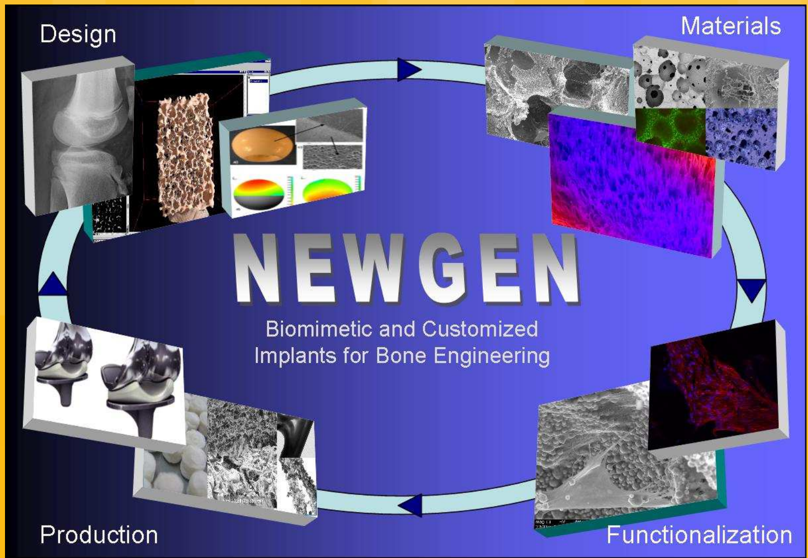
Science des Procédés Céramiques et de Traitements de Surface

Additive manufacturing of bioceramic scaffolds: State of the art



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CNRS
Université de Limoges

COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

NEWGEN, Sofia, October 13-14, 2015

Background

Scaffolds for bone tissue engineering: several requirements

(PV Giannoudis, TA Einhorn, G Schmidmaier, D Marsh. The diamond concept - open questions. Injury, 2008)

(JR Jones, LL Hench. Regeneration of trabecular bone using porous ceramics. Current Opinion Solid State Mater Sci, 2003)

Osteoinduction

Biocompatibility

Resorbability

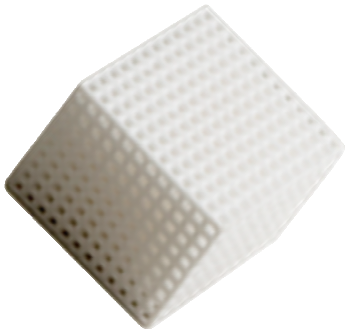
3D porous template

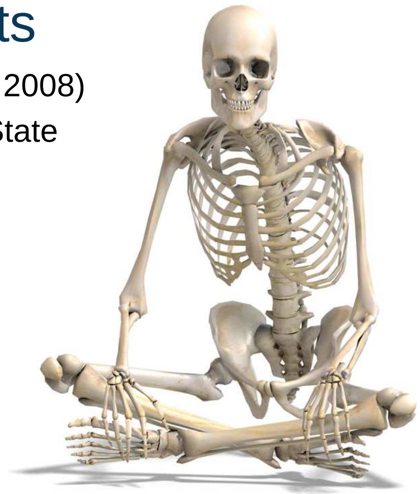
Osteoconduction

Mechanical Stability and stiffness to constructs

Vascularization

Match the defect shape





Calcium phosphates   **Architectural design**

Pores: size, geometry and 3D network at the microscopic scale

Scaffold shape: complex 3D geometry at the macroscopic scale

Customized implants

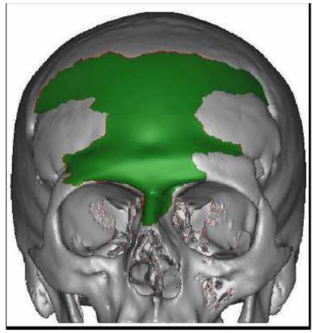
Background

Additive Manufacturing

- Technologies implemented to produce prototypes or parts, within a short time, via an automated process.
- CAD/CAM using (generally) layer-by layer fabrication procedure.
- Initially set up for polymers and metals
- Some have been adapted to the shaping of 3D ceramic parts

