Smart Materials in Dentistry: Pioneering the Future of Oral Healthcare

INTRODUCTION

Human teeth are not only an important masticatory organ but are also closely associated with both pronunciation and the facial aesthetics of human beings. Thus, beyond all doubt, teeth play an extremely significant role in our daily life but they have limited regeneration capabilities, thus, with ageing, various pathological factors and traumas, tooth lesions such as caries, partial or overall tooth tissue loss occurs unavoidably. Once tooth tissue loss occurs, their restoration becomes mandatory.

Traditionally materials used in dentistry were designed to be passive and inert, and they were often judged on their ability to survive without interacting with the oral environment. A change in the scenario was noticed by the beginning of 1960's. Since then materials that are bioactive rather than passive or inert in the mouth began to be more common. Currently materials used in dentistry can be grouped as bioinert (passive), bioactive, and bioresponsive or smart materials based on their interactions with the environment.[1]

"Smart materials" are those 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. The first smart behavior noted in the field of dentistry was the release of "fluoride" from some dental materials and the first smart dental material to be used in dentistry were the nickel-titanium alloys, or SMAs used as orthodontic wires.[2]

There are two types of smart materials: passive and active. Passive materials (Glass ionomer cements, Resin-modified glass ionomer, Compomer, Dental composites) respond to external change without external control. They also possess self-repairing characteristics. Active materials(Smart GIC- Glass Ionomer cement, Smart composites, Smart ceramics, Smart impression material, Shape memory alloys, Ni-Ti rotary instruments, Smart prep burs, Fluoride releasing pit and fissure sealants, ACP- Amorphous Calcium Phosphate releasing pit and fissure sealants, Smart suture, Smart antimicrobial peptide, Smart coatings for dental implants, smart seal obturation system, smart fibres for laser dentistry) sense a change in the environment and respond to them by utilizing a feedback loop to enable them to function like a cognitive response through an actuator circuit.[3]

These copious materials have made restorative, prosthetic, orthodontic, pediatric &preventive, endodontic and laser dentistry easier and more efficient in their own ways in day to day practice, delivering quality, effective, and comprehensive care.

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".[2]

In the coming years smart materials may prove to be one such under- the-radar, yet ultimately inevitable theme.

This article aims to provide a comprehensive review of smart materials used in pediatric dentistry. By examining the available literature, research studies, and clinical experiences, this article seeks to offer valuable insights into the optimal use of smart materials to ensure the best possible outcomes in pediatric dental practice.

PROPERTIES OF SMART MATERIALS

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

a. Piezoelectric	It is a property of certain dielectric materials to physically deform in the presence of an electric field, or conversely, to produce an electrical charge when mechanically deformed e.g., smart ceramics, piezoelectric bone surgery
b. Shape memory	This property states that the material has the property of changing the shape according to the applied pressure and

	regains its original shape once the pressure is released, e.g., NiTi rotary instruments
c. Photochromic	These materials show the property of color change according to changes in the environment, e.g., Clinpro™ Sealant(3M)
d. Thermochromic	These materials show the property of altering according to temperature changes, e.g., smart impression material-smart alginate material
e. Magnetorheological	Material changes its state from fluid to solid when kept in magnetic field, e.g, smart composites
f. Biofilm formation	The formation of biofilm on the surface of the material helps to form a barrier between the environment and the surface , e.g., GC Tooth Mousse, Caridex, and Papacarie
g. pH-sensitive	They change their shape i.e, swell/collapse according to the change in pH , e.g., smart composites and ACP-releasing pit and fissure sealants[4]

Table No. 1: Properties of Smart Materials

CLASSIFICATION OF SMART MATERIALS

Smart materials are of two types passive and active materials

I. **Passive Smart Materials**: They sense the external change and react to it without external control. They also possess self - repairing property.

a. GIC

b. Resin Modified GIC

c. Compomer

d. Dental Composites

e. Giomer

II. **Active Smart Materials:** Active materials sense change in the environment and respond

to them. Utilize a feedback loop to enable them to functions as a cognitive response through a controlled mechanism or system.

a. **Restorative Dentistry**

- Smart GIC.
- Smart composites.
- Smart Prep Burs.
- Smart bonding system.

b. **Prosthetic Dentistry**

- Smart ceramics.
- Smart impression materials.

c. **Orthodontics**

- Shape memory alloys.
- Smart orthodontic adhesive.

