Biomaterials: Properties, Types and applications

Part II- Ceramics

MECH 634- SPRING SEMESTER 2010

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OUTLINES

Biomaterials: Properties, Types, and Applications

4.1 Ceramics properties and application
4.2 Case study

Ceramic Biomaterials (Bioceramics)

- The class of ceramics used for repair and replacement of diseased and damaged parts of the musculoskeletal system are referred to as **bioceramics**.

- **OBJECTIVES**
  - To examine chemical/physical properties of ceramics
  - To introduce the use of ceramics as biomaterials
  - To explore concepts and mechanisms of bioactivity

Ceramics

- *(keramikos- pottery in Greek)*

- Ceramics are polycrystalline compounds
  - Usually inorganic
  - Highly inert
  - Hard and brittle
  - High compressive strength
  - Generally good electric and thermal insulators
  - Good aesthetic appearance

- Applications:
  - orthopaedic implants
  - dental applications
  - compromise of non-load bearing for bioactivity

Types of Bioceramics

TABLE 1.3. Ceramics Used in Biomedical Applications

Ceramic	Chemical Formula	Comment
Alumina	Al_2O_3	Bioinert
Zirconia	ZrO_2	
Pyrolytic carbon		
Bioglass	$Na_2OCaOP_2O_3{-}SiO$	Bioactive
Hydroxyapatite (sintered at high temperature)	$Ca_{10}(PO_4)_6(OH)_2$	
Hydroxyapatite (sintered at low temperature)	$Ca_{10}(PO_4)_6(OH)_2$	Biodegradable
Tricalcium phosphate	$Ca_3(PO_4)_2$	

Mechanical Properties

TABLE 1.4. Mechanical Properties of Ceramic Biomaterials*

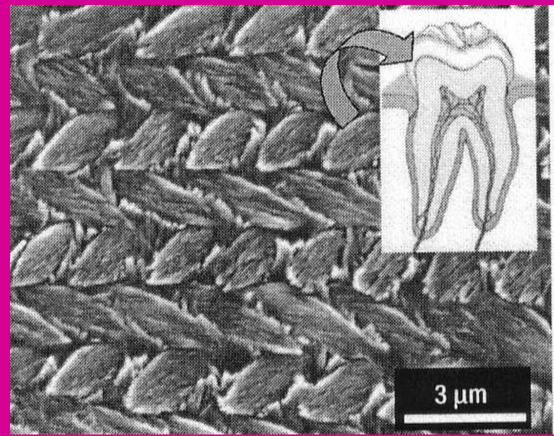
	Young's Modulus, E (GPa)	Compressive Strength, σ_{UCS} (MPa)	Tensile Strength, σ_{UTS} (MPa)
Alumina	380	4500	350
Bioglass-ceramics	22	500	56–83
Calcium phosphates	40–117	510–896	69–193
Pyrolytic carbon	18–28	517	280–560

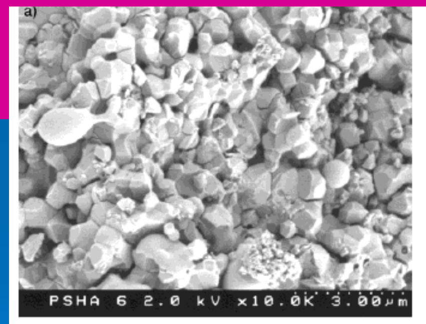
Summary of the physical and mechanical properties of various implant materials in comparison to natural bone

Properties	Natural bone	Magnesium	Ti alloy	Co–Cr alloy	Stainless steel	Synthetic hydroxyapatite
Density (g/cm^3)	1.8–2.1	1.74–2.0	4.4–4.5	8.3–9.2	7.9–8.1	3.1
Elastic modulus (Gpa)	3–20	41–45	110–117	230	189–205	73–117
Compressive yield strength (Mpa)	130–180	65–100	758–1117	450–1000	170–310	600
Fracture toughness (MPam$^{1/2}$)	3–6	15–40	55–115	N/A	50–200	0.7

Nature's Ceramic Composites

- Natural hard tissues are "ceramic"-polymer composites:
  - Bones, Teeth
- Tissue = organic polymer fibers + mineral + living cells
- Mineral component (Ceramic)
  - Bone: hydroxyapatite (HA) – $Ca_5(PO_4)_3OH$
- Mineralization under biological conditions:
  - Many elemental substitutions
  - Protein directed crystallization
  - Unique characteristics – crystal morphology and solubility
- Synthetic calcium phosphates are used as biomaterials – "bioactive"





Synthetic HA

Bone HA

Bioactivity vs. Biocompatibility

- Biocompatibility :
- Objective is to minimize inflammatory responses and toxic effects

- Bioactivity - Evolving concept:
  - The characteristic that allows the material to form a bond with living tissue (Hench, 1971)
  - The ability of a material to stimulate healing and trick the tissue system into responding as if it were a natural tissue (Hench 2002).
  - Advantages: Bone tissue – implant interface, enhanced healing response, extends implant life

- Biodegradability:
  - Breakdown of implant due to chemical or cellular actions
  - If timed to rate of tissue healing transforms implant to scaffold for tissue regeneration
  - Negates issues of stress shielding, implant loosening, long term stability