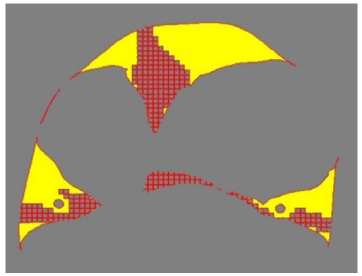
Versatile technologies of particular interest in the biomedical field

Example. HA cranio-facial implant



CAD of implant

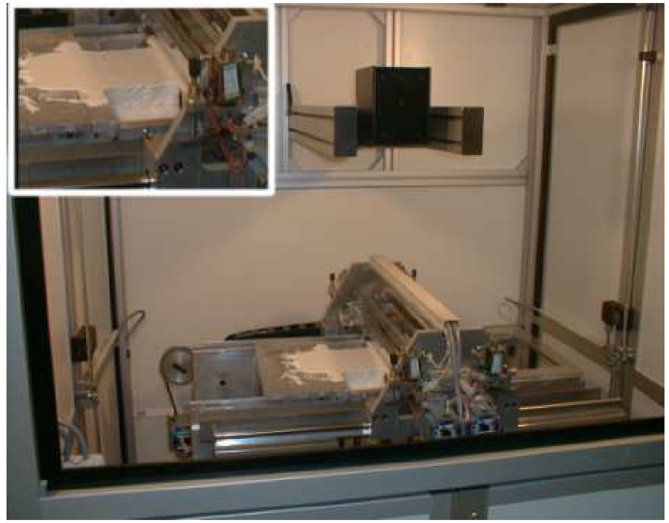
CAD in STL format (including shrinkages & strains)



2D Slicing

Additive Manufacturing

Cleaning

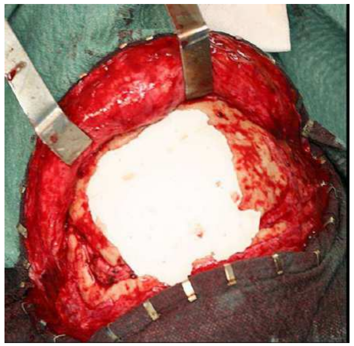


Stereolithography

Debinding | Sintering

Final ceramic implant

Check of the geometry on the skull model



Surgery

AM technologies

3D AM techniques	Tolerance	Advantages	Limitations
Material extrusion	1 mm	- Ease of support removal - Good mechanical properties - No material waste	- Precision limited by the filament diameter
Selective laser sintering	0.2 to 0.5 mm	- High production rates, low cost - Complex designs - Good surface finishing	- High roughness of the surface - Poor mechanical properties - Limited to materials which absorb IR light
Binder jetting	0.05 to 0.1 mm	- Wide variety of materials - Simple technology	- High roughness of the surface - Expensive technology - Poor mechanical properties - Use of toxic organic binders
Vat photopolymerization	0.01 to 0.1 mm	- Complex designs - Good surface finishing - Good mechanical properties - High accuracy	- Expensive photosensitive resins - Cleaning step necessary - Control of the vertical accuracy

(T Chartier, C Dupas, M Lasgorceix, J Brie, E Champion, N Delhote, C Chaput. Review: Additive manufacturing to produce 3D ceramic parts. J Ceram Sci Tech, 2015)

AM technologies

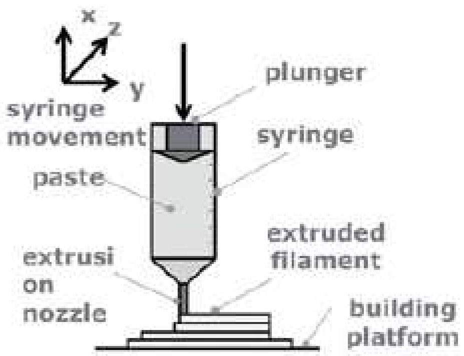
Type of feedstock	Habitus	Rheological and physical properties	Notes about processability	Technology	Notes about composition
Powder	Particle size > 20 µm >20 µm 80 µm> <80 µm	Solid	Poor flowability Good flowability Excellent flowability; high powder packing density	P-3DP P-SLS P-SLM	Several possible binder systems, organic or inorganic based.
Paste	Filament diameter 50 µm< <1000 µm	Viscosity:[107, 110, 146] 10–100 Pas @ 100 s^{-1} G′ (eq) = 10^5–10^6 Pa Yield stress 10^2–10^3 Pa	Shear thinning	DIW Robocasting	Ceramic solid loading 35–55 vol%. Use of flocculated suspensions or of polymeric binders
	100 µm< <1000 µm			FDM	Typical ratio ceramic/polymer = 60/40 vol
Suspension	Layer thickness 10 µm< <50 µm	Viscosity:[11, 64] 100 mPa·s–110 Pa·s @ 100 s^{-1}	Shear thinning, suitable viscosity highly depends on the recoating system	SL	Typical composition includes: monomer, photoinitiator, dispersants Ceramic solid loading 40–60 vol%
	10 µm< <50 µm	Viscosity:[97, 98, 147, 148] 5–15 mPa·s @ 1000 s^{-1} Surface energy: 20–70 mN/m	Shear thinning	DIP	Solids loading 2–30 vol%
	50 µm< <200 µm	Viscosity:1 mPa·s–1 Pa·s	Shear thinning	S-3DP S-SLS	Water basedCeramic solid loading 30–50 vol%