d. **Pediatric And Preventive Dentistry**

- Fluoride releasing pit and fissure sealants.
- ACP releasing pits and fissure sealants.
- Smart varnish.

e. **Endodontics**

- Niti Rotary Instruments.
- Smartseal obturation system.
- Smart fiber posts.

f. **Laser Dentistry**

g. **Smart Fibers.**

h. **Periodontics**

- Smart antimicrobial peptide.

i. **Implant Dentistry**

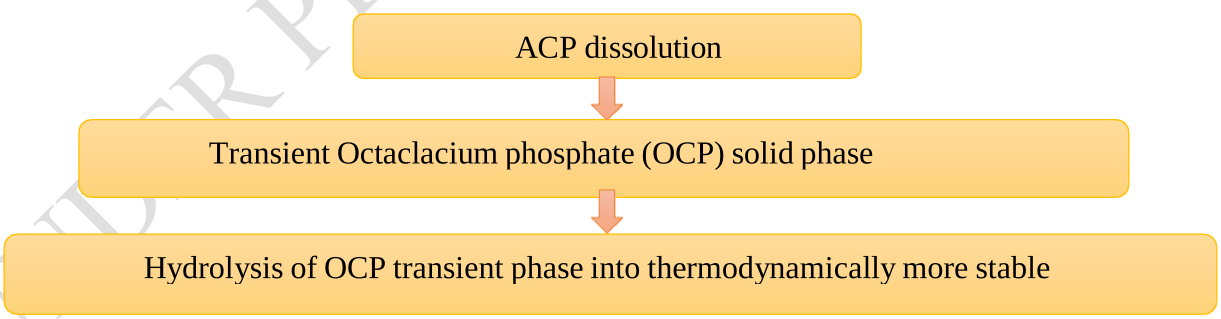
- Smart coatings on implant.

j. **Oral surgery**

- Smart sutures.
- Bioactive glass.

AMORPHOUS CALCIUM PHOSPHATE (ACP)

Amorphous calcium phosphate (ACP) is a noncrystalline form of calcium phosphate which remineralizes the tooth structures and aid in the prevention of tooth decay. Amorphous Calcium Phosphate compounds (ACPs) are considered prime candidates for remineralization therapy due to their high solubility under oral conditions and ability to rapidly hydrolyze to form apatite[5].Mechanism of action of Amorphous Calcium Phosphate (Flow chart 1) and example of commercially available Amorphous Calcium Phosphate (Fig.1).



Flow chart 1: Transformation mechanism of Amorphous calcium phosphates (ACP)

Fig.1: Aegis pit and fissure sealant

CASEIN PHOSPHOPEPTIDES-AMORPHOUS CALCIUM PHOSPHATE

Casein, a bovine milk phospho-protein is known to interact with calcium and phosphate and is a natural food component. It's technical name is casein phospho-peptides-amorphous calcium phosphate or CPP-ACP (Fig.2). Other than fluoride, Casein Phosphopeptides-Amorphous Calcium Phosphate is the most extensively researched remineralization technology[6].

Recaldent™

Fig.2: CPP-ACP marketed as Recaldent

SMART GLASS IONOMER CEMENT

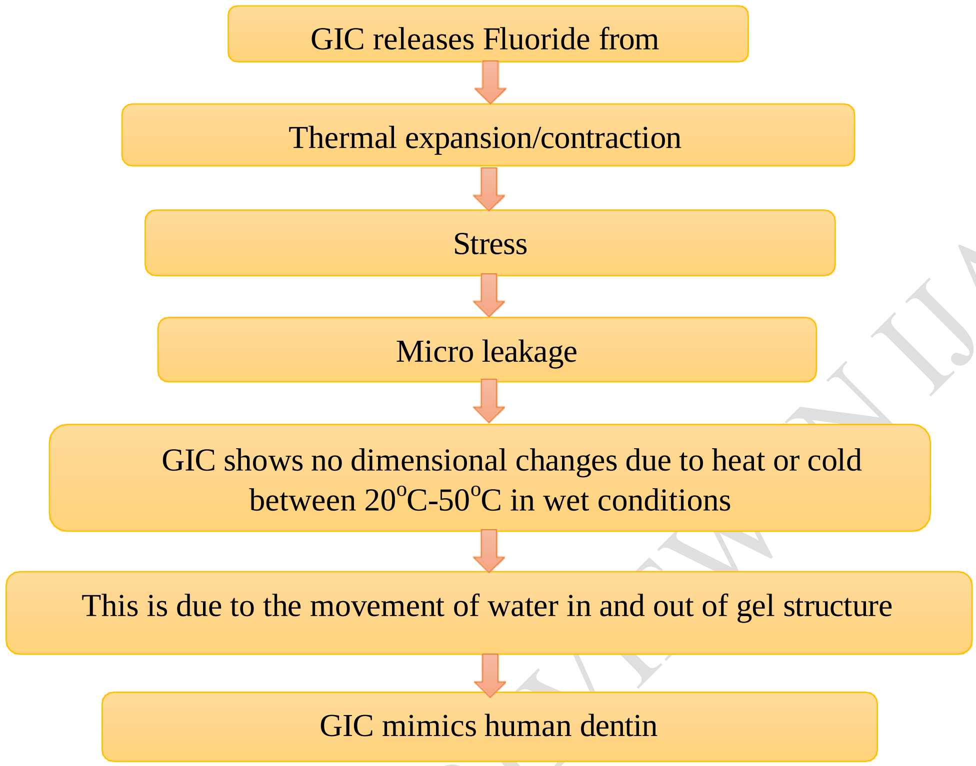
Davidson first observed the smart behavioral property of Glass Ionomer Cement (GIC)[7].