Inert Ceramics: Alumina

- History:
  - since early seventies more than 2.5 million femoral heads implanted worldwide.
  - alumina-on-alumina implants have been FDA monitored
  - over 3000 implants have been successfully implemented since 1987

Smaller the grain size and porosity, higher the strength

- E = 380 GPa (stress shielding may be a problem)

High hardness:

- Low friction
- Low wear
- Corrosion resistance

Friction: surface finish of <0.02 um

Wear: no wear particles generated – biocompatible

Inert Ceramics: Aluminum Oxides (Alumina – Al_2O_3)


- Applications
  - orthopaedics:

    - femoral head
    - bone screws and plates
    - porous coatings for femoral stems
    - porous spacers (specifically in revision surgery)
    - knee prosthesis
  - dental: crowns and bridges

Alumina

Bioinertness

- Results in biocompatibility – low immune response

- Disadvantage:
  - Minimal bone ingrowth
  - Non-adherent fibrous membrane
  - Interfacial failure and loss of implant can occur

Bioactive Ceramics: Glass Ceramics

- Glass:
  - an inorganic melt cooled to solid form without crystallization
  - an amorphous solid
  - Possesses short range atomic order → Brittle!

- Glass-ceramic is a polycrystalline solid prepared by controlled crystallization of glass

- Glass ceramics were the first biomaterials to display bioactivity (bone system):
- Capable of direct chemical bonding with the host tissue
- Stimulatory effects on bone-building cells

- Composition includes SiO_2, CaO and Na_2O
- Bioactivity depends on the relative amounts of SiO_2, CaO and Na_2O
- Cannot be used for load bearing applications
- Ideal as bone cement filler and coating due to its biological activity

Calcium (Ortho) Phosphate

- Structure resembles bone mineral; thus used for bone replacement
- 7 different forms of PO_4 based calcium phosphates exist - depend on Ca/P ratio, presence of water, pH, impurities and temperature

Calcium Phosphate

- Powders
- Scaffolds
- Coatings for implants – metals, heart valves to inhibit clotting
- Self-Setting bone cement

	Name	Acronym	Formula	Ca/P
1	monocalcium phosphate anhydrate	MCPA	$Ca(H_2PO_4)_2$	0.5
2(b)	dicalcium phosphate anhydrate	DCPA	$CaHPO_4$	1
3	octacalcium phosphate	OCP	$Ca_8(HPO_4)_2(PO_4)_4 5H_2O$	1.33
4(a)	alpha tricalcium phosphate	TCP	$Ca_3(PO_4)_2$	1.5
4(b)	beta tricalcium phosphate	TCP	$Ca_3(PO_4)_2$	1.5
5	amorphous calcium phosphate	ACP	$Ca_x(PO_4)_y nH_2O$	1.1-1.5
6(a)	hydroxyapatite	HA	$Ca_5(PO_4)_3OH$	1.67
6(b)	calcium deficient hydroxyapatite	cd-HA	$Ca_9(HPO_4)(PO_4)_5OH$	1.5
7	tetra calcium phosphate	TetCP	$Ca_4(PO_4)_2O$	2

Calcium Phosphates

- Uses
  - repair material for bone damaged trauma or disease
  - void filling after resection of bone tumors
  - repair and fusion of vertebrae
  - repair of herniated disks
  - repair of maxillofacial and dental defects
  - ocular implants
  - drug-delivery
  - coatings for metal implants, heart valves to inhibit clotting

Why Use Bioceramics?

General Options	Toxic/ Imunogenic/ Disease transmission?	Mechanical Properties?	Bioactive?	Degradable?
Autograft	Excellent	Excellent	Excellent	Excellent
Allograft	Low	Excellent	Moderate	Moderate
Metals	Moderate	Excellent	Low	Low
Ceramics	Excellent	Low	Excellent	Excellent
Polymers	Moderate	Moderate	Moderate	Moderate
Composites				

Excellent
Moderate
Low

Advantages to Bioceramics:

- Biological compatibility and activity
- Less stress shielding
- No disease transmission
- Unlimited material supply

Disadvantage of Bioceramics:

