

Review Article

Smart Dentistry: “Smartness at hand”

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ABSTRACT:

Smart materials are designed materials that have one or more properties that can be changed in a controlled fashion by external stimuli; such as stress, temperature, moisture, pH, electric or magnetic fields. In dentistry, smart materials would potentially allow new and ground-breaking dental therapies with a significantly enhanced clinical outcome of treatments. On the other hand, bioactive materials are defined as materials which have an effect on or elicit a response from a living tissue, organisms or cells as inducing the formation of hydroxyapatite. As the saying goes, “Every tooth in a man’s head is more valuable than a diamond.” Thereby in the interest of all the dentists the introduction of smart materials have been made, which would help them to be more conservative and efficient with their treatment plans.

Key words: Smart dental materials, smart dentistry.

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INTRODUCTION:

THE FIRST SMART DENTAL MATERIALS:

The term “smart material” or “smart behaviour” in the discipline which is now loosely defined as “dental materials science” , was probably was first used in connection with nickel-titanium alloys or shape memory alloys (SMAs), which are used as orthodontic wires.[1]

SMART MATERIALS OVER CONVENTIONAL MATERIALS- WHY?

Conventional fillings failed due to the formation of secondary caries, fracture of restoration, fracture of tooth, marginal discrepancies or wear whereas smart materials

respond by preventing secondary caries, preventing fracture of restoration, preventing fracture of tooth, providing adequate marginal integrity, reducing wear. The key of smart behaviour includes the ability to return to the original state after the stimulus has been removed. Smart materials are also called as responsive materials. The use of smart materials in the field of dentistry is referred to as bio smart dentistry. One main advantage of bio smart dentistry in the field of orthodontics is a cosmetic advantage. A smart structure may have sensors (nerves), actuators (muscles), and a control (brain).

CLASSIFICATION

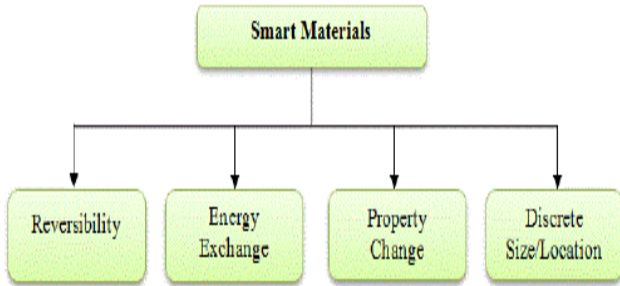
Smart Materials	
Passive materials:	Glass ionomer cements Resin-modified glass ionomer Compomer Dental composites
Active materials:	Dental materials: Smart composites Smart ceramics Prosthodontics: Smart impression material Orthodontics : shape memory alloys Pediatric and preventive dentistry : Fluoride releasing pit and fissure sealants ACP releasing pit and fissure sealants Conservative dentistry and endodontics: Ni-Ti rotary instruments Smart prep burs Oral surgery : Smart suture Periodontics: Smart antimicrobial peptide #ACP: Amorphous calcium phosphate, Ni-Ti: Nickel-titanium [2]

Passive smart materials:

The materials that release ions in the oral cavity with or without the necessity to prevent caries. E.g., glass ionomer cements, resin modified glass ionomers, compomers.

Active smart materials:

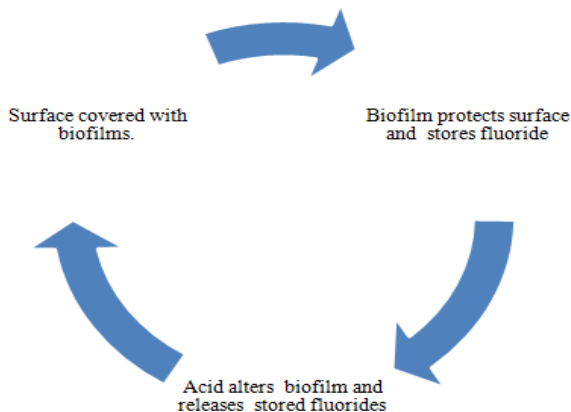
These are the materials that act favourably when there is a hazardous variation in the environment surrounding the restoration or when there is a need for materials. E.g; smart GICs, smart composites, shape memory orthodontic alloys, fluoride releasing pit and fissure sealants etc. [3]



