Review Article

Smart Materials-making Pediatric Dentistry Bio-smart

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Abstract

As of now, there has been no single material in dentistry that fulfills all the requirements of an ideal material. While the search for an "ideal material" continues, a newer generation of materials has been introduced. The adjective "smart" implies that these materials are able to sense changes in their environments and then respond to these changes in predetermined manners – traits that are also found in living organisms. These materials may be altered in a controlled fashion by stimulus such as stress, temperature, moisture, pH, and electric or magnetic field. Some of these are "bio-mimetic" in nature while others are "bio-responsive." These materials would potentially allow new and groundbreaking dental therapies with a significantly enhanced clinical outcome of the treatment procedures. This paper attempts to highlight some of the currently available "smart materials" in pediatric dentistry which may over the course of years help us move toward a new era of bio-smart dentistry.

Keywords: Biomimetic, bioresponsive, bio-smart dentistry, materials, pediatric dentistry, smart

Introduction

McCabe *et al*.[1] defined "Smart materials" as materials whose properties may be altered in a controlled fashion by stimuli, such as stress, temperature, moisture, pH, and electric or magnetic fields. A key feature of smart behavior includes an ability to return to the original state after the stimulus has been removed.

These materials respond to environmental changes or external impacts, and are also known as "responsive materials." The response may exhibit itself as a change in shape, stiffness, viscosity, or damping. When embedded in host materials and activated, they can compensate for faults or cracks produced, a phenomenon called the called self-repairing effect and helps to keep the material in a "safe condition."

Takagi (1990) explained them as intelligent materials that respond to environmental changes at the most optimum conditions and reveal their own functions according to the environment.[2,3]

Many of the smart materials were developed by government agencies working on military and aerospace projects. This involved the use of nickel as a sonar source during World War I to find German U-boats by allied forces. Despite the fact that some of the so-called smart materials have been around for decades, the first use of the terms "smart" and "intelligent" materials started from the USA in 1980.

Recently, there has been a surge in the requirement of an increasing safety margin of infrastructure, biomedical, and engineering (automotive, aerospace, and marine) elements. This has led to a rapid increase in the development of smart materials and structures, at the levels of micro- and nano-scale. The use of smart material has also been expanded into some everyday items, and the number of applications for them is growing steadily.[2,3]

Smartness of materials describes self-adaptability, self-sensing, memory, and multiple functionalities. Dictionary definition of "smart" is astute or operating as if by human intelligence and this is what smart materials are. However, as a matter of fact, materials or structures can never achieve true intelligence or reasoning without the addition of artificial intelligence through computers, microprocessors, control logic, and control algorithms. Truly speaking, the materials can only be active, and the ultimate structures could ultimately be intelligent (performing sensing, control, and actuation; a primitive analog of a biological body).[2,3]

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All disciplines involved in the use of smart materials embed the sensor and actuator technology. They integrate the sensor (that detects an input signal), actuator (that performs 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.

Smart materials are generally programmed by material composition, special processing, introduction of defects, or by modifying the microstructure. The "IQ" of smart materials is measured in terms of their "responsiveness" to environmental stimuli and their "agility." The first criterion requires a large amplitude change, whereas the second assigns faster response materials with higher "IQ"[2,3]

There are a number of types of smart material available including piezoelectrics, shape-memory alloys, electrostrictive materials, magnetostrictive materials, electrorheological fluids, magnetorheological fluids, polyelectrolyte gels, pyroelectrics, photostrictive materials, photoferroelectric materials, magneto-optical materials, and superconducting materials.[2,3]

Piezoelectric materials respond by generating electric charges/voltages (referred to as the direct piezoelectric effect); conversely, these materials can also induce mechanical stresses or strains in response to applied electric charges/fields (referred to as the converse piezoelectric effect). The phenomena were first observed by the Curie brothers (Jacques and Pierre) in 1880 on quartz crystals (Piezo means "press" in Greek). The behavior of magnetostrictive materials is analogs to that of the piezoelectric ceramic materials, except that they are responsive to magnetic fields.