- It is related to the ability of a gel structure to absorb or release solvent rapidly in response to a stimulus such as temperature, change in pH etc.

- The number and size of pores with the cement can be controlled by the method of mixing conveniently measuring using micro-computed tomography scanning, hence this aspect of the smart behavior can be controlled by the operator.

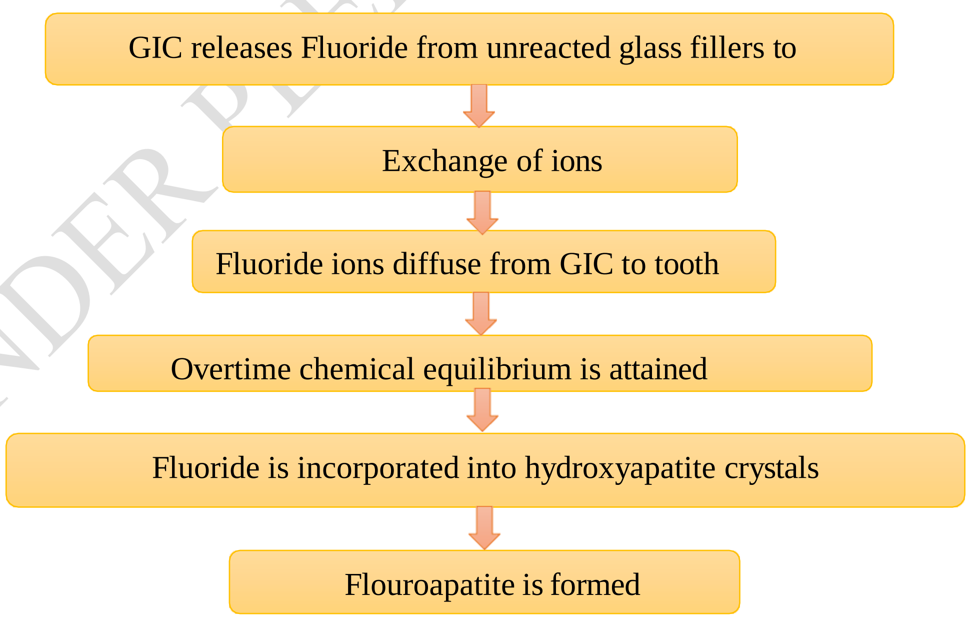
Example for commercially available smart glass ionomer (Fig.3).

i) Based on Coefficient of Thermal Expansion (Flow chart 2)



Flow chart 2: Coefficient of thermal expansion of glass ionomer cement

ii) Based on Fluoride Release and Recharge Capacity (Flow chart 3)



Flow chart 3: Fluoride releasing mechanism of glass ionomer cement

ADVANTAGES

i. Adhesion to tooth structure

ii. High retention rate.

