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Smart Materials In Orthodontics-A Review

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Abstract: Smart materials are engineered substances that can change their physical or chemical properties when exposed to certain external stimuli. They have emerged as transformative components in dentistry including modern orthodontics. These materials offer dynamic functionality and adaptability in clinical settings, enhancing treatment effectiveness, appliance precision, and patient experience. This review synthesizes current knowledge on smart materials used in orthodontics, including their classification, working mechanisms, clinical relevance, benefits, challenges, and future scope.

Keywords- Smart materials, Orthodontics, Shape memory alloys, Shape memory polymers,Nanotechnology.

1. Introduction

Orthodontics has evolved significantly, moving beyond traditional biomechanics towards biologically responsive and technology-integrated strategies. Among these innovations, smart materials stand out for their unique ability to adapt to intraoral conditions and deliver precise, controlled force systems. Their use spans a variety of orthodontic components, facilitating more efficient and patient-friendly treatments.

Smart materials can be active or passive.Passive are those materials react to external stimuli without any control. For instance, glass ionomer cement, compomers, resin-modified glass ionomer cement, etc release fluoride ions continuously. Active materials react favourably to the surrounding environment only when the need arises[1].

Stress, temperature, moisture and pH, and electric or magnetic fields are some of the environmental factors that can change the properties of smart materials.A main feature of smart behavior is the capacity to return to the original state even after the stimulus has been eliminated. The numerous applications of smart materials have revolutionized they have revolutionized many areas of dentistry including orthodontics[1].

2. Types of Smart Materials in Orthodontics

2.1 Shape Memory Alloys (SMAs)

Nickel-Titanium (NiTi) alloys are among the most commonly adopted smart materials due to their temperature-sensitive phase transitions, which enable controlled force delivery. It has two salient features namely shape memory effect (enables the material to revert to a predefined shape upon heating) and superelasticity (recovery from deformation without permanent alteration). Employed in archwires, coil springs, and temperature-responsive wires for initial alignment phases due to their ability to apply continuous gentle forces on the teeth which are in physiologic range over a longer period of time [2,3].

2.2 Shape Memory Polymers (SMPs)

SMPs attain their original shape when deformed by applying any of the recovery triggers such as light, heat, electrical or magnetic fields, infrared radiation or immersion in water due to interatomic bonds [4]. These polymers can be programmed to change shape when exposed to stimuli like temperature or pH, offering potential applications in customizable orthodontic aligners and brackets.

Their advantages include easy workability, low density, reduction in cost and esthetically pleasing being transparent in nature [5]. Their shape returning force lasts approximately for 3 months [6]. They generally have a glass transition temperature, which is near the body temperature [7]. These polymers have increased utility in the correction of malaligned and severely rotated teeth [8].

2.3 Piezoelectric Materials

These substances generate an electric charge in response to mechanical stress. While still under exploration, their role in stimulating cellular activity during tooth movement is a promising area for future research.

2.4 pH-Sensitive Materials

Smart glass ionomers and composites are designed to release therapeutic ions such as fluoride in acidic environments, to serve a preventive role by reducing the risk of enamel decalcification during orthodontic treatment.

2.5 Magneto-Responsive and Electroactive Polymers

These materials respond to magnetic fields or electric currents and are being investigated for applications in remotely controlled or self-adjusting orthodontic devices.

2.6 Nanomaterials

Nanocomposites have filler particles of size 0.005-0.01 micron which improves compressive strength, tensile strength and fracture resistance making them more suitable for bonding of brackets and orthodontic auxiliaries [9]. Elastomeric ligatures having anti-inflammatory, antibiotic drug molecules and anticariogenic nanoparticles embedded in their matrix are a boon in orthodontic practice [10]. SMPs with nanocomposites used as esthetic archwires can produce continuous forces over a long range thus producing desirable tooth movements. Metallic nano particles coated on surfaces have antimicrobial benefits [9].