- Brittleness – not for load bearing applications

Pros and Cons Ceramics and glasses

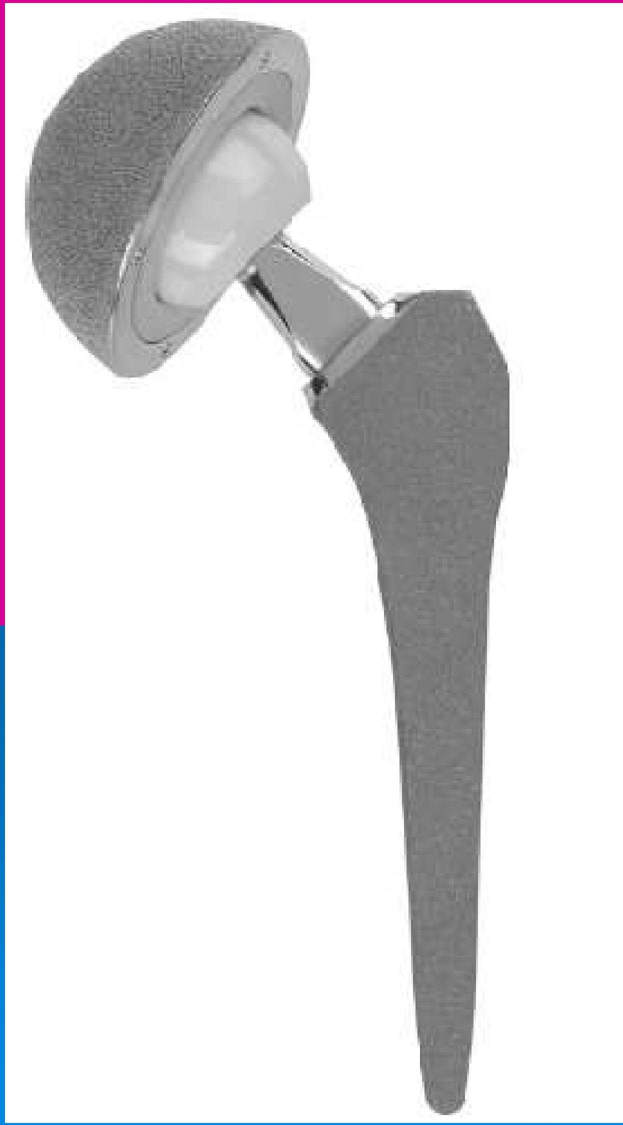
Advantages

- Very biocompatible (particularly with bone)
- Inert
- Low wear rates
- Resistant to microbial attack
- Strong in compression

Disadvantages

- Brittleness
- Potential to fail catastrophically
- Difficult to machine

Ceramics and glasses-Application 1-déjà vu!



In this artificial hip joint, the polymer bearing surface and some of the metallic components have been replaced by ceramics to improve the durability of the joint replacement. This design features a ceramic femoral head and acetabular cup. (Photograph of the LINEAGE 1 ceramic– ceramic acetabular cup system is courtesy of Wright Medical Technology, Inc.)

Due to the high melting point of most ceramics, which prevents them from being cast or extruded, ceramic components are typically made from powdered stock.

the porosity must be nearly totally removed or the residual porosity acts as microcracks within the material and weakens it.

In other applications such as bone graft substitutes it is desirable to have large pores like those in trabecular or cancellous bone so that cells can infiltrate the material and grow new vital tissue. In this case, pores are typically created by using second phases, such as polymer beads, that maintain pore space during the early processing steps and are then burned out during the final sintering stage.

If there is an insufficient amount of the patient's own bone or donor bone available to fill a bone defect, synthetic bone graft substitutes made of calcium phosphate or calcium sulfate may be used. (Photograph of OSTEOSET1surgical grade calcium sulfate resorbable beads is courtesy of Wright Medical Technology, Inc.)

Homework II

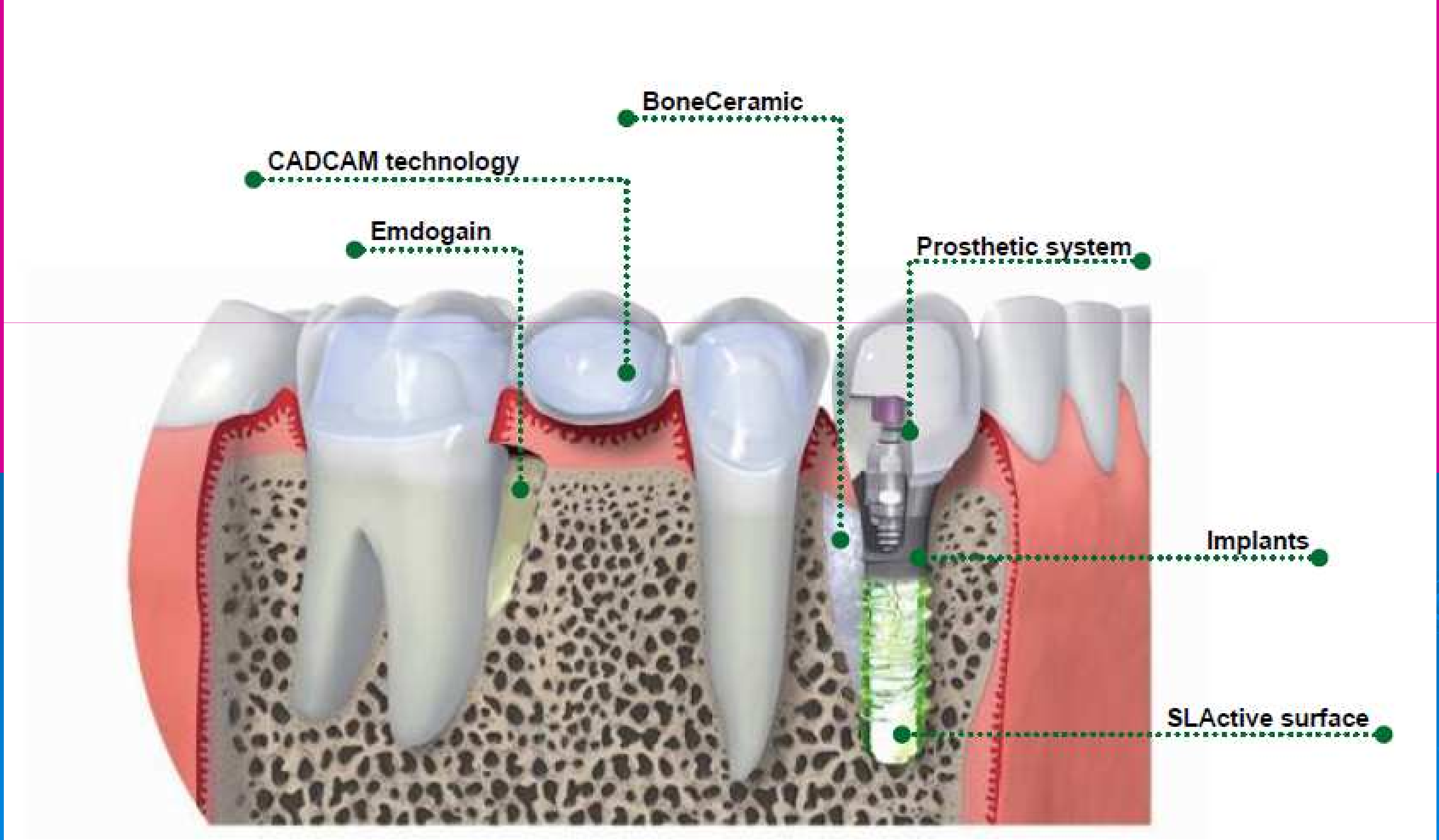
What material is preferred for the acetabular cup of a hip implant? What design parameters are utilized during the selection process? Use scientific, corporate, and patent websites to locate information on this topic using keywords such as "ceramic" and "hip replacement."