(A Zocca, P Colombo, C Gomes, J Günster. Additive manufacturing of ceramics: issues, potentialities and opportunities. J Am Ceram Soc, 2015)

Material Extrusion

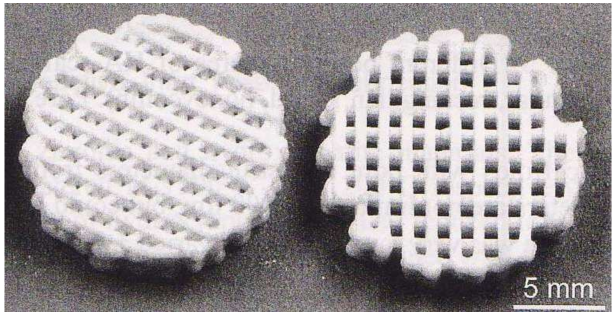
(Robotic dispensing, fused deposition modeling, 3D-printting, multiphase jet solidification)

Material (liquid or paste) is selectively extruded through a nozzle and deposited as rods

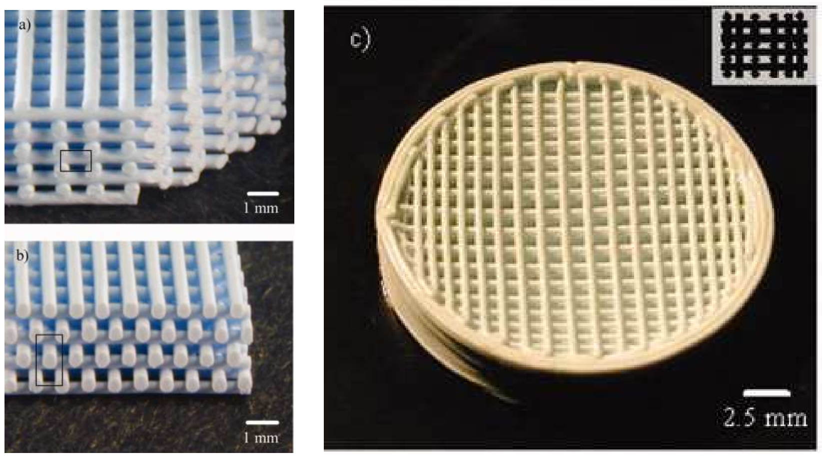


(A Zocca *et al*. J Am Ceram Soc, 2015)

Examples (sintered parts after shaping)



HA scaffolds with different pore geometries (U Deisinger *et al*. Key Engng Mat, 2008)



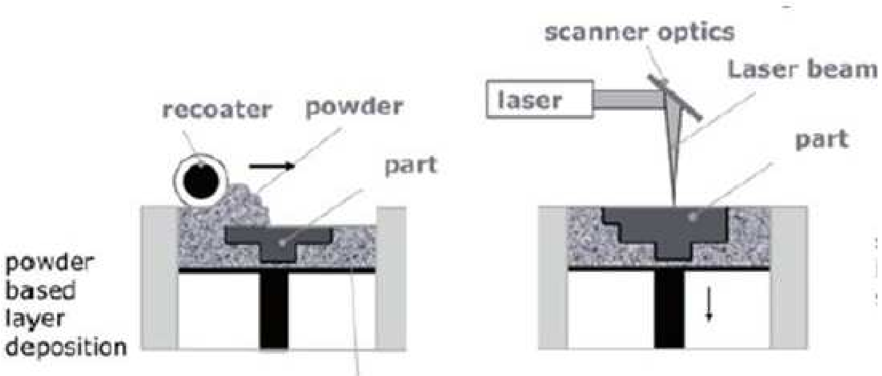
HA scaffold with multiscale porosity
(JG Dellinger *et al.* J Biomed Mater Res A, 2007)