PROPERTIES OF SMART MATERIALS:

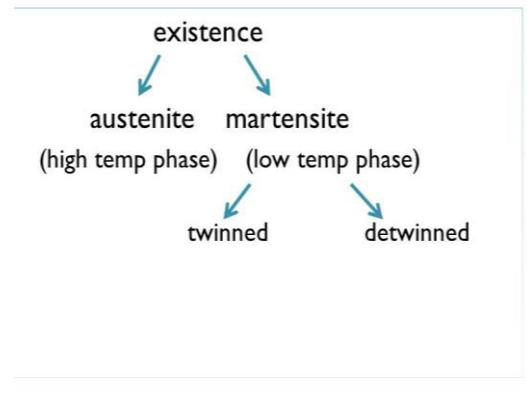
Smart materials sense changes in the environment around them and responds in a predictable manner. In general, these **properties** are:

- **Piezoelectric**- when a mechanical stress is applied, an electric current is generated.
- **Shape memory** - can change the shape whenever required and can return back to original shape once force / pressure applied is removed.
- **Thermochromic**- these materials change color in response to changes in temperature.
- **Photochromic**- these materials change color in response to changes in light conditions.
- **Magneto rheological**- these are fluid materials become solid when placed in a magnetic field.
- **pH sensitive**-when pH of the surroundings gets altered they will change their shape.
- **Biofilm formation**- presence of biofilm on the surface of material alters the interaction of the surface with the environment. [4].