iii. Little shrinkage and good marginal seal

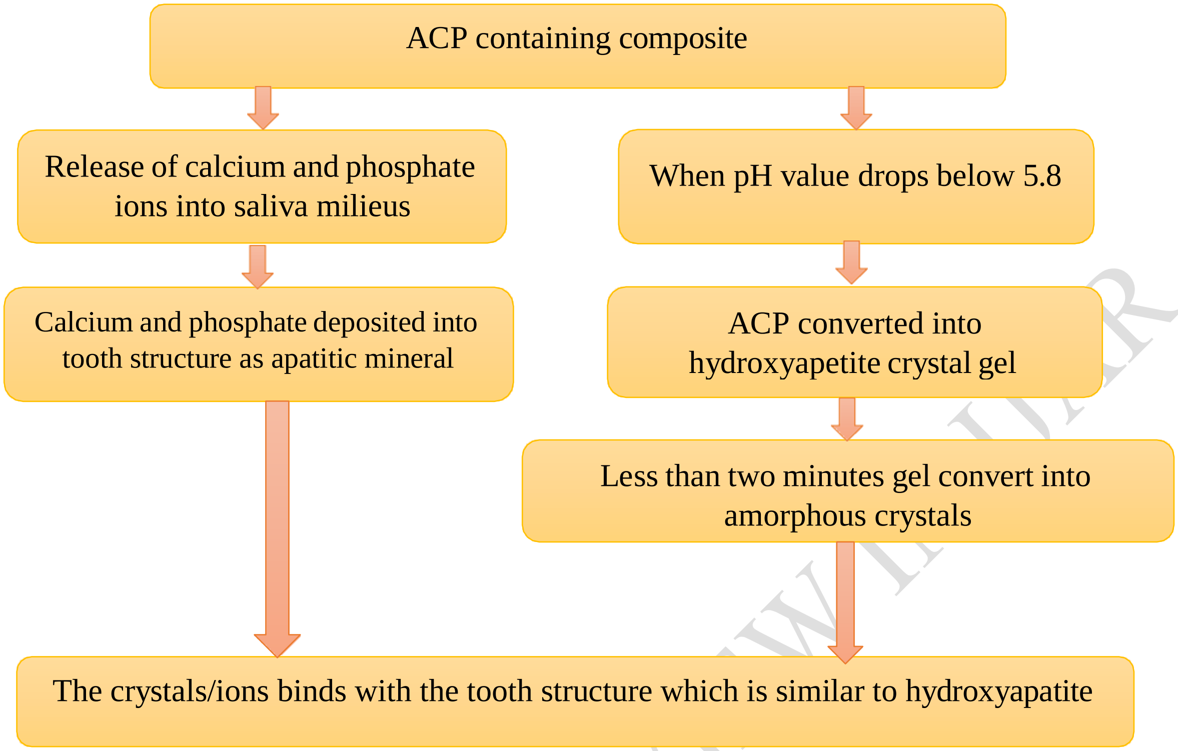
iv. Fluoride release hence anticariogenic

Fig.3: GC Fuji IX GP EXTRA (Zahn Fabrik Bad Säckingen, Germany).

SMART COMPOSITE

As per Author- Kelly, Davidson and Uchino in 2017, Smart composites are defined as the Systemic composition of smart materials to provide enhanced dynamic sensing, communicating, and interacting capabilities via Interactive Connected Smart Materials (ICS Materials).

Smart Composites can be explained simply as these are designed materials, where smart materials are embedded in polymer, metal or concrete etc. to sense, control, communicate etc[8].Mechanism of action of smart composite (Flow chart 4) and example of commercially available smart composite (Fig.4)