Low accuracy

Selective Laser Sintering

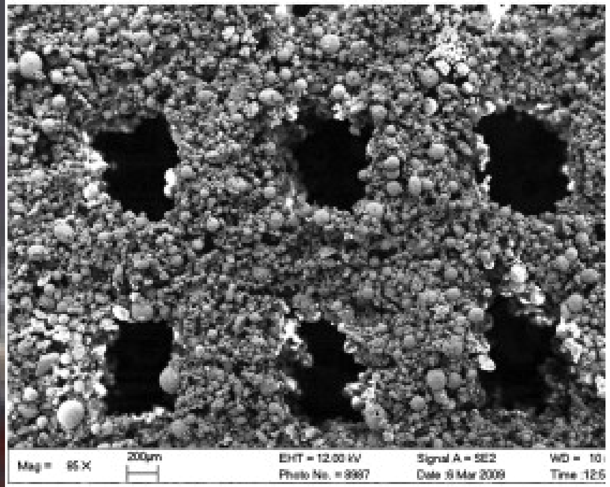
(Selective laser sintering, selective laser melting, electron beam metling)

Thermal energy (laser or electron beam) selectively sinters or melts scanned regions of a powder bed mixed with a binder



(A Zocca *et al*. J Am Ceram Soc, 2015)

Example



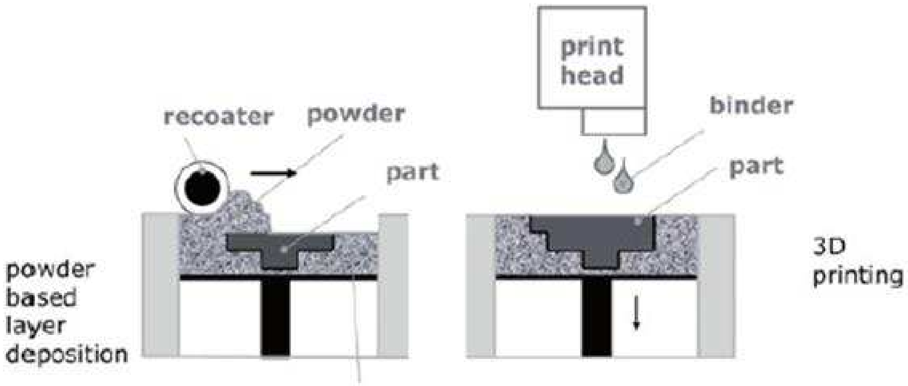
Ca-P/polymer scaffold.

(B Duan *et al*. Acta Biomater, 2010)