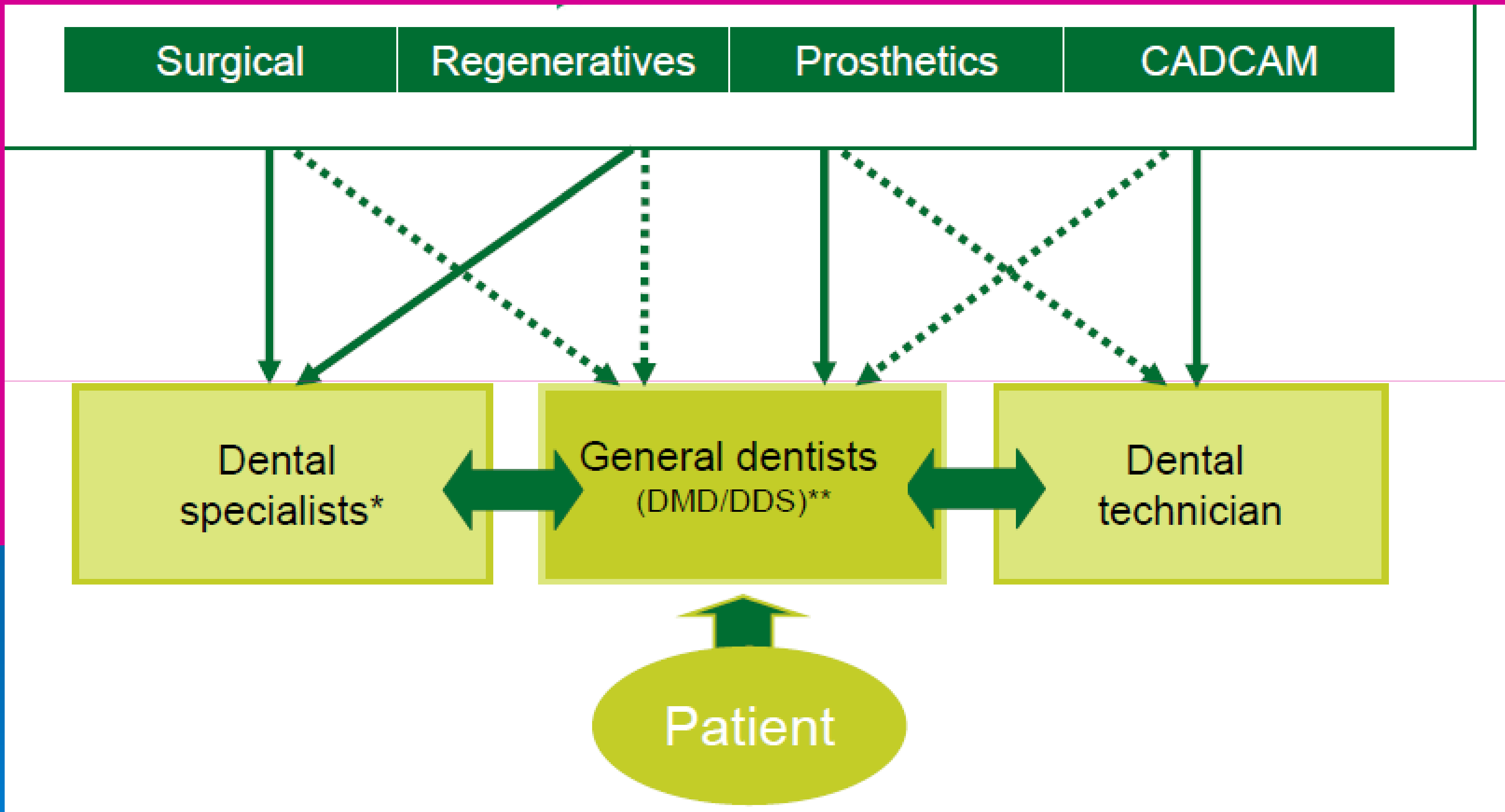
Case Study for Ceramics

- Quality
- Esthetics
- Precision

DENTAL IMPLANTS AND USE OF CERAMICS

Dental Prosthesis-Strautman-Germany



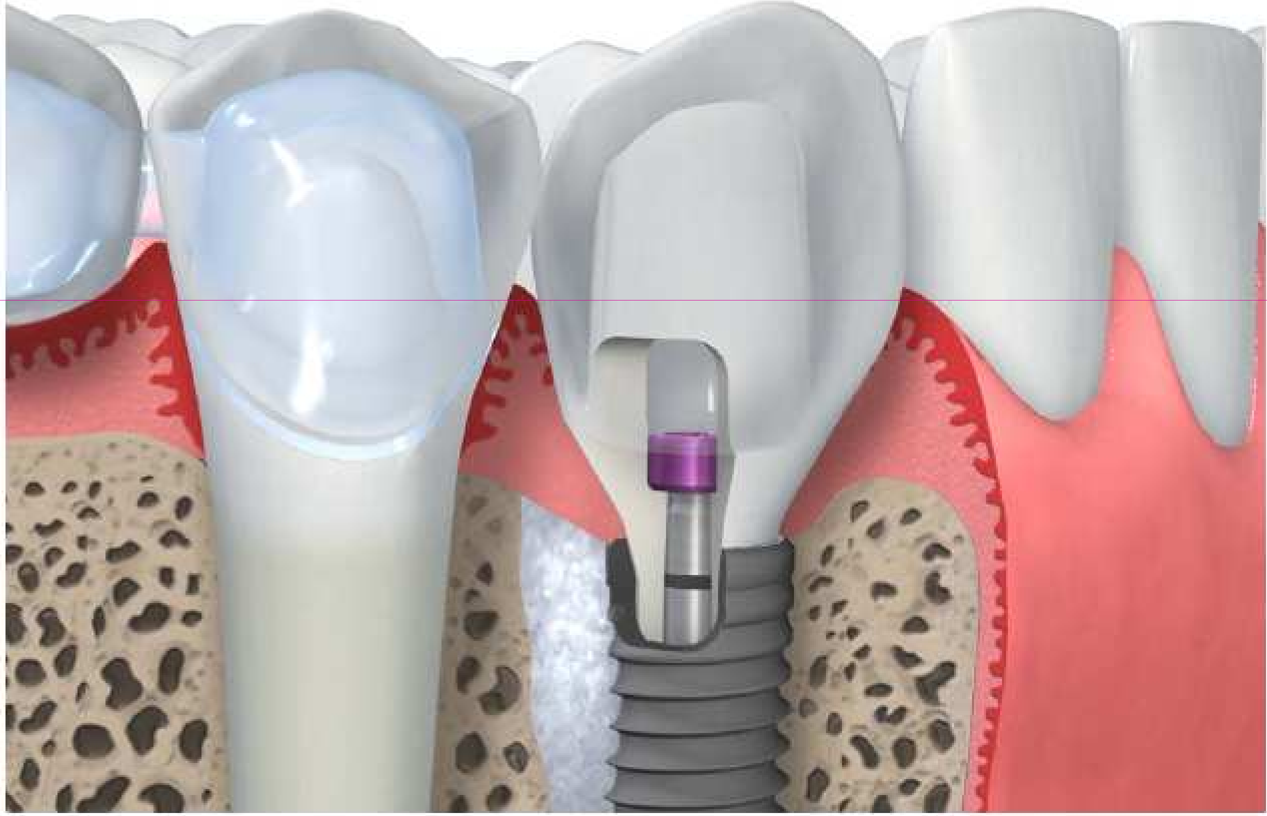

Surgical
Regeneratives
Prosthetics
CADCAM
Dental specialists*
General dentists
(DMD/DDS)**
Dental technician
Patient