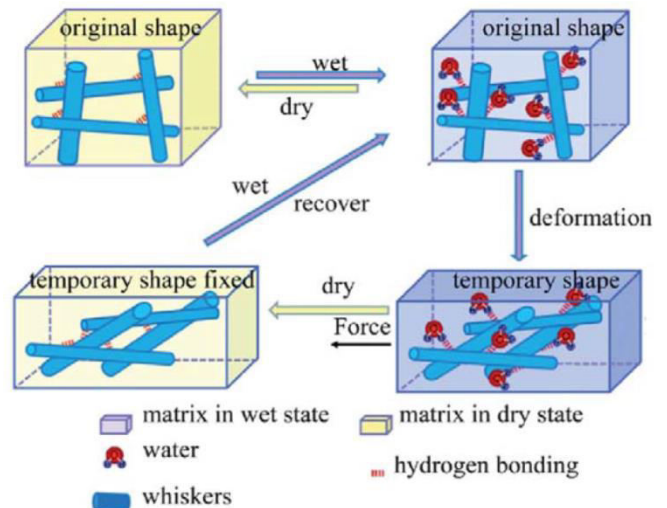
SMART CYCLE

TRANSFORMATION MECHANISM OF SMART MATERIALS



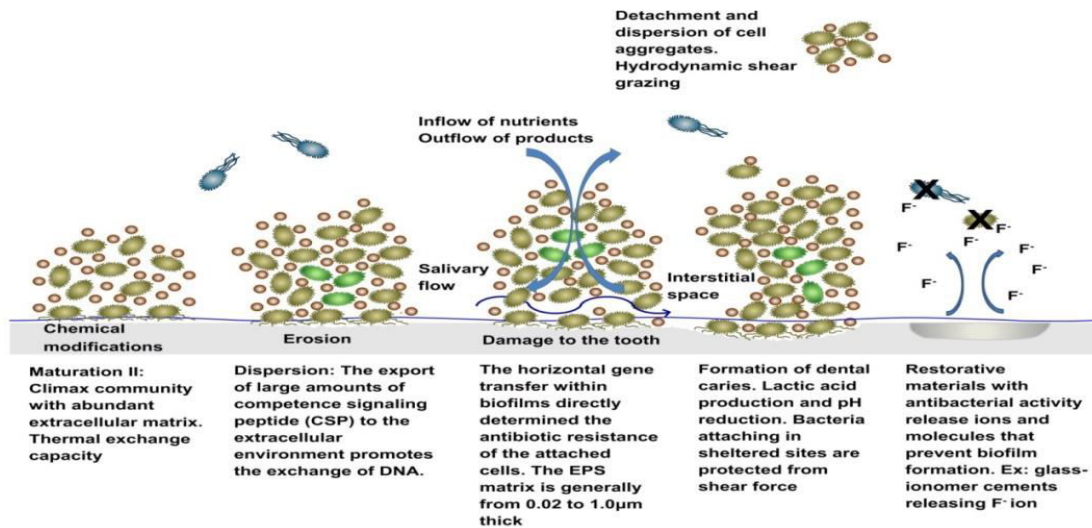
THE ROLE OF WATER

Many types of smart behaviour are related to the ability of a gel structure to absorb or release solvent rapidly in response to a stimulus such as temperature. In the oral environment the key solvent is water and the structures may be gels or salts which contain water which may be bound either strongly or loosely and therefore may be absorbed or released at different rates. Some types of smart behaviour may also be defined by any species such as fluoride ions dissolved in the water and which are capable of undergoing reversible interactions with the gel, salt or oral structures. Depending upon the nature of the water and how strongly it is bound, the observed changes may be dependent upon the dimensions of the structures.



THE ROLE OF POROSITY

The smart behaviour of glass ionomers and related materials is closely linked to their water content and the way in which this can react to changes in the environment. Clearly, there are different ways in which water can be retained in and transported through the cement structure. One important feature which may provide a location for the formation of reservoirs within the material is porosity.



The number and size of pores within a cement can be controlled by the method of mixing and is conveniently measured using micro-CT scanning. In the low viscosity material, hand mixing reduces the porosity significantly compared to mechanical mixing; either by shaking or rotation. For the viscous material the levels of porosity are low and not significantly affected by mixing. Hence, this aspect of the smart behaviour of dental cements can be controlled by the operator. [5]

FLUORIDE RELEASE FROM RESTORATIVE MATERIALS:

Release of fluoride is under the influence of some internal variables such as matrix formulation, filler and fluoride content. In addition, some experimental factors such as the storage environment, number and frequency of changing the preserving solution, composition and pH of saliva, formation of plaque and pellicle, powder-to-liquid ratio, mixing, curing time and the exposed surface rather than on the specimen bulk. Generally, the highest and the lowest fluoride release have been recorded in the demineralizing-rem mineralizing regimens are selected to simulate the cycle of pH variations during caries attack. However, the release of fluoride increases in the human saliva. It has been demonstrated that release of fluoride from RMGI in artificial saliva containing esterase is higher than that in artificial saliva without the enzyme. Bleaching and brushing have no effect on fluoride release. Covering of the surface of these restorative materials with an adhesive or surface covering agents to prevent contamination with moisture and dehydration during the initial stages, results in a decrease of fluoride release up to 1.4-4 folds. [14]

BIOFILMS AND SMART BEHAVIOUR

Biofilms formed on the surface of materials in the mouth may enhance the smart behaviour of materials containing fluoride releasing salt phases. The presence of a biofilm on the surface of a material alters the interaction of the surface with the environment and in the case of a restorative material the biofilm may act as a lubricant

which prevents abrasive wear. The formation of biofilms and the way in which this changes the interaction of the materials with the environment represents a clear example of smart behaviour for these materials. It seems that biofilms can protect surfaces from abrasive forces and at the same time concentrate fluoride which is liberated through a change in pH or mechanical debridement.

DESIGN OF SMART MATERIALS

Materials demonstrating an optimum combination of smart interactions and longevity are likely to have some combination of stable resin matrix combined with a co-existent salt matrix or discrete phase.