Thermoresponsive materials, either shape memory alloys (SMAs) or shape memory polymers, are materials that can hold different shapes at different temperatures and can revert back to their original shapes when the temperature is changed (referred to as the shape-memory effect). This property can be attributed to the different crystal structures at low and high temperature (martensitic and austenitic, respectively). The shape-memory effect was observed in Cu-Zn and Cu-Sn alloys by Greninger and Mooradian in 1938. However, the first series of SMAs, the nickel–titanium alloys were developed by Buehler, Gilfrich and Wiley at the Naval Ordnance Laboratory in 1962. This shape-memory alloy is now called Nitinol (NiTi) and has found numerous applications. Shape memory polymers are commonly used in biodegradable surgical sutures.[4]

Electrorheological and magnetorheological fluids are liquids that experience dramatic changes in viscosity on the application of electric and magnetic fields, respectively.

pH-sensitive materials are the materials that change shape or color in response to a change in. Photochromic materials change color in response to light. Common application as photochromic lenses and photochromic paints. Chromogenic systems can change color in response to electrical, optical, or thermal changes. Common application as liquid crystal displays.

Ionic polymeric gels, such as hydrogels, have a cross-linked polymer structure inflated with a solvent, such as water. They have the ability to swell or shrink (up to 1000 times in volume) due to small changes in environmental conditions, such as temperature, pH, light, electrical fields, and electrical charges. They find application in artificial corneas, medical implants, drug delivery systems, etc.

Classification of Smart Materials

The concept of smart materials has changed from a conventional "passive" elastic system are to an "active" or adaptive (lifelike) multifunctional structural and electronic system with inherent capabilities for self-sensing, diagnosis, and control capabilities.

1. Active smart materials – they sense a change in the environment and respond to them. Fairweather (1998) defined active smart materials as those materials which possess the capacity to modify their geometric or material properties under the application of electric, thermal or magnetic fields, thereby acquiring an inherent capacity to transduce energy[3]
2. Passive smart materials – they can act as sensors but not as actuators or transducers. Example includes fiber optic material.[3]

Smart Materials in Dentistry

Dentistry has been through an era which has seen widespread use of passive and inert materials. They were designed in such a way that they do not interact with body tissues and/or fluids. Materials such as amalgam are often judged on their ability to survive without reacting to the oral environment. This was followed by a period when some materials having caliber to act as "active" materials were noticed. The first active behavior noted in the field of dentistry was the release of "fluoride" from some dental materials.[1]

Based on their interactions with the environment, dental materials are currently broadly categorized as bioinert (passive), bioactive, and bioresponsive or smart materials.

The first smart dental materials to be used in dentistry were the nickel-titanium alloys, or SMAs used as orthodontic wires.[1]

Likewise, the potential thermo-responsive smart behavior of some glass-ionomer cements was first suggested by Davidson and was then demonstrated as a result of attempting to measure the coefficient of thermal expansion.[5]

Active Smart Materials in Dentistry According to their Use

1. Restorative dentistry
   - Smart glass ionomer cement (GIC)
   - Smart composites
   - Smart seal obturation system
   - Self-healing composites.

2. Prosthetic dentistry
   - Smart ceramics
   - Smart impression materials.
3. Orthodontics
   - SMAs.
4. Preventive dentistry
   - Amorphous calcium phosphate (ACP) releasing pit and fissure sealants.
5. Periodontics
   - Smart antimicrobial peptide.
6. Endodontics
   - NiTi rotary instruments.
7. Oral and maxillofacial surgery
   - Smart sutures.
8. Smart fibers for laser dentistry
   - Hollow core photonic-fibers.

Smart Materials with Significant Application in Pediatric Dentistry

Smart glass ionomer cement

The smart behavior of GIC was first suggested by Davidson.[5] When samples of restorative materials were heated to determine their values of coefficient of thermal expansion, for composite materials, expansion and contraction occurred in the expected way irrespective of dry or wet conditions. However, for glass-ionomers, in wet conditions, little or no change in dimension was observed when heating and cooling between 20°C and 50°C. In dry conditions, glass-ionomers showed a marked contraction when heated above 50°C.