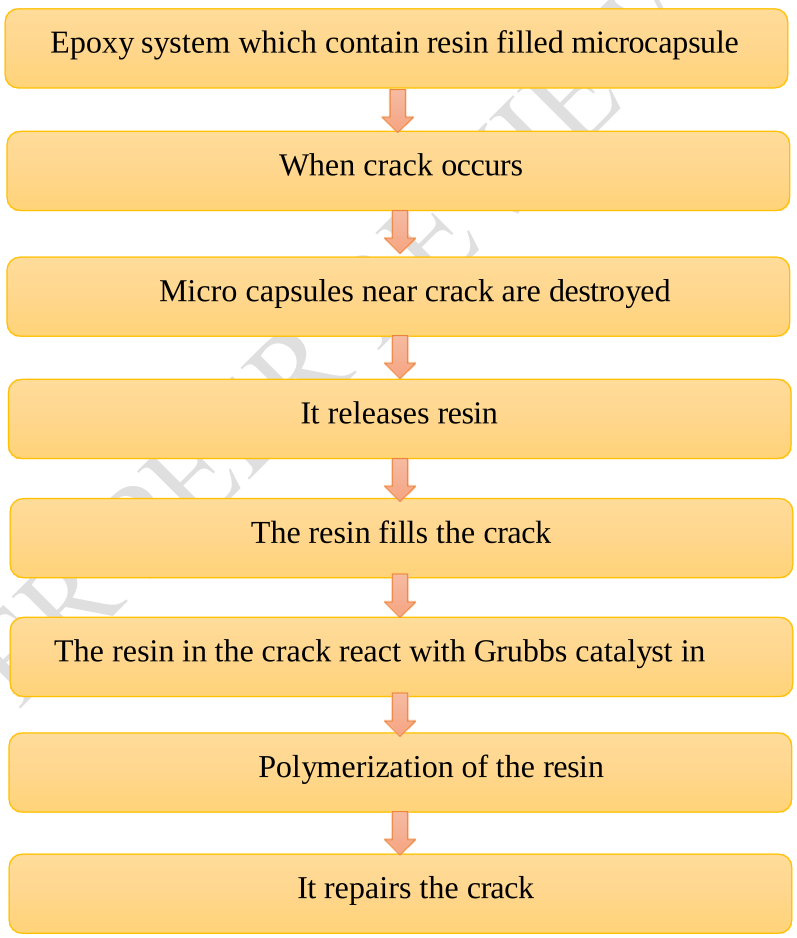


Flow chart 4: Mechanism of action of amorphous calcium phosphate in composite

Fig.4: Kulzer Charisma Smart Composite 4 Syringe Kit Gluma Bond5 Dental

SELF-HEALING COMPOSITE

Materials usually have a limited lifetime and degrade due to different physical, chemical, and/or biological stimuli. These may include external static (creep) or dynamic (fatigue) forces, internal stress states, corrosion, dissolution, erosion, or bio degradation. This gradually leads to a deterioration of the materials structure and finally failure of the material[9]. Mechanism of action of self healing composite (Flow chart 5) and example of commercially available self healing composite (Fig.5)



Flow chart 5: Mechanism of action of self-healing composite

ADVANTAGES

i. This technique can be applied to highly cross linked thermoset

ii. Numerous different healing chemistries and encapsulation techniques makes the healing mechanism tunable and hence, suitable for different matrices.

Fig.5:Prevest DenPro Self Comp Universal Composite Resin

ARISTON pHc ALKALINE GLASS RESTORATIVE MATERIAL

It is a light-activated alkaline, Nano-filled glass restorative material. It recommended for the restoration of class I and II lesions in deciduous and permanent teeth[10].Mechanism of action of Ariston pHc alkaline glass restorative (Flow chart 6) and example of commercially available Ariston pH control alkaline glass restorative material (Fig.6).

Below pH 5.5

↓

It releases calcium, fluoride and hydroxyl ions

↓

It counteracts demineralization and promotes remineralisation

Flow chart 6: Mechanism of action of Ariston pHc alkaline glass restorative

Fig. 6: Ariston pH control alkaline glass restorative material introduced by Ivoclar-Vivadent Company

SMART CERAMIC

Due to their metal-free, biocompatible design, these restorations resemble natural teeth in their surroundings[11]. They facilitated an uncomplicated and predictable process for returning teeth to their normal structure[12].Mechanism of action of smart ceramic (Flow chart 7) and example of commercially available product of smart ceramic (Fig.7)

In room temperature tetragonal is metastable

↓

Trapped energy which exists drives it back to monoclinic

↓

When highly localized stress is applied

↓

The propagating crack is sufficient to trigger grain of ceramic to transform in the vicinity of the crack tip

↓

Grain volume increases

↓

Tetragonal transformed to monoclinic

↓

It decreases the local stress intensity

↓

Compressive or crack closure stress is produced which slows down or stops the crack

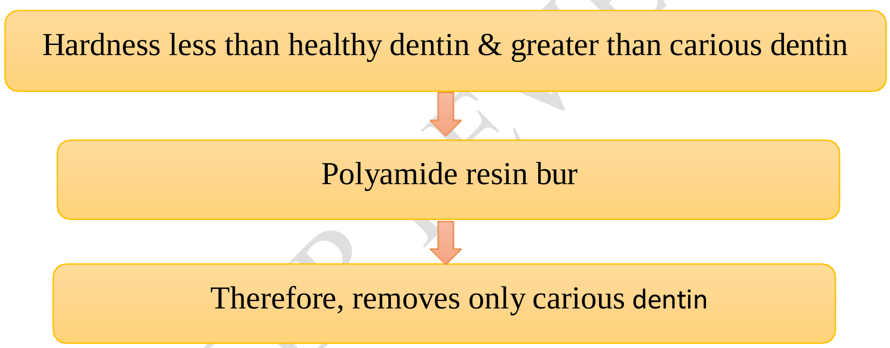
Flow chart 7: Mechanism of action of smart ceramic