SMART THERMAL BEHAVIOUR:

One problem with dental filling materials is their tendency to expand and contract to a greater extent than the natural tooth tissue when subjected to hot or cold stimuli. When samples of restorative materials were heated in order to determine their values of coefficient of thermal expansion an interesting observation was made. For composite materials, expansion and contraction occurred in the expected way and a coefficient could readily be determined. Whether testing was done dry or wet made little or no difference. For glass ionomers little or no change in dimension was observed when heating and cooling between 20°C and 50°C in wet conditions. In dry conditions the materials showed a marked contraction when heated above 50°C. The explanation for this behaviour is that the expected expansion on heating is compensated by fluid flow to the surface of the material to cause a balancing of the dimensional changes. On cooling the process was reversed. In dry conditions the rapid loss of water on heating results in the observed contraction. This behaviour is akin to that of human dentine where very little dimensional change is observed on heating in wet conditions and a marked contraction is noted in dry conditions. Both results can be explained by flow of fluids in the dentinal tubules. Hence, the glass ionomer materials can be said to be mimicking the

behaviour of human dentine through a type of smart behaviour.[5]

SMART BEHAVIOUR OF DENTAL MATERIALS:

Glass ionomer cement:

The first GIC was produced in the late 1960s by Alan Wilson and his group in a chemistry laboratory in London. The aluminium-to-silica ratio in the powder of this cement has increased compared to silicate cement, which gives rise to an increase in the reactivity of glass hence, it reacts faster with polyacrylic acid, because this acid is weaker than the phosphoric acid used in the silicate cement. In most cases, the glass used in polyalkenoic acid aluminosilicate cement (ASPA) is calcium-aluminosilicate glass system, which was introduced by Wilson and Kent. It contains calcium oxide along with the fluoride, alumina, and silica. In the initial GI, the liquid was an aqueous solution of 50% polyacrylic acid, which converted into gel form only after a few months because of the presence of inter-molecular hydrogen bonds. This gelation process decreases or is eliminated by the use of copolymers instead of homopolymers. At present, the liquid contains an aqueous acrylic acid or a copolymer of maleic acid/acrylic acid. In 1972, it became evident that the incorporation of a positive isomer of tartaric acid can improve manipulation properties of the cement and its setting time. Although, Aluminium is present within the GI structure, calcium is added as a flux, in the form of calcium fluoride, to the aluminosilicate powder, forming a superficial bond. Therefore, calcium is released faster than aluminium. During glass production, fluoride flux is added to prevent oxidation. Then, fluoride is released after mixing of powder with the polyalkenoic acid and becomes available for absorption by the tooth structure. The presence of fluoride decreases its melting point; increases cement strength, improves manipulation properties of the cement and finally has a cariostatic effect. Ngo et al, used a newer material (Fuji IX) in an in vitro study, in which strontium has replaced calcium in order to confer the material. Calcium and strontium can, to some extent, replace each other. These researchers reported a deep penetration of strontium into the demineralized dentin on the cavity floor. These studies showed the possibility of dentin remineralization by GI. [14]

Setting reaction: An acid-base reaction takes place between the polyacrylic acid as a proton donor and aluminosilicate glass as a proton recipient. The acid destroys the glass network and releases cations such as Al^{3+} , Ca^{2+} , Na^{+} , etc. These cations are trapped by the carboxylate polymer and chelated, finally producing cross-links in the polymer network and forming a hard polysalt matrix. It is of interest to note that the majority of silicate glasses are resistant to acid attacks due to highly covalent characteristics of Si-O-SiO-O-bond; however the glass becomes more sensitive to acid attacks with an increase in the ionic properties of silicates.

GI has the capacity to bond chemically to polar materials such as bone, enamel and dentin. These materials have a

high surface energy, but are not able to react with the noble metals and porcelain. This kind of adhesion is divided into two stages:

- The free $-COOH$ groups form hydrogen bonds with the substrate.
- With the progression of the reaction, the flexible hydrogen bonds are converted into stronger ionic bridges.

The carboxyl groups of the ionic polymers of polyalkenoic acid enter the structure of hydroxyapatite by replacing phosphate; they are the main agent with the hydroxyapatite component of the tooth structure. Therefore the bonding is permanent because all the adhesive groups are connected to each other with covalent bonds and all the bonds should fail simultaneously for the bonding to fail. [14]

In some recent studies, bioactive glass (BAG) has been added to GI structure to improve its bioactivity and tooth regeneration capacity. BAG contains silicon, sodium calcium and phosphorus oxides with specific weight percentages, which was introduced by Larry Hench in 1969 as 45S5 bioglass. Clinically, this material was initially used as a biomaterial to replace the lost osseous tissues in the human body. It produces a strong bond between the collagen and the hydroxyapatite. [14]