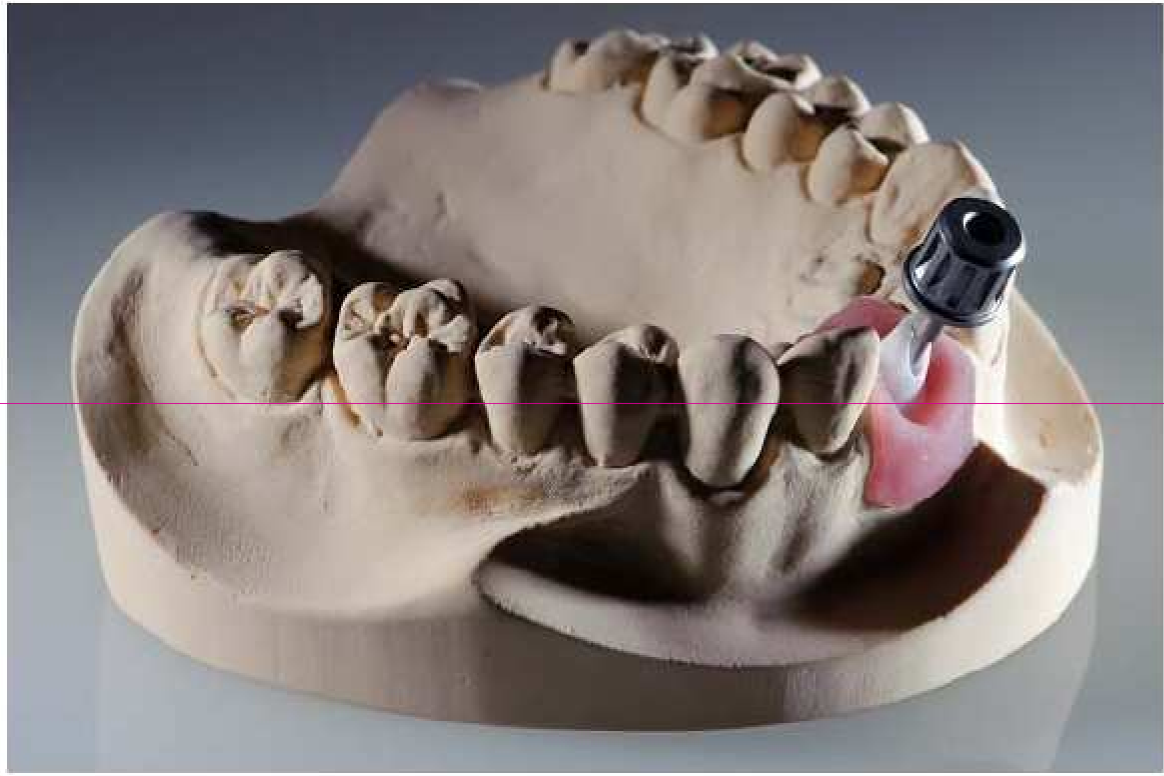

OPEN SYSTEM
1. Treatment plan
2. Fabrication of scan prosthesis
3. CT scanning
4. Software based planning
Fabrication of surgical template

- Minimal bone loss

- Perfect complement to tissue level range
- Maximum flexibility, minimum complexity: small number of components covering all indications and preferences

The champion's secret is… functionality, reliability, and esthetics





- A standardized premium ceramic restoration with prepared mucosa margins for perfect esthetics and high stability
- Highly flexible: two gingival heights, two shades, two configurations (straight and angled); easily shaped by grinding
- Outstanding mechanical strength and durability
- Produced in IPS e.max zirconium dioxide ceramic exclusively for Straumann by...

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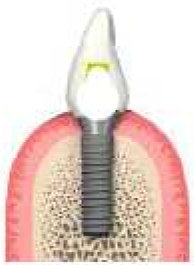
All the benefits of the Bone Level Implant system

Consistent Emergence Profiles™
- Matching geometries
- Soft tissue management

SLActive® surface
- Fast healing
- Higher security

CrossFit™ Connection
- Precise tight fit
- Easy handling

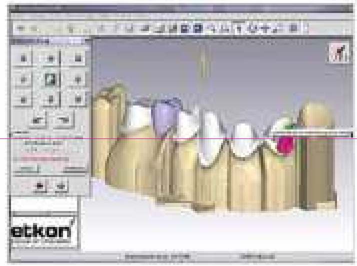


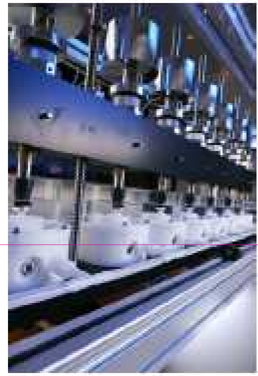
Bone Control Design™
- Bone preservation
- Tissue stability

