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Smart Dental Materials: Unravelling the Exciting Future of Dentistry

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Abstract
Dental materials have changed significantly over the years, with new materials being developed and introduced at a rapid pace. Smart materials are used in dentistry because of their excellent biocompatibility and ability to respond to physiological changes and local environmental stimuli to protect the teeth and promote oral health. Smart dental materials change one or more of their characteristics in response to inputs. They actively contribute to the functionality of the structure or apparatus. Smart materials are an answer to the requirement of environment-friendly and responsive materials. Smart materials are a new generation of materials which hold a good promise for the future in the field of bio-smart dentistry. They offer significant possibilities, but considerable research is required in this field of material science. It is the need of the hour that all dentists should be aware of these innovative materials to enable their use and utilize their optimal properties in day-to-day practice to provide quality and effective holistic treatment. The objective of this article is to shed light and improve understanding on the various bioactive and smart materials being used in dentistry today and to provide a perspective on the exciting future of these smart dental biomaterials.

Keywords: Smart Dental Materials, Bioactive, Intelligent, Biocompatibility, Technological Breakthrough, Esthetics

Introduction

In this age of smart devices and smart appliances, there is a demand from the consumers for every item that they use to be intelligent or smart. There has been a gradual evolution of dental materials over the years, with new products being introduced and existing materials being improved. This is primarily due to the increased demand of esthetics from restorative materials, hastened by the rapid improvements in dental adhesive materials. The continuous search for an ideal material in dentistry has led to the development and introduction of a newer generation of materials which are collectively called **smart materials**. These materials are labelled smart as they are amenable to modification by stimulus such as stress, temperature, pH, moisture, electric or magnetic field or chemical compounds, in a controlled manner. These materials are thus capable of changing their shape, color, or size in a predictable fashion [1].

The use of the terms "smart" and "intelligent" to describe materials and systems came from the USA and started in the 1980s inspite of some of these so-called smart materials having been around for decades. Smart materials include a variety of materials utilised in the dental clinic from filling materials to antimicrobial peptides, pit and fissure sealants to impression materials, and sutures. The development of these materials has been dictated both by patient requirements of esthetics and the dental surgeons' requirement of ease and convenience of use, cost of the material and need for more body compatible materials [2]. The following are the predominant contributory factors:

- **Improved esthetics:** Dental composite has replaced dental amalgam, and porcelain-fused-to-metal and all-metal restorations have been replaced with reinforced dental ceramics.
- **More fracture-resistant materials:** Modern dental ceramics can be matched to the color of a patient's teeth and are used for crowns, bridges, and veneers.
- **Regenerative materials:** Bioactive glass and composite materials release ions that stimulate the regeneration of tooth enamel and dentin.
- **Mercury-free alloys**, **Quartz-free ceramics and Gold-reduced or gold-free alloys** have been introduced.

- **Fewer colors:** Dental composite products are moving away from adding colors to create shades and are instead built with shade matching built-in.
- **More body-compatible products:** Dental composite products are moving towards being more compatible with the body.
- **Dynamic products:** Some dental composite products are being developed to be "dynamic" for the lifetime of the material.

Recent studies have indicated that while dentists and newly graduating dental students have an inclination to use smart dental materials, lack of inclusion of these materials in the dental curriculum is an impediment to their effective utilization [3]. This article aims to provide a summary of the characteristics of smart dental materials and the variety of options available for use in the dental operatory. It is intended that by understanding the nature and scope of the materials and devices explored in this article, readers will be able to gain a better comprehension of the implications of use of these materials for the betterment of dental patient community and realize their importance in the success of dental procedures and treatments.

Oral Cavity and Biomaterials

The materials intended for dental uses face one of the most difficult known biological environments, which is the oral cavity. Before proceeding to smart materials, it is vital to understand what constitute dental biomaterials. A modern, widely accepted definition of biomaterials was coined during the "Consensus Conference" of Chester, UK in 1991: "Any substance or combination of substances, other than drugs, synthetic or natural in origin, which can be used for any period of time, which augments or replaces partially or totally any tissue, organ or function of the body, in order to maintain or improve the quality of life of the individual" [4]. It is important to remember that while all definitions point to the biocompatibility of materials, it is only the outermost layers of the surface that interact with the environment.