Anti-bacterial GICs for Atraumatic Restorative Treatment (ART)

In vitro studies:

ART is one of the minimal intervention procedures in which demineralized tooth tissues are removed using manual instruments, and the cavity, including adjacent pits and fissures are restored using a GIC. In an attempt to achieve GIC with anti-bacterial effect, Chlorhexidine (CHX) which is known to be bactericidal against caries-associated bacteria, as an antimicrobial was to be incorporated. To determine the optimal concentration of CHX incorporation, CHX diacetate combined with less water soluble compound CHX dihydrochloride was added to the powder of Fuji IX to obtain certain concentrations, and the properties of GIC were then evaluated. By agar diffusion methods, all experimental GICs showed anti-bacterial activity against *S.mutans*, *L.casei* or *A.naeslundii* due to the release of CHX at both the set and unset stages. [15]

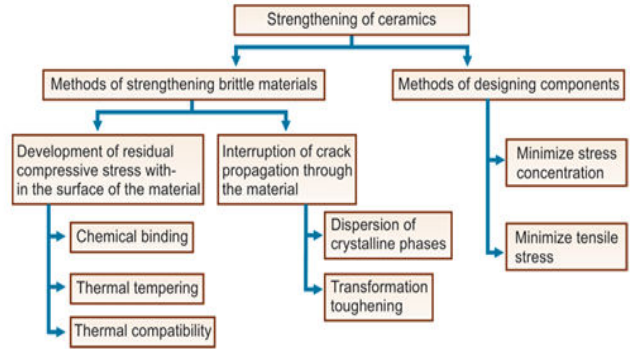
Resin modified GIC (RMGICs):

The term "resin-modified" denotes the addition of resin groups (e.g. HEMA) by virtue of the attachments of these molecular groups to the "acidic liquid component". These light-cured RMGICs offered many benefits. The speed of light curing vastly shortened the setting time. RMGICs were produced by adding methacrylate to polyacrylic acid. Some of them are light-cured, which is supplementary to the basic acid-base reaction. In comparison, polyacid-modified composite resins consist of commonly used macromonomers in composite resins, which include Bisphenol A-Glycidyl dimethacrylate or urethane dimethacrylate along with small amounts of acidic monomers. They have the same ion-releasing glass

as filler particles used in conventional GI, but in small sizes. The initial setting reaction is triggered by the light, which is followed by acid-base reaction after absorption of water. A large number of researchers have reported that RMGIs can release fluoride at a rate comparable to that by conventional GI. However, this release is not only under the influence of formation of complex fluoride derivatives with their reaction with polyacrylic acid, but also it might be affected by the type and amount of the resin used in the light polymerization. Release of fluoride from various RMGIs during the first 24 hr is maximum with 5-35 $\mu\text{g}/\text{cm}^2$ depending on the storage environment. Daily fluoride release begins from 8 ppm to 15 ppm on the 1st day and decreases to 1-2 ppm on the 7th day and stabilizes in 10 days to 3 weeks. Most recently, a new group of light cured RMGICs have been introduced, all with varying recommendations and abilities. One material Ionolux, has demonstrated a wider variety of applications than previously recommended for RMGI materials. This modified restorative does dual cure in that the GI aspect self-cures with an acid-base reaction and the resin aspect is light cured. It has composite like aesthetics, non-sticky handling, and is immediately packable. This material offers enhanced physical properties, continued fluoride release, better longevity, does not require dentin conditioning and is excellent at preventing leakage from the intraoral fluids with a low water solubility coefficient. The advantage these have is that they show an early resistance to water uptake in the nearly set cement as well as enhanced translucency.