Fig.7: Multilayer smart zirconia and smart Cercon zirconia

SMART BURS

These are polymer burs made of polyamide resin. Their hardness is less than healthy dentin (53 to 80 KHN) and greater than carious dentin (14 to 38 KHN). Thus, these burs are capable of removing soft carious dentin, but when it comes in contact with the hard dentin, they burn out, avoiding unnecessary cutting of tooth structure[13].

Smart burs are developed to remove decayed dentine without harming healthy tooth structure, combined with a specially designed polymer; this bur system is designed to distinguish healthy dentine from carious dentine based on the hardness of sound dentine. Mechanism of action of smart bur (Flow chart 8) and example of commercially available smart bur (Fig. 8)



Flow chart 8: Mode of action of smart bur

ADVANTAGES

i. Used for deep caries removal in lieu of indirect capping procedure.
ii. Chances of iatrogenic pulp exposure are less.
iii. Minimum removal of tooth structure.

Fig.8: Smart prep burs

SMART IMPRESSION MATERIALS

They are hydrophilic to get a void-free impression. They possess Shape memory so during elastic recovery it resists distortion for more accurate impression and toughness resists tearing. They have a snap - set behavior which results in precise fitting restorations without distortion. They cut off working and setting times by at least 33%. They have low viscosity and hence high flow.

Aquasil Ultra Smart Wetting Impression Material

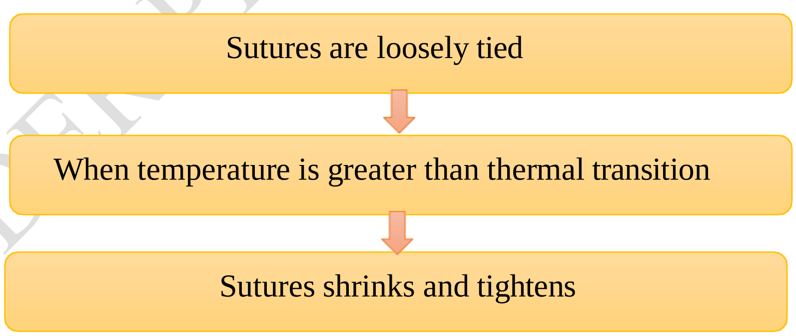
This new formula of Aquasil, is an addition silicone impression material designed with a reduced contact angle, an increase in tear strength, and maintenance of a low viscosity during the working time (Fig.9) Hydrophilic nature is advantage of this materials and it provide void free impressions[14].

They have shape memory which allows elastic recovery and prevents distortion for accurate impressions. They have high flow and low viscosity allowing for higher accuracy.

Fig.9: Aquasil Ultra Smart Wetting® Impression Material.

SMART SUTURES

They are made up of thermoplastic polymers that have both shape memory and biodegradable properties. Smart sutures made of plastic or silk threads covered with temperature sensors and micro-heaters can detect infections. Sutures are loosely tied, once the temperature is increased above the thermal transition temperature; sutures gets shrinked and tightened[15].Mechanism of action of smart suture (Flow chart 9).



Flow chart 9: Mechanism of action of smart sutures

There are Smart sutures that detects infections (Fig.10) and Polymer sutures for simultaneous wound healing and drug delivery.

Fig.10: Smart sutures that detects infections

SMART ANTIMICROBIAL PEPTIDE

Antibiotics have an impact on a wide variety of microorganisms, including the natural flora. Antibiotic treatment often causes ecological disruption that leads to subsequent infections or other unfavourable clinical outcomes. A novel class of pathogen-selective compounds known as specifically (or selectively) targeted antimicrobial peptides (STAMPs) has recently been developed in response to this issue. STAMPs are based on the fusion of a wide-spectrum antimicrobial peptide domain with a species-specific targeting peptide domain[16].Mechanism of action of Smart antimicrobial peptide (Fig.11)