Smart Materials in Dentistry

Dental materials science has changed and evolved over the years. Materials used in dentistry can be classified broadly as bioinert (passive), bioactive, and bio responsive or smart materials based on their interactions with the environment. While smart and Nano materials can both perform like living systems, nano materials are specifically used in dentistry to improve the physical properties of teeth and to prevent dental caries, without any capacity for reaction to physical or chemical stimulus. Earlier dental materials were passive and inert, meaning they rarely interacted with human fluids and tissues [5]. In the case of smart biomaterials, they have the capability to react in the presence of saliva and other environmental factors and go through intentional modification. The knowledge about liberation of fluoride from the various dental cements, restorative materials, etc. may have been the first stimulus for dental researchers to investigate whether an active instead of a passive material could be appealing in dentistry [6].

Smart materials are defined as "the designed materials that have one or more properties that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, and electric or magnetic fields" [7]. When a dental material can detect environmental stimuli and respond to it in a practical, controlled, and typically reversible manner, it is said to exhibit smart behavior. An extremely effective material can use the response to the stimuli from the outside environment to start or initiate an active response [8]. The basic principle of smart materials is that they embed the sensor and actuator technology. This involves a sensor- that identifies an input signal, an actuator- that returns a responsive and adaptive function, and the control circuit, commonly called the 'brain' to analyze the condition and control the necessary reaction of the structures into a single unit.

Dental smart materials are broadly classified as either passive or active materials [9]:

Passive materials: These dental materials respond to external changes without external control and have self-repairing characteristics. These materials also release ions in the oral cavity continuously with or without the requirement for prevention of dental decay. Examples include glass ionomer cement, resin-modified glass ionomer cement, and compomers.

Active materials: These materials present a favorable response to hazardous changes in the environment and respond to them.

Smart dental materials can be further categorized by their **properties**:

Self-healing materials: These materials can automatically repair damages without external intervention.

Shape memory alloys: These materials can recover their original shape when subjected to stimuli like magnetic or thermomechanical variations.

Smart composites: These materials can be altered in a controlled fashion by stimuli such as stress, temperature, moisture, pH, electric or magnetic field.

Characteristics of Smart Dental Materials [1, 5]

Thermochromic materials: Thermochromic materials are made of pigments or dyes that have optical properties that change with temperature. They adapt their color to temperature changes.

Piezoelectric materials: These generate an electric current in response to the application of mechanical tension.

Photochromic materials: Light changes the color of these compounds.

pH sensitive materials: The term "pH sensitive" refers to a category of materials that either expand or contract in response to variations in the pH of their immediate environment.

Thermo-responsive materials: Due to impressive and well-controlled structural changes, objects take on diverse shapes at various temperatures.

Magnetorheological: When subjected to a magnetic field, these molecules transform from a fluid to a solid.

Smart Dental Materials

Nickel-Titanium Smart Alloy/ Shape Memory Alloys (SMA)

The first use of the term 'smart material' or 'smart behaviour' in the field of dentistry is commonly associated in connection with Nickel-Titanium (NiTi) alloys, or shape memory alloys (SMAs), which are used as orthodontic wires. The shape memory effect was first observed in copper-zinc and copper-tin alloys by Greniger and Mooradian in 1938. Nickel-Titanium was developed 50 years ago by Buehler *et al*. in the Naval Ordinance Laboratory (NOL) in Silver Springs, Maryland. In endodontics, 55 wt% Ni and 45 wt% Ti are commonly used, referred to as "55NiTiNOL."

The smart behavior of NiTi alloys is because of two important features called 'superelasticity' and 'shape memory'. This 'smart' property is due to the ability of the material to undergo a phase change—in which atoms in the solid subtly shift their positions in response to a stimulus like a change in temperature or application of mechanical stress. The superelasticity of NiTi rotary instruments results in access to curved root canals during the chemico-mechanical preparation, with less lateral force exerted. It allows more balanced canal preparations with less canal transportation and a decreased incidence of canal aberrations. Nitinol commonly exists in an austenitic crystalline phase that transforms to a martensitic structure on being stressed at a constant temperature. In this martensitic phase, only a light force is required for bending. If the stress is released, the structure recovers to an austenitic phase and its original shape. This phenomenon is called stress-induced thermoelastic transformation [10]. In orthodontics, NiTi arch wires are used in place of stainless steel due to these properties which results in the application of continuous gentle forces on the teeth, which are in physiologic range over a longer period.

Smart GIC: Glass Ionomer Cement (GIC) behaves like human dentin because its gel structure quickly takes in and then releases solvent in response to temperature, pH, and pressure changes. GIC has improved marginal adaptability because of these interventions. Food and drinks can cause considerable temperature variations in the oral cavity, expanding or contracting materials. GIC is considered intelligent because it releases fluoride. This trait aids in preventive dentistry [5].