Smart ceramics:

Ceramics are available for a long time and were used to fabricate crowns. The most recent advancement to the dental ceramics family is Zirconia, which in its pure form is a polymorphic material that occurs in three-temperature dependent forms: Monoclinic crystal structure between the room temperature and about 950°C. Above, 950°C Zirconia converts to the tetragonal crystal structure. This transformation accompanies a greater than 1% shrinkage during heating and an almost equivalent expansion during cooling. At higher temperatures, the zirconia changes from a tetragonal to a cubic structure. With properly controlled chemical additions and heat treatments a microstructure can be achieved during cooling that consists of lens-shaped preipitates of tetragonal Zirconia in cubic grams of Zirconia. Normally, during cooling, the tetragonal material would transform to the monoclinic form, but expansion is a must. The high strength of the surrounding cubic Zirconia prevents this expansion, so it retains its tetragonal form when it cools back to the room temperature. Each tetragonal precipitate will try to expand if a crack tries to form, for breaking the ceramic. Tetragonal precipitates next to the crack are now able to expand and transform back to their stable monoclinic forms. This expansion adjacent to the crack presses against the crack and stops it. [3]



Shape memory alloys:

Shape memory alloys are of three types:

Copper-Zinc-Aluminium-Nickel, Copper –Aluminium-Nickel, Nickel-Titanium (NiTi).

NiTi alloys change from austenite to martensitic to upon cooling. M_f is the temperature at which the transition to Martensite is finished during cooling. Accordingly, during heating A_s to A_f are the temperature sat which the transformation from martensite to Austenite start and finishes. Repeated use of the shape memory effect may lead to a shift of the characteristic transformation temperatures. This effect is known as the functional fatigue, as it is closely related with a change of microstructural and functional properties of the material

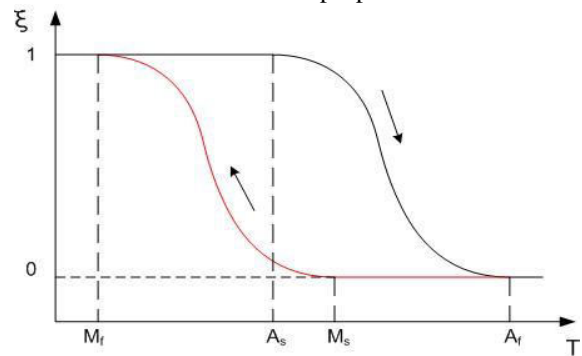


Fig: ξ (T) represents the martensite fraction. The difference between the heating transition and the cooling transition gives rise to the hysteresis effect where some of the mechanical energy is lost in the process. The shape of the curve depends on the material properties of the shape memory alloy, such as alloying and work hardening.

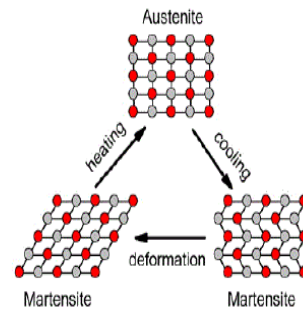


Figure: Reverse transformation process of SMA

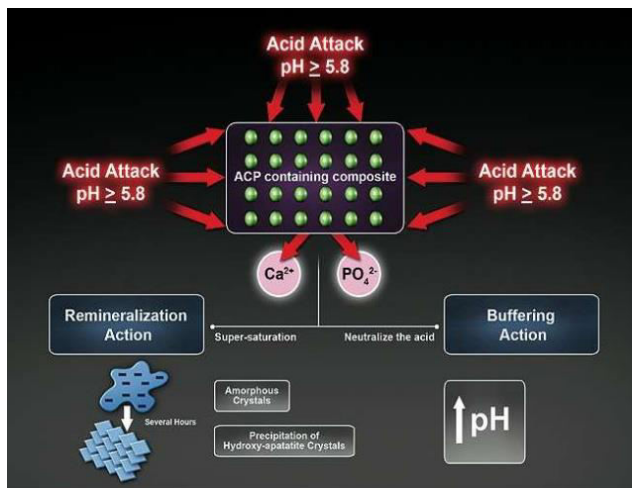
Amorphous calcium phosphate:

These are supersaturated solution of solid calcium phosphate particles. Crystalline octa calcium phosphate(OCP) or apatite products are derived from it. It plays a specific role as a precursor to bioapatite and in the transitional phase of remineralization. In the physiologic pH , ACP is first dissolved and re-deposition of solid phase OCP occur through the growth of core and its hydrolysis to a more stable apatite phase.OCP may be a mediator in conversion of ACP to phosphate calcium phosphate. In a lower pH (below 9.25) OCP and in higher pH values apatite is formed.