Low accuracy and mechanical properties

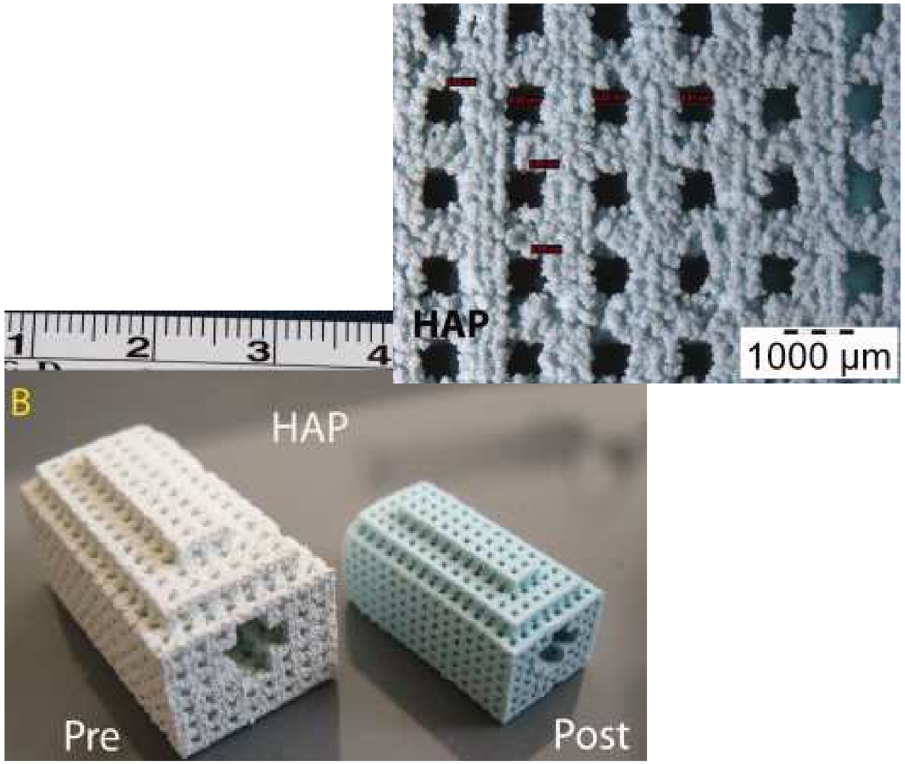
Binder Jetting

A liquid bonding agent is selectively deposited to consolidate a powder bed



(A Zocca *et al*. J Am Ceram Soc, 2015)

Example



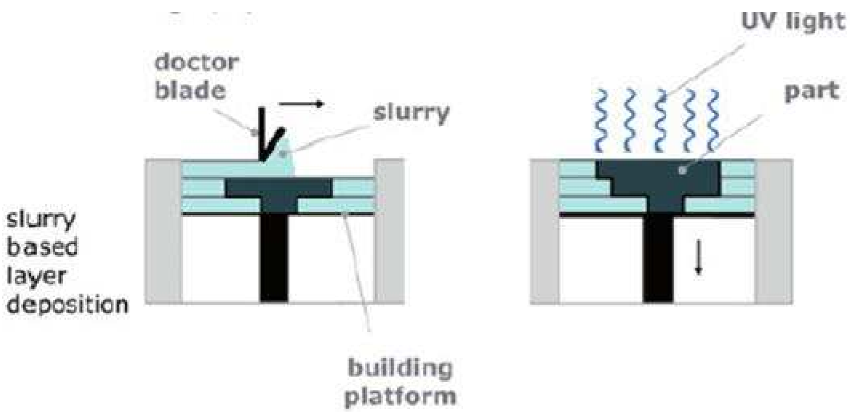
HA scaffold after shaping (Pre) and after sintering (Post).
(PH Warnke *et al*. J Biomed Mater Res B Appl Biomater, 2010)

Low mechanical properties

Vat Photopolymerization

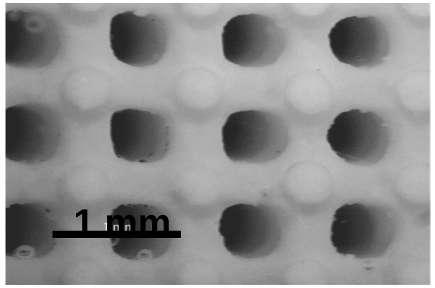
(stereolithography, microstereolithography)

A reactive suspension is selectively cured by light-activated polymerization



(A Zocca *et al*. J Am Ceram Soc, 2015)

Examples



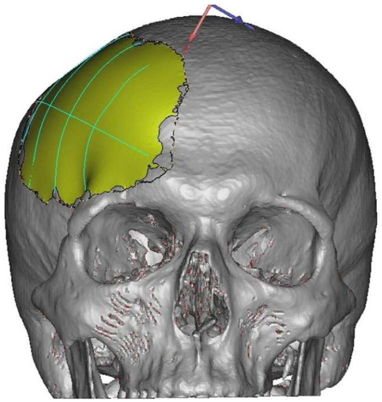
HA scaffolds (bone substitute & occular implant)

- Number of commercially available products
- On-demand large implants with complex shape

Good accuracy and mechanical properties

Vat photopolymerization (Stereolithography)