Smart Composite: Composite materials are the material of choice for dental restorations because they are tooth-colored and robust, benefiting both doctors and patients. The functionality of smart composite, a restorative product made of nano-filled, alkaline, light-activated glass, has been improved through the incorporation of nanoparticles, amorphous calcium phosphate (ACP), and several other components. When pH in the oral cavity falls below 5.5, it releases hydroxyl, calcium, and fluoride ions to remineralise the tooth surface. Class 1 and 2 lesions for primary and permanent tooth restorations are indicated [5]. ACP is used as a remineraliser and has better osteo-conductivity and biodegradability than hydroxyapatite and tricalcium phosphate.

Smart Dentin Replacement (SDR): SDR is a Class I and II dentin substitute and access repair made of bulk-fill flowable, fluoride-containing, radiopaque, visible light-cured resin composite. SDR is an easy-to-place dentin replacement material that may be injected directly into the cavity and cured in 4-mm increments with minimum polymerization shrinkage. This modified flow of the material makes it self-leveling and cavity wall adaptable, speeding restoration [11].

Smart Impression Materials: The Aquasil Super Smart Wetting Impression Material® is a silicone-based impression material that has been enhanced to exhibit increased tear strength, reduced contact angle, and low viscosity when utilized. The substance exhibits characteristics of regular, fast-set stiffness, substantial weight, monophase composition (maroon), low viscosity (teal), and extra-low viscosity (orange) [1].

Smart Sutures: Smart sutures are medical devices that can be used in dentistry to detect infection, promote healing, and monitor wounds. The ends of the suture are fastened, and they are applied in a loosely applied manner to maintain their provisional form. The suture goes through a contraction phase, when the temperature increases beyond the thermal transition temperature, resulting in the tightening of the knot and the exertion of maximal force. The thermal transition point closely approximates the temperature of the human body, hence possessing therapeutic implications for achieving optimal stress levels when placing surgical knots. The facilitation of infection detection can be achieved by employing intelligent sutures, consisting of plastic or silk threads embedded with temperature sensors and micro-heaters [12]. These sutures can also be coated with hydrogels that can release drugs or cells to treat inflammation.

SmartPaste Bio: SmartPaste Bio is a resin-based bioceramic sealer. The SmartPaste Bio undergoes a process that forms a biocompatible layer of calcium hydroxide and hydroxyapatite, which also has antibacterial properties. It sets slowly in around 4–10 hours, and is hydrophilic, encouraging the material to hydrate and expand to fill the gaps. Lateral forces are also less than dentin's tensile strength and withstands standard techniques. SmartPaste Bio's bioceramics cause the sealer to stabilise and thus prevents root canal resorption [13].

Smart Antimicrobial Peptide: These materials may also be called as probiotic antibiotics due to associated with antibiotics, such as secondary infections and the elimination of commensal organisms. The primary advantage of developing a pheromone-guided 'smart' antimicrobial peptide is to effectively put an end to the predominant strain of *Streptococcus mutans*, primarily responsible for dental cavities [14].

Thermochromic Materials in Dentistry

Thermochromic materials are used in dentistry because they possess the capability to change color in response to temperature changes. The word 'thermochromic' comes from the Greek words thermos, meaning temperature, and chromos, meaning color.

Thermochromic Toothbrushes: This is a dental brush characterized by the presence of a dispersed thermochromic material in its head and/or bristles, in such a manner that a change in color of these elements occurs in a time which the user associates to the minimum adequate time for a good brushing. This change of color occurs between 1 and 5 minutes and generally between 1 and 2 minutes, compatible with the adequate brushing time. Few brushes also have a layer of thermochromic crystal liquid inserted in the brush handle, so that there is a change in color of this material caused by the heat transmitted by the user's hand, after a certain amount of time of use, associated with longer than normal brushing time. This serves both an educational purpose as also a safeguard against prolonged, aggressive brushing.

Thermochromic Impression Material: Thermochromic material for dental impression is capable of changing color in a reversible manner depending on the temperature and includes a bicomponent silicone composition in combination with a thermochromic pigment. These dental materials change color based on the temperature of use. They are used to indicate when the impression is ready to be removed from the oral cavity. Thermochromic impression material changes from green to yellow to indicate that the working time is completed. Zhermack's Chromatic technology is an example of thermochromic impression materials. This technology is a series of alginate impression materials that change color to indicate the stage of the impression-taking process. They change color from purple during mixing, to grey during seating and tray loading, and to green during setting in the mouth. It has a mint scent and is designed to be tear-resistant, dust-free, and safe for patients and dental professionals. The chromatic variation provides a visual guide for processing the material and can produce highly accurate and detailed impressions.