ACP is used as a filler in ionomer cement, for the restoration of carious lesion to enhance their remineralization or demineralization in the form of colloidal suspension in tooth pastes, Recaldent chewing gums, tooth bleaching gels and mouthwashes. [13]

These are referred to as smart materials because :

- They remain in their original form at neutral or high pH. Whenever the surrounding pH drops they release calcium and phosphate ions.
- ACPs act as a reinforcement of tooth’s natural defense system only when it is needed.
- It has a long life.



Smart burs:

These are polymer burs that cut only infected dentin. The design of the polymer bur is based on the differential hardness of the tooth tissues. The knop hardness number of enamel is approximately 380-400 and that of dentine is 66-80. The knop hardness number for carious dentine is 30KHN. In order to achieve effective removal of caries from enamel, dentine and to match KHN with sound teeth, the polymer burs with KHN 50 have been devised. Since this bur removes only infected dentin there are fewer chances that the odontoblasts are exposed. These burs rotate at a speed of 500-800 rpm. In vitro studies, by T.Dammaschke et al, revealed that these burs were ineffective in caries removal as compared to carbide burs. One of the reasons being stated as the inability of the dentists to handle the small, split sample teeth. Although, in a more clinical type of experiment, both the bur systems might show better histological results, but it can

be assumed that the relation of caries free specimens between Smart Prep and bud bur will be similar.

A microbiological study confirmed that the effectiveness of polymer burs in the removal of carious dentine has no statistically significant differences in the reductions of the numbers of CFU/ml as compared to carbide burs and hence preserves the sound dentin. [12]

Smart impression materials:

These materials exhibit more hydrophilic to get void free impressions and have a shape memory. Its Snap set behaviour results in the precise fitting of restorations without distortion. [6]

Self-Healing Composites:

One of the first self-repairing or self-healing synthetic materials was an epoxy system which contained resin filled microcapsules.

If a crack occurs in the epoxy composite material, some of the microcapsules are destroyed near the crack and release the resin. The resin subsequently fills the crack and reacts with a Grubbs catalyst dispersed in the epoxy composite, resulting in a polymerization of the resin and a repair of the crack.

Advantage:

Longer duty cycle and enhanced clinical performance.

Problems may arise from the potential toxicity of the resins in the microcapsules and from the catalyst, which needs to be present in the composite.

Smart seal Obturation System:

The C Point system (EndoTechnologies, LLC, Shrewsbury, MA, USA) is a point-and-paste root canal filling technique that consists of premade, hydrophilic endodontic points and an accompanying sealer.

The deformable endodontic point (C Point) is available in different tip sizes and tapers and is designed to expand laterally without expanding axially, by absorbing residual water from the instrumented canal space and that from naturally-occurring intraradicular moisture. This non-isotropic lateral expansion is said to enhance the sealing ability of the root canal filling, thereby reducing the possibility of reinfection and potentiating the long-term success of root canal treatment. [7]

Smart paste bio:

It is a resin based sealant designed to swell through the addition of a ground polymer.

Smart paste bio produces calcium hydroxide and hydroxyapatite as by products of a setting reaction, rendering the material both anti-bacterial while setting and very biocompatible once set.

Also, it has a delayed setting time and is hydrophilic in nature, allowing the C point to hydrate and fill any voids. [8]

Smart fibres in lasers

Hollow-core photonic-crystal fibres (PCF) for the delivery of high fluence laser radiation are used for ablating tooth enamel.

The hollow-core PCF is shown to support the single fundamental-mode regime for 1.06µm laser radiation,

serving as a spatial filter and allowing the laser beam quality to be substantially improved.