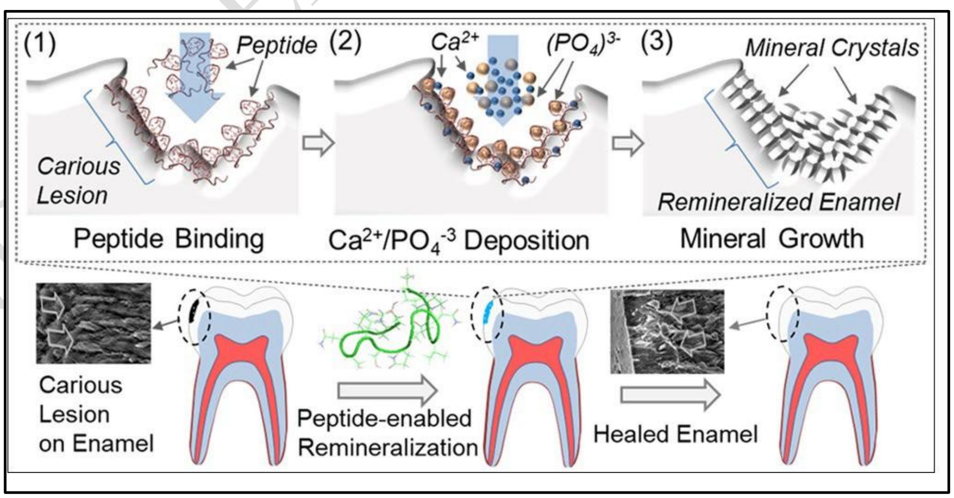


Fig.11: Smart antimicrobial peptide

SMART FIBERS FOR LASER DENTISTRY

Transmission of high-energy laser pulses capable of ablating dental tissues is a crucial issue in laser dentistry (Wigdor et al; Fried; Strassl et al).

Hollow-core photonic fibers for the delivery of high-fluence laser radiation capable of ablating tooth enamel have been developed. These photonic fibers are known as smartfibers (Fig.12)[17].

Fig. 12: Smart fiber tips for laser dentistry

NICKEL-TITANIUM (NITI) ALLOYS: FIRST SMART MATERIAL

The term "smart material" or "smart behavior" in the field of dentistry was probably first used in connection with Nickel-Titanium (NITi) alloys, or shape memory alloys (SMAs), which are used as orthodontic wires. The shape memory alloys constitute a group of metallic materials with the ability to recover a previously defined length or a shape when subjected to an appropriate thermomechanical load. 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. who created and patented Nitinol, a nickel-titanium (NITi) alloy in the Naval Ordinance Laboratory (NOL) in Silver Springs, Maryland, USA.

Shape memory alloys have come into wide use because of their exceptional superelasticity, their shape memory (Fig.13),their good resistance to fatigue and wear, and their relatively good biocompatibility. They currently seem to hold the most promise in radiology, cardiovascular applications, urology, and other medical applications for use as prostheses, tissue connectors, and endovascular stents. As in dentistry they are noted for their contribution as NiTi files,rotary instrument(Fig.14), NiTi orthondontic wires ,NiTi bone plates etc[18].Mechanism of action of NiTi alloy (Flow chart 10).

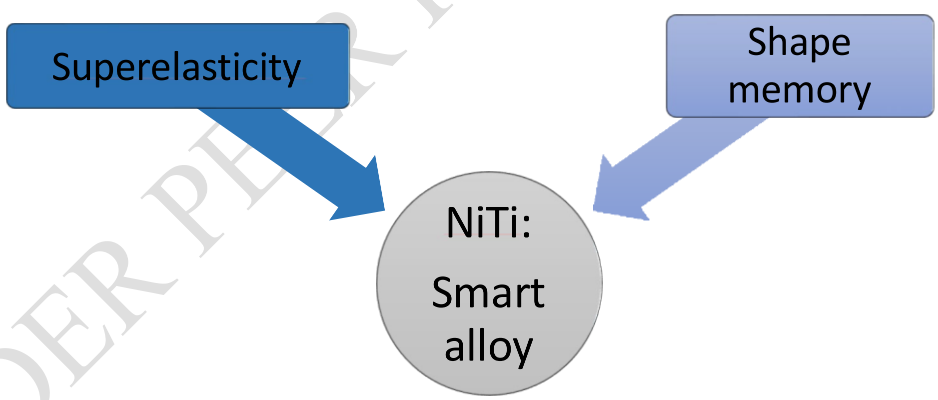


Fig.13: Properties of Ni-Ti smart alloys.