Piezoelectric Materials in Dentistry

Piezoelectric smart materials include materials that can convert mechanical energy into electrical energy, or vice versa. Piezoelectric materials are biocompatible, stable, and highly bioactive. Some of the uses of these materials are:

SmartBurs: SmartBurs are paddle-shaped burs which has a unique flute design and is constructed from a medical-grade polyether-ketone-ketone (PEKK), with a specific Knoop hardness of 50 KHN. Thus, these burs can easily remove the soft carious dentin, but when they encounter the hard dentin, they blunt out preventing unnecessary removal of the affected and the healthy dentin. Thus, these burs can remove delicate carious dentin but burn out when they meet strong dentin, limiting tooth structure loss [1].

Smart Ceramic: These metal-free, biocompatible, and lifelike restorations blend in with natural teeth. It is simple and predictable to restore teeth to their previous shape. Eg: Cercon Zirconium Smart Ceramic System [15].

pH Sensitive Materials in Dentistry

Low pH, which is less than 4.5, is a characteristic signal of the localised carious environment, compared to a healthy oral pH range of 6.8 to 7.4 [16]. The introduction of pH-responsive delivery systems that give out antibacterial agents in response to low pH is now being used as a targeted therapy for dental caries. Release is initiated by high levels of acid producing bacterial agents and establishment of plaque and biofilm communities. In recent times, pH-sensitive chitosan nanoparticles have been utilized to deliver antibacterial drugs [17]. These chitosan nanoparticles help to stop drug degradation at physiological saliva pH levels and release antibacterial agents to combat dental caries immediately when plaque biofilms start producing acid. Some pH sensitive materials used in dentistry include:

Oxime bonds: These bonds are stable in a pH range of 4 to 8,and are useful for creating pH responsive biomaterials.

Chitosan: The solubility of this polymer can be changed by the pH value.

Hydrogels: These materials are pH sensitive due to phosphate groups being present. They enlarge less in low pH environments.

pH-responsive micelles: These materials have the capability to incorporate hydrophobic antibacterial agents.

Polymer micelles: These micelles have the potential for targeted delivery of drugs in cancer therapy.

Acetals: With each unit of pH decrease, these acid-sensitive linkages can be hydrolyzed.

Alginic acid: Based on the environmental pH, this material swells more at higher pH of 7.4 than at lower pH.

Carrageenan: This material's hydrogels are pH sensitive due to the presence of sulphate and –OH functional groups.

Thermo-responsive Materials in Dentistry

Thermo-responsive polymers (TRPs) are stimulus-responsive, that is they can change their properties in response to environmental triggers like temperature, pH, and ionic strength. Thermo-responsive (agarose and cellulose), pH-responsive (alginate and carrageenan), and physicochemical-responsive biopolymers (fucoidan and ulvan) derived from seaweeds can be used as smart materials in dental and other biomedical applications as it is possible to be tuned to make them economically affordable [18]. These materials are used in dentistry for a variety of purposes, including:

Debonding dental restorations: Thermally degradable moieties, such as hetero Diels–Alder (HDA) functionalities, can be used to break the bonds of failed dental restorations.

Drug delivery: These materials can be used to deliver drugs and genes in a controlled and sustained manner. For example, PNIPAAm copolymers can be used to deliver insulin and calcitonin orally.

Tissue engineering: Thermo-responsive polymers can be used in tissue engineering. TRPs can be mixed with cells at room temperature and injected into the body. When the temperature increases to body temperature, the polymer forms a gel that encapsulates the cells. This allows for the delivery of cells, nutrients, and growth factors to defects of any shape. TRPs can also be used to create systems that deliver drugs and genes in a controlled and sustained manner.

Some challenges with using thermos-responsive polymers include: Poor mechanical strength, high critical gelation concentrations (CGC), solutions that are too viscous, toxicity, and gelation temperatures that are incapable of coexisting at physiological body temperatures.

Photochromic Materials in Dentistry

Photochromism is a reversible transition of a chemical substance between two states with different absorption spectra, the transition being caused at least in one direction by electromagnetic radiation. Photochromic materials are made up of pigments or dyes that change their optical properties when exposed to light, temperature, pressure, humidity, or other external stimuli. These contain a photochromic material like a photochromic dye, a photochromic glass, a photochromic ceramic and/or a photochromic glass ceramic and which can be visually distinguished from natural tooth material after irradiating with light, but which assume their original color again after a certain period has transpired.