Nickel-titanium (ni-ti) rotary instruments:

The advantage of using rotary Ni-Ti files is that there are less chances of file breakage within the canal during instrumentation, less fatigue to the operator, less transportation, decreased incidence of canal aberration and minimal post-operative pain to the patient. [11]

Casein Phosphopeptide (CPP):

It is a milk derivative, in combination with ACP is used for the remineralisation of incipient white spot lesions in some dentifrices. [4]

Smart Coatings for Dental Implant:

Researchers at North Carolina State University have developed a “smart coating” that helps surgical implants bond more closely with bone and ward off infection. The coating creates a crystalline layer next to the implant and a mostly amorphous outer layer that touches the surrounding bone. The amorphous layer dissolves over time, releasing calcium and phosphate which encourages bone growth. “The bone grows into the coating as the amorphous layer dissolves, resulting in improved bonding, or Osseo integration. “This bonding also makes the implant more functional, because the bonding helps ensure that the bone and the implant do a better job of sharing the load. It is called as a **smart** coating because the rate at which the amorphous layer dissolves to match the bone growth rate of each patient can be tailored. The researchers have also incorporated silver nanoparticles throughout the coating to ward off infections. Currently, implant patients are subjected to an intense regimen of antibiotics to prevent infection immediately following surgery. However, the site of the implant will always remain vulnerable to infection. But by incorporating silver into the coating, the silver particles will act as antimicrobial agents as the amorphous layer dissolves. This not only will limit the amount of antibiotics patients will need following surgery, but also will provide protection from infection at the implant site for the life of the implant. Moreover, the silver is released more quickly right after surgery, when there is more risk of infection, due to the faster dissolution of the amorphous layer of the coating. Silver release will slow down while the patient is healing. That is another reason why the authors call it smart coating. [7]

Bio-medical applications of smart materials:

Smart pressure bandages:

Polyethylene glycols bonded to various fibrous materials such as cotton and polyester possess the intelligent properties of thermal stability and reversible shrinkage. Such materials could be used for pressure bandages that contract when exposed to blood, thereby putting pressure on the wound.

Hydrogels:

These exhibit plastic contraction with changes in temperature, pH, magnetic or electrical field. E.g. Soft actuators in the biomedical field or for controlled drug release.

Smart Shirt:

Developed by Georgia Tech along with Sensa Tex Inc., “Smart Shirt”, is a T-shirt that functions like a computer, with optical and conductive fibres integrated into the garment. The shirt monitors the wearer’s heart rate, EKG respiration, temperature and a host of vital functions. [9]

In disputing radioactive rays:

Composite suppression structures can be utilized for disputing the radioactive or chemical waste materials. Radiation or chemical waste when sensed, fibers having chemical or radioactive subtle coatings can be provided which are revised for releasing the scavenger compounds. [10]

Advantages of smart materials:

- Smart materials have better durability and reliability.
- Smart materials get smarter with the ability to better control of shape and size.
- Smart materials are self-repairable, if damaged.

Limitations of smart materials:

- They are very expensive
- They need proper storage as they are very sensitive materials.

Conclusion:

The development of smart materials at the atomic scale is still some way off, although the enabling technologies are still under development. Although application of smart materials over conventional ones is proving to be a success as they offer better responses to all the considered factors, the era we are stepping into will demand more of everything therefore we not only have to be smart but rather more efficient with our materials. When we talk about smart materials, we only have limited ourselves to the restorative materials, despite being well aware of the fact that dental problems are overlooked by the people until they suffer from pain. Therefore, in the interest of the public, we should incorporate smartness in materials which can provide better treatment results and reduce the chair-side time. When we have to ponder over the future prospects of smart materials then why not should we plan to design a material that would help us to maintain the pH of the oral cavity everytime it falls. As per my view, the tooth pastes and mouthwashes which are available in the market today should also be considered as smart materials. Tooth pastes, although are topically beneficial but are somewhere more popular than the restorative materials. Toothpastes, available are somewhat smarter than the conventional materials, as they have been offering temporary cure for sensitivity and minimal caries protection.

Not only this but even toothpastes with the ability to repair enamel, whiten the teeth as well as anti-plaque toothpastes have come up. Although, the content of whitening toothpastes can be questioned upon but these methods are more appealing to the masses than to undergo a restorative procedure. For the masses, like pain can be subsided using an analgesic, a sensitive tooth can

be desensitised using a tooth-paste. Then why are dentrifices not considered as smart materials?

Smartness can also be seen in the variety of toothbrushes we have today, earlier there had to be a toothbrush and floss separately, but now they are incorporated in a toothbrush itself. Are they not smart?

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