CrossFit™ Plan Set

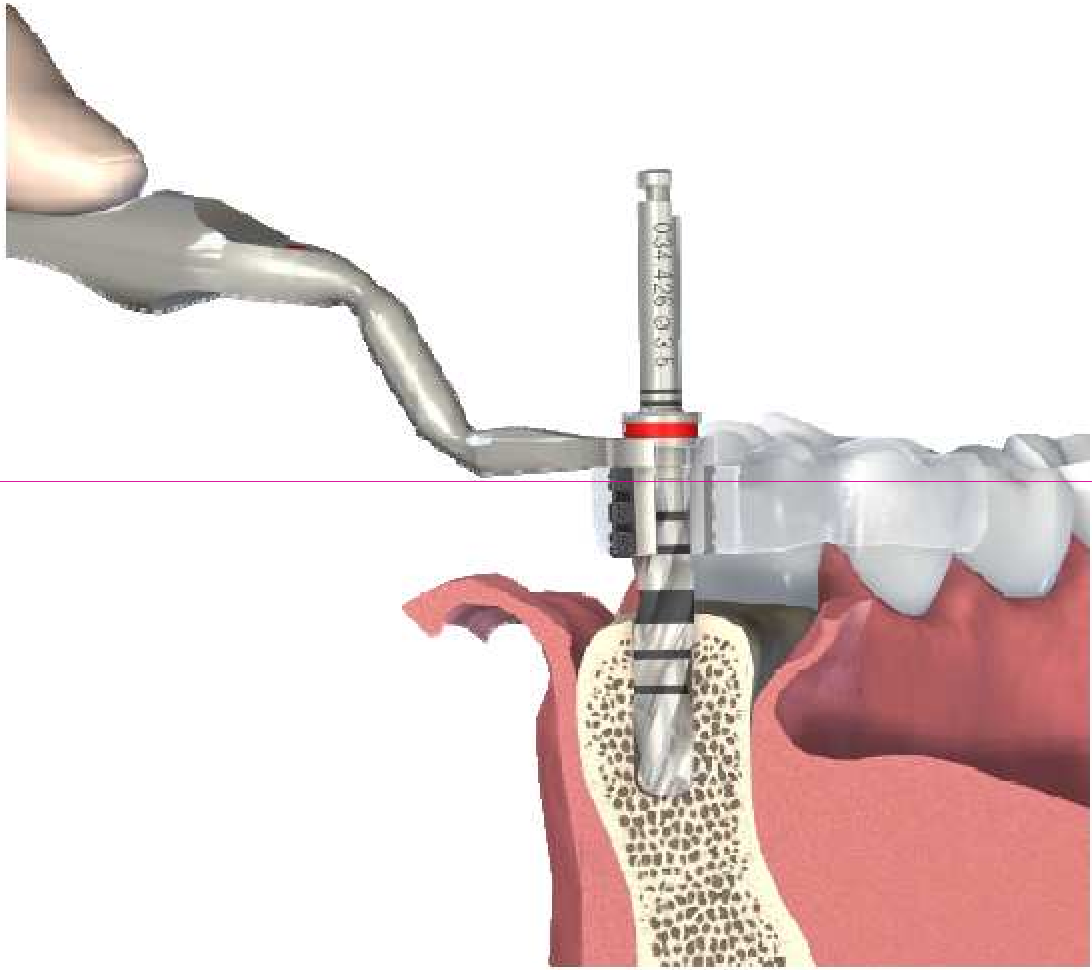
- Highly esthetic, translucent, colorable material for natural looking restorations
- High strength (360 MPa), quality and durability
- Clinically proven material

Integrated processes, compliant with medical device regulations (MDD, FDA)