The smart behavior of glass-ionomers [1,5,6] and related materials is closely linked to their water content and the way in which this can react to changes in the environment. On heating, increased fluid flow to the surface and rapid loss of water is the mechanism behind the observed contraction. This behavior is akin to that of human dentine where similar changes are seen as a result of flow of fluids in the dentinal tubules. Hence, the glass-ionomer materials can be said to be mimicking the behavior of human dentine through a type of smart behavior. Due to this smart behavior of GIC, it provides good marginal adaptation to the restorations.

The other aspect of the smart behavior of GIC is the fluoride release and recharge capacity. Normally, the fluoride release in products is seen as a high initial fluoride release followed by a gradual decrease over a period. The smart behavior of materials containing GIC salt phases is attributed to their property of getting "recharged" when the material is bathed in a high concentration of or mouthrinse fluoride as may occur in toothpaste or mouthrinse.

Commercially available as GC Fuji IX GP EXTRA (incorporates a "SmartGlass" filler).

Casein phosphopeptide-amorphous calcium phosphate

Fluoride uptake is influenced by the concentration of calcium and phosphate ions in the saliva or biofilm. For every two fluoride ions, ten calcium ions, and six phosphate ions are required to form one unit cell of fluorapatite. Calcium and phosphate in soluble and insoluble forms have their own limitations when used as remineralizing agents, however, certain specific forms are available commercially to improve the bioavailability of these ions.

Casein phosphopeptides (CPP), a milk derivative (casein being the predominant phosphoprotein in bovine milk) have been shown to stabilize calcium and phosphate as nanoclusters together with fluoride ions, preserving them in an amorphous or soluble form termed as ACP. ACP, a precursor in hydroxyapatite formation, exhibits a high solubility, is readily converted into hydroxyapatite and shows biocompatibility with both hard and soft tissues, making it a suitable remineralizing agent.

The concept of using CPP-ACP as a remineralizing agent was introduced in 1998, using casein for caries prevention was addressed in the 1980s, and ACP technology was introduced in the early 1990s.

CPP-ACP[7-9] has been shown to bind readily to the surface of the tooth, as well as to the bacteria in the plaque surrounding the tooth, thereby maintaining a high concentration of ACP in close proximity to the tooth surface. ACP acts as reinforcement to the tooth's natural defense system only when its needed. ACP at neutral or high pH remains ACP. In response to an acidic challenge (at or below 5.8 occurs during a carious attack), there is an increase in plaque calcium and phosphate ions which maintain the supersaturation state inhibiting demineralization and enhancing remineralization.

Unstabilized ACP, CPP stabilized ACP, and bioactive glass containing calcium sodium phosphosilicate are some of the systems available.[6,7] They have both preventive and restorative properties, which justify their use in dental cements and adhesives, pit and fissure sealants and composites. CPP-ACP is available in dentifrice formulation, as a mouth rinse and as a nonsugar containing chewing gum. It is commercially available as GC Tooth Mousse Plus®.

Amorphous calcium phosphate releasing pit and fissure sealants

Aegis® is a light-cured sealant that contains the "smart material" ACP.[8,10,11] The ACP filler has been claimed to have controlled flowability along with being resilient and flexible, creating a stronger and longer lasting sealant. Studies have demonstrated the remineralization potential of Aegis®.

Smart composites

It is a light-activated alkaline, nanofilled glass restorative material.[12] It releases calcium, fluoride and hydroxyl ions when intraoral pH values drop below the critical pH of 5.5, counteracting the demineralization process of the tooth surface and making conditions favorable for remineralization.[9] The material relies on mechanical retention, requiring no etching and bonding agent and can be adequately cured in bulk thicknesses of up to 4 mm. The application is quick and easy. It finds its use in restoration of class I and class II lesions in both primary and permanent teeth. Commercially available as Ariston pH control – introduced by Ivoclar – Vivadent (Liechtenstein) Company. It is available only in a single universal white shade, and is not tooth-colored; therefore, it is suitable only for posterior restorations.

Self-healing composites

After a period of use, materials degrade due to different physical, chemical, and/or biological stimuli. This leads to deterioration in the properties of the material finally leading to its failure. Self-healing has become one of the most desired properties in material development.