Photochromic dental materials: These are prepared by merging organic photochromic dyes with heat-hardening composites. In restorative dentistry, tooth-colored restoration materials are the norm due to obvious esthetic requirements. However, these materials have the disadvantage that they are difficult to be visually distinguished from the natural tooth substance, resulting in removal of excess normal tooth structure when these restorations fail. Photosensitive materials allow the introduction of dental restorations which are easy to match in terms of color to their environment by irradiation with UV light and subsequent heating. The only downside of this material is that the florescence only occurs upon simultaneous irradiation with a suitable light source, so that, together with the clinician's usual tools, a light guide must also be utilised in the oral cavity, as a result of which the dentist's work in the mouth is made challenging.

Photochromic nanoparticles: These nanoparticles can be introduced into the body to change color when they meet specific cells or molecules. This allows for precise diagnostics.

Photochromic materials in drug delivery: Photochromic materials have to capability to release drugs when exposed to light, which can lead to targeted treatment.

Photosensitive dental materials: A very encouraging approach to combat microbial infections involves the use of reactive oxygen species (ROS) as antimicrobial agents. This strategy aims to generate ROS, which can disrupt bacterial growth and replication through various mechanisms like causing DNA damage and interfering with cellular metabolism. Antimicrobial photodynamic therapy (aPDT) is an antimicrobial strategy based on ROS. This is a non-invasive treatment that uses safe photosensitizers (PSs) [19]. When oxygen is present, the activation of PSs using a visible light source leads to the generation of ROS, which subsequently deactivates microorganisms.

Magnetorheological Materials in Dentistry

Rheology is the study of how matter flows or deforms when an external force is applied. It is concerned with the relationship between deformation, time, and force. Magnetorheological materials are made up of micron-sized magnetic particles dispersed in a fluid or elastomer. Their rheological properties can be quickly modified by applying a magnetic field [20]. The type and size of the magnetic particles, the type of elastomer matrix, and the type of non-magnetic fillers all affect the properties of this material. These materials can be used in dentistry for a variety of applications, including:

Targeted drug delivery: Magnetic particles can be precisely manipulated with external magnetic fields to deliver drugs to specific areas.

Magnetic resonance imaging: Magnetic materials can be used in dental MRI.

Hyperthermia therapy: Magnetic materials can be used for hyperthermia therapy.

Diagnostic assays: Magnetic materials can be used for diagnostic assays.

Dental implants and orthodontic treatments: Pre-adjusted magnets can be used in dental implants and orthodontic treatments to improve tissue engineering and tooth movement.

Clinical Implications

Smart dental materials are used to protect teeth and promote oral health due to their superior capabilities of responding to environmental stimuli and physiological changes. They can be used in a variety of applications, including:

(a). **Preventing caries:** Smart dental materials can respond to changes in oral pH to suppress caries and promote mineralization.
(b). **Preventing fractures:** Smart materials can help prevent tooth and restoration fractures.
(c). **Improving marginal integrity:** Smart materials can help provide a good marginal integrity.
(d). **Reducing wear:** Smart materials can help reduce wear.
(e). **Preventing marginal discrepancies:** Smart materials can help prevent marginal discrepancies.
(f). **Extending longevity:** Smart materials can help extend the longevity of dental devices.

However, smart dental materials may not be suitable for all situations due to the following reasons:

(a). **Thermal expansion and contraction:** Smart dental materials can expand or contract when exposed to hot or cold food and fluids. This can cause stresses at the interface between the restoration and the tooth structure, which may result in microleakage.
(b). **Water transport:** Some smart materials can transport water, which can cause changes in dimensions and has the potential for biofilm formation.
(c). **Reduced Biocompatibility:** Smart dental materials should be carefully chosen so that they have superior biocompatibility, meaning they are harmless to soft tissues and do not contain toxic substances. Also it is essential to ensure that materials used in the mouth are neutral and inert, and do not damage the tooth's structure.

Smart dental materials have many potential uses in the future, including:

- **Improved efficacy:** Smart materials can be more effective in treating dental problems.
- **Better control:** Smart materials can reduce distortion and increase precision.
- **Improved preventive maintenance:** Smart materials can increase the system's functionality by improving preventive maintenance.
- **More conservative dentistry:** Smart materials can actively participate in the curing process.
- **Improved longevity:** Smart materials can improve the longevity of dental devices.
- **Cost-effective care:** Smart materials can improve the longevity of restorations, which can lead to cost-effective care.

Conclusion

The present times are witnessing phenomenal research, introduction and use of smart dental materials, leading to enhanced opportunities for their application in the fields of biomedicine and dentistry. These technological breakthroughs herald the beginning of the **bio-smart dentistry era**, which will achieve greater heights with channelized research and sustained funding. It is in the interest of dental clinicians to introduce and utilise intelligent and smart dental materials in dental practice together with evidence based and strategic thinking to facilitate safe and predictable procedures for patients.

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