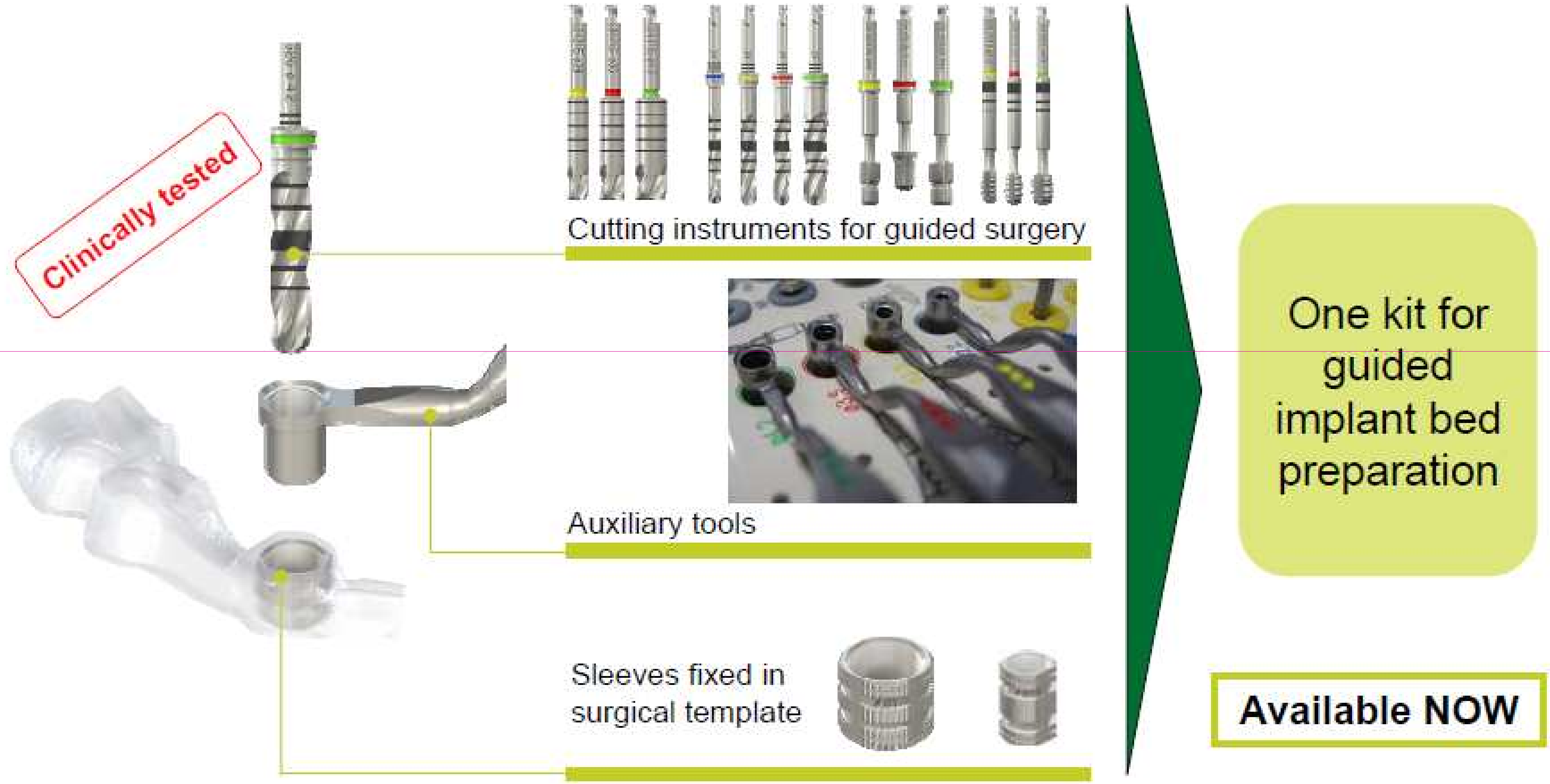




Scan model → Design restoration → @ Centralized milling → Finishing (ceramic layer, coloring)



Increased safety for implant placement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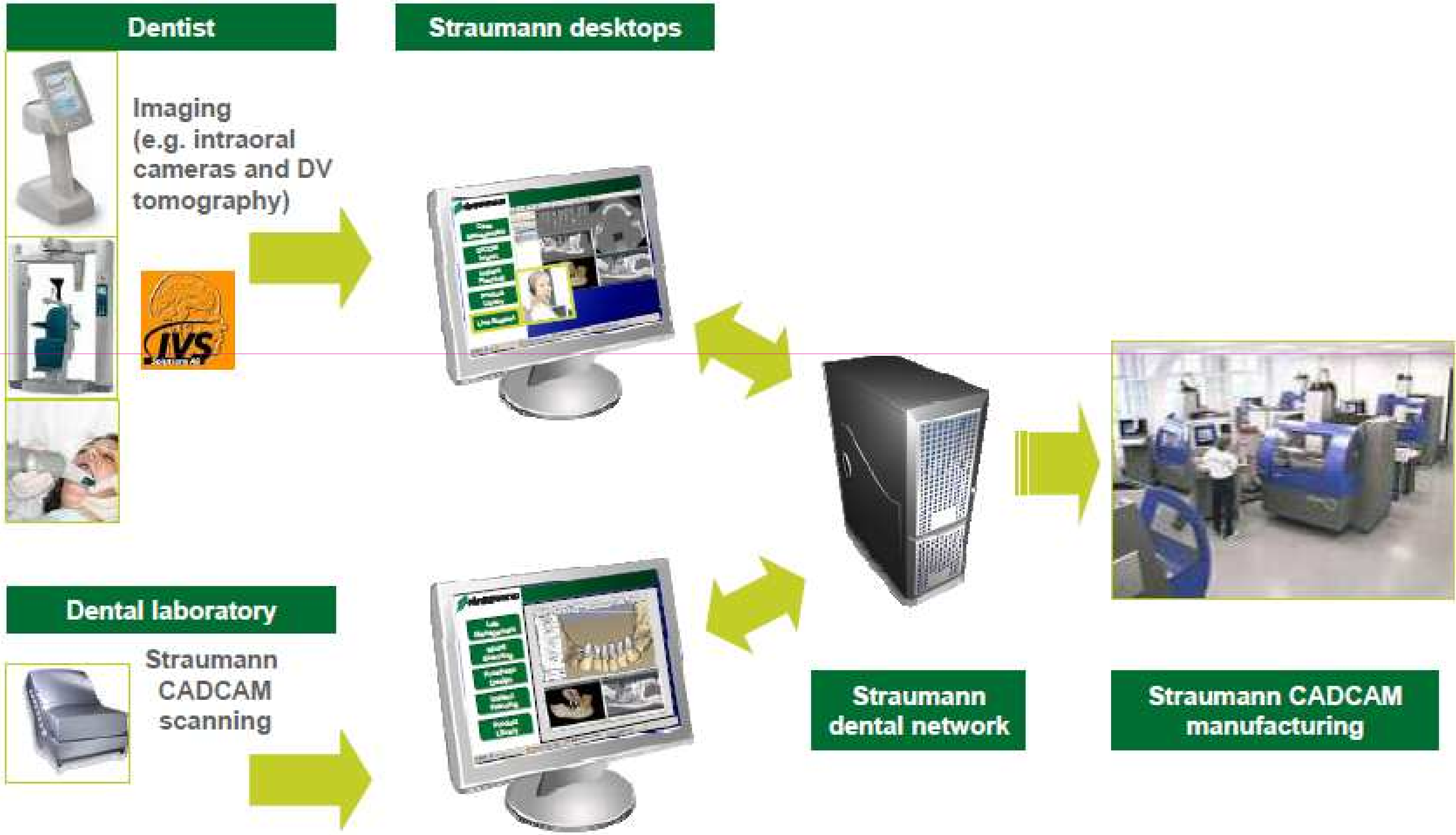
The changing face of dentistry: the digital worktop



quality

Innovative, state-of-the-art concepts and products
Rigorously tested in clinical centers and everyday practice
Backed by peer reviewed publications
Tested premium titanium, stringent in-process quality checks
After-sales support, 'hotline'
Convenient ordering and delivery
Quality education and training
Guarantee and support
Certainty of replacement
Network (ITI etc)
Transparency