Martensitic phase ←→ Austenitic phase (high strength)

↓

Austenitic phase cool down to

↓

Martensitic phase (low strength)

↓

It is easy to bend

↓

It will release the stress

↓

Structure recovers to Austenitic phase and regain its original memory

↓

It is known as “Stress induced thermoelastic transformation”

Flow chart 10: Mechanism of action of smart memory alloy

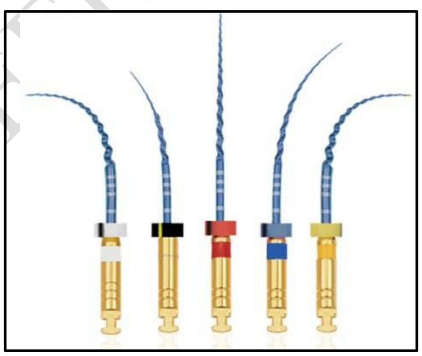


Fig.14: NiTi rotary files

SMARTSEAL OBTURATION SYSTEM

The Smartseal Obturation System aims to prevent periradicular disease by filling the instrumented canal, accessory canals, and dead spaces.(Fig.15) The C Point System is a point-and-paste technique with hydrophilic endodontic points and a sealer[19](Fig.16).

Smartseal Bio is a resin-based sealant that inflates when ground polymer is added, providing nonresorbability and dimensional stability. It is highly biocompatible, antibacterial, hydrophilic, and has a delayed setting time (4-10 hours). Both systems aim to minimize voids and prevent the growth of residual biofilms[20](Fig.17) .

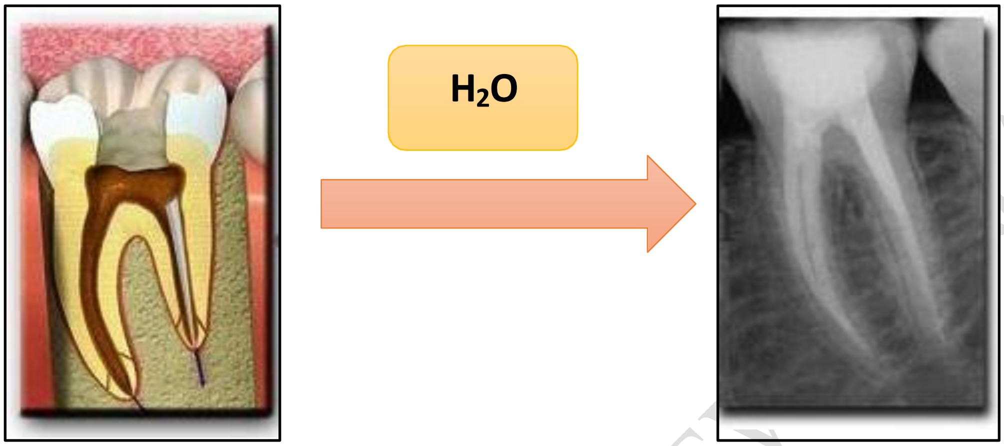


Fig. 15:Smart seal obturation

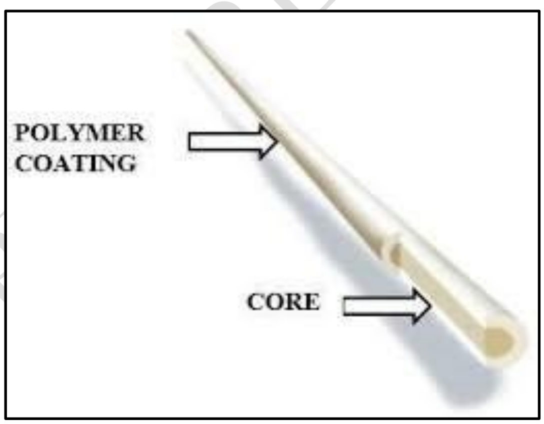


Fig.16: Structure of C-point (hydrophilic endodontic points simulating conventional Gutta percha points).

Fig. 17: Smartpaste bio sealer

CONCLUSION

In the 21st century, the development of smart materials has led to the creation of environmentally friendly and responsive materials. These smart materials can adapt to changes in their environment and fulfill specific purposes, offering potential for biosmart dentistry. Dental professionals should be aware of these cutting-edge materials to use them effectively in their daily work. Recent developments in "stimuli-responsive" materials, such as stress, moisture, temperature, pH, electric field, or magnetic field, have opened up new possibilities for dental therapy. These intelligent materials can intelligently perform functions in response to changes in the environment, making dental therapy more comfortable and efficient. As the field of bio-smart dentistry continues to grow, more material science research is needed to advance this promising new generation of materials.

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