In the body, the best example of self-healing is the healing of a broken bone in the presence of nutrients and a source of blood supply. Continuous efforts are being made to replicate this biological model in material science.[13] The first self-healing resin-based synthetic material has been developed by White *et al*. The material was an epoxy system which contained resin filled microcapsule dicyclopentadiene, a highly stable monomer with excellent shelf life, encapsulated in thin shell made of urea formaldehyde. In response to environmental stimuli, some of the microcapsules rupture and release resin, which further reacts with Grubbs catalyst in epoxy composite, causing a polymerization reaction to take place and repair the crack. The main concern is the potential toxicity of the resins in the microcapsules and from the catalyst. However, their amount is relatively small, and the concentration may well be below the toxicity threshold.

Shape memory alloys

They were the first smart materials to be used in dentistry. These alloys have exceptional properties such as superelasticity, shape memory, good resistance to fatigue and wear, and relatively good biocompatibility. They show reversible changes in the crystal structure at the yield stress point.[2,13,14]

NiTi alloys exist as different crystal structures at low and high temperature (martensitic and austenitic, respectively). In the martensitic/daughter phase (a body-centered cubic lattice), the material is soft and ductile and can easily be deformed requiring only a light force. In the austenitic or parent phase (hexagonal lattice), the material is quite strong and hard. The lattice organization can also be altered by stress, and on the removal of the stress, the structure returns to an austenitic phase and its original shape; a phenomenon called as stress-induced thermoelastic transformation.

They are used for fabrication of brackets and orthodontic wires. Super elastic wires are preferred owing to their flexibility and resistance. SMA applies gentle, continuous forces, which are in physiological ranges, over a longer period. The superior flexibility, durability, torque ability, when compared to stainless steel, is the fundamental advantage of these materials, thus producing greater ease of use and increased patient comfort. The NiTi braces are more comfortable for patients during installation and also during treatment. Consumption of very hot or very cold food does not lead to complications in these braces if the austenite and martensite phases are well chosen.

NiTi alloys have also found use in rotary endodontics. Introduced by Walia *et al*. in 1988, rotary NiTi files have made instrumentation easier and faster than conventional hand instrumentation during the biomechanical preparation of root canal treatment. The advantage of using rotary NiTi files are improved access to curved root canals during cleaning and shaping with less lateral force exerted. This reduces operator fatigue and gives a more centered canal preparation with less canal transportation, a decreased incidence of canal aberration, and minimal postoperative pain to the patient.

Smart ceramics

In 1995, at ETH Zurich, the first “all ceramic teeth and bridge” was invented based on the process that enables the direct machining of ceramic teeth and bridges. The process involved machining a prefabricated ceramic blank made of zirconia ceramics with a nanocrystalline porous structure in the presintered state, followed by sintering. The sintered material shrinks homogeneously in all spatial directions to its final dimensions. The material gains its high hardness, high strength, and toughness during the final sintering. The veneering of the high strength ceramic framework then adds the required esthetic and wear characteristics. The process has advantages of high accuracy in an easy, fast, and fully automated way.

This invention was introduced in the market as CERCON®-Smart Ceramics System by the dental supplier Degudent. It then opened up a new era of ceramics in dentistry. It showed superior characteristics with respect to esthetics demands, excellent biocompatibility, and absence of hypersensitivity reactions.[15,16]

In pediatric dentistry, they find use in making porcelain veneer restoration and full cast or porcelain fused to metal crown restoration. They also find use as smart bracket braces containing microchip capable of measuring the forces applied to the bracket/tooth line.

SmartPrep burs (SS White, Lakewood, NJ, USA)

These are polymer burs with shovel-like straight cutting edges.[17] The polymer material has been designed to be harder than carious, softened dentin but softer than healthy dentin. It is claimed to remove carious dentin selectively; whereas, healthy dentin is not affected (minimally invasive excavation); the cutting edges wear down in contact with harder materials. SmartPrep burs are available in three ISO sizes 010, 014, and 018 and are meant for single-use only (self-limiting action). They should be used with light pressure and excavation should be done from the center to the periphery to avoid contact with the harder dentin.

Conclusion

Science and technology in the 21st century rely heavily on the development of new materials, which are expected to respond to the environmental changes and manifest their own functions according to the optimum conditions. Smart materials are an answer to this 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 are in their initial stages of development, and considerable research is required in this field of material science. Pediatric 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.

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Conflicts of interest
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