies throughout, allowing much more aesthetically pleasing results for monolithic restorations. The fit of restorations fabricated by pressed or milled processing methods are no different if the prepared margins are ideal – smooth with no imperfections and the impression captured is also ideal. However, in preparations where the margin or data acquisition is not ideal, pressed ceramics will have a superior marginal fit. The cutting tools of milled machines are not small enough to accommodate small discrepancies of the preparation.

Conclusion

Patients now have more demands and expect dentists to deliver good aesthetic results while maintaining a high-quality level of care. When deciding on a ceramic material to use, it essentially comes down to the operator's preference and the material that works best in their hands, as each dentist has their own unique set of skills. However, it is still important to appreciate the theory and science behind the dental ceramics being used as they influence the final result with regards to optical and physical properties. Furthermore, it is important that as the world is becoming more automated, dentistry is no different.

Ethics declaration
The authors declare no conflicts of interest.

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Author contributions
Mojgan Talibi: co-author, conceptualisation, drafting and editing of the manuscript to create the final version, photographing images and producing figures. Kiran Kaur: co-author, conceptualisation, drafting and editing of the manuscript to create the final version and referencing. Hiten Parmar and Hussein Patanwala: supervisors and reviewing the manuscript. Mojgan Talibi and Kiran Kaur contributed equally towards this manuscript.

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