2.7 Nanodevices

Nano electromechanical systems (NEMS) are nano devices which integrate mechanical and electrical functions at nanoscopic levels thus producing enhanced orthodontic tooth movements. Nano LIPUS (Low intensity pulsed ultrasound) are very efficient in supporting the osseous growth after distraction osteogenesis and upon the insertion of titanium porous surface coated implants. It also reduces root resorption associated with the orthodic therapy [9].

2.8 Self-healing materials

These materials are incorporated with nanosized bubbles filled with auto-polymerised monomer which are mainly used for arch wires and brackets.
When a bracket breaks, particles scatter and the monomer leaks in the air, creating space which is polymerised and filled [11]. This results in a minimized damage to the brackets and archwires and simultaneously leads to an overall reduction in treatment duration [8].

2.9 Biomimetic adhesives

Brackets bases covered with L-3,4-dihydroxyphenylalanine (DOPA), an important glue protein of mussels, provides sufficient bond strength with the enamel surface [12]. Hence, enamel conditioning before bonding would not be required and the structural changes to enamel are minimized [8].

2.10 Biodegradable mini-implants

These are made of polylactic and polyglycolic acid (PLA/PGA) [13,14]. These materials have simpler compounds that can easily be excreted from the body making them ideal to be used as temporary anchorage devices in orthodontic treatment. By altering their ratio, change in the degradation, excretion rate and biomechanical properties of these implants can be achieved [15].

3. Clinical Applications

3.1 Archwires

Thermally activated NiTi wires provide low, continuous forces over extended activation ranges, contributing to more efficient and comfortable tooth movement. Nanomaterials incorporated into arch wires offers friction free orthodontic arch wires

3.2 Smart Bracket

Smart brackets have a nanomechanical stress sensor system implanted in their base for evaluating three dimensional forces and moments experienced by it. This helps in measuring the forces and moments and thus helps in frequent utilization of two couple system in orthodontics. They provide favourable tooth movement within biological range and minimal side effects [8,16].

Telemetric smart bracket involves a sensor system equipped with a slot component of the standard ceramic bracket that could be telemetrically read out over a distance sufficient to allow contactless operation in orthodontic applications [17]. Improving the accuracy of force measurements and integrating components for telemetric energy transmission and data communication defines the next steps towards intelligent orthodontic appliances based on smart brackets [18].

3.3 Self-Ligating Brackets

When integrated with smart materials, self-ligating systems can offer better control over friction and force modulation, supporting quicker and more predictable treatment outcomes.

3.4 Clear Aligners

Emerging research into SMPs suggests their potential use in aligners that adapt to temperature shifts, allowing stage-by-stage force delivery without needing manual replacement.

3.5 Adhesives and Bonding Agents

Innovative bonding systems containing pH-responsive materials can proactively manage enamel demineralization by releasing ions in cariogenic conditions.

3.6 Removable Devices and Functional Appliances

By incorporating smart polymers, these appliances can achieve a better adaptive fit, improving function and patient compliance.

4. Advantages of Smart Materials

- Deliver biologically favorable, light, and consistent forces
- Minimize need for frequent adjustments
- Enhance comfort and aesthetics, especially with transparent materials
- Enable potential integration with monitoring technologies for remote supervision

5. Limitations and Challenges

- Higher manufacturing costs compared to conventional materials
- Risk of allergic reactions or biocompatibility concerns (e.g., nickel sensitivity)
- Sensitivity to handling conditions and environmental stability
- Need for more robust long-term clinical data and regulatory guidance

6. Future Perspectives

Combining smart materials with digital workflows—such as 3D printing, artificial intelligence, and CAD/CAM systems—promises the development of individualized and minimally invasive orthodontic protocols. Technologies like sensor-enabled feedback systems and remotely activated components may redefine clinical management in orthodontics.

7. Conclusion

The integration of smart materials has significantly enhanced orthodontic care, providing clinicians with tools that improve precision, reduce treatment duration, and elevate patient experience. Continued interdisciplinary research will be crucial in validating these innovations and expanding their clinical applicability.

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