Example: On-demand cranio-facial implants made in hydroxyapatite



Efficiency of SLA to produce large complex ceramic implants or scaffolds but…

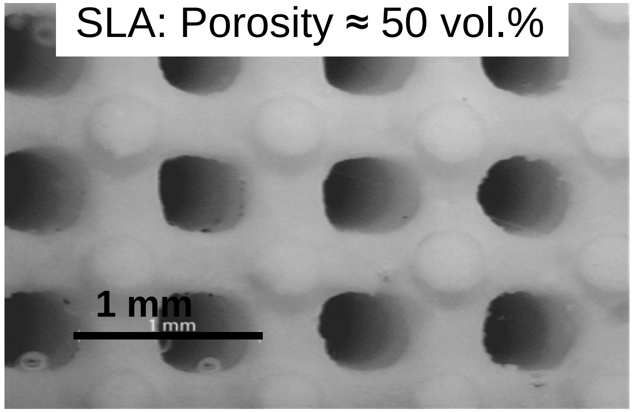
(J Brie, T Chartier, C Chaput, C Delage, B Pradeau, F Caire, MP Boncoeur, JJ Moreau. A new custom made bioceramic implant for the repair of large and complex craniofacial bone defects. J Cranio-Maxillofac Surg, 2013)

Enhance new tissue ingrowth

Increase the dimensionnal resolution: microstereolithography

(SLA ≈ 100 µm - µSLA ≈ 10 µm)

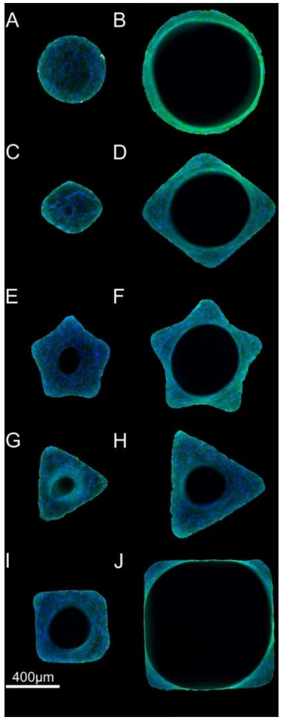
SLA: Porosity ≈ 50 vol.%

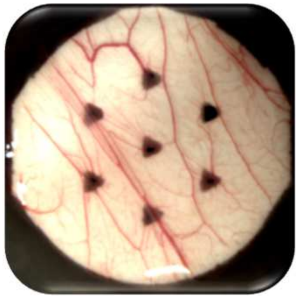


Highly porous scaffolds (Porosity > 70%)

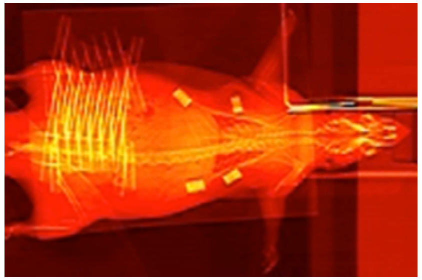
& Adjusted geometry and network of pores

In vitro cell proliferation





Ex-ovo vascularization



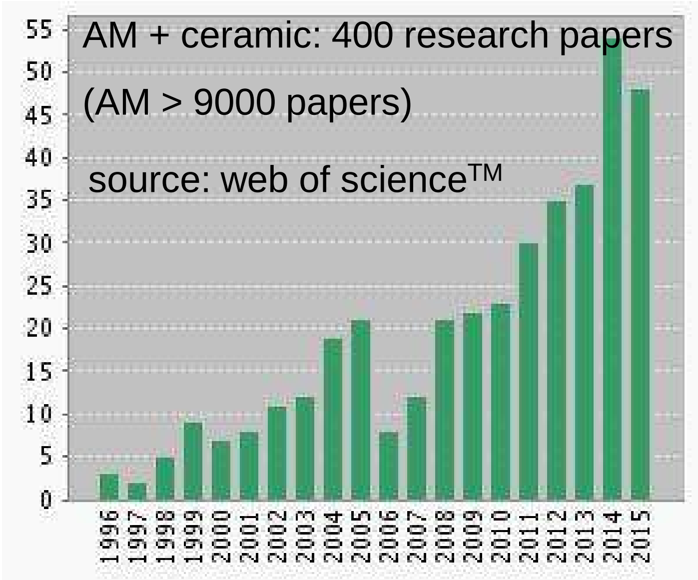
In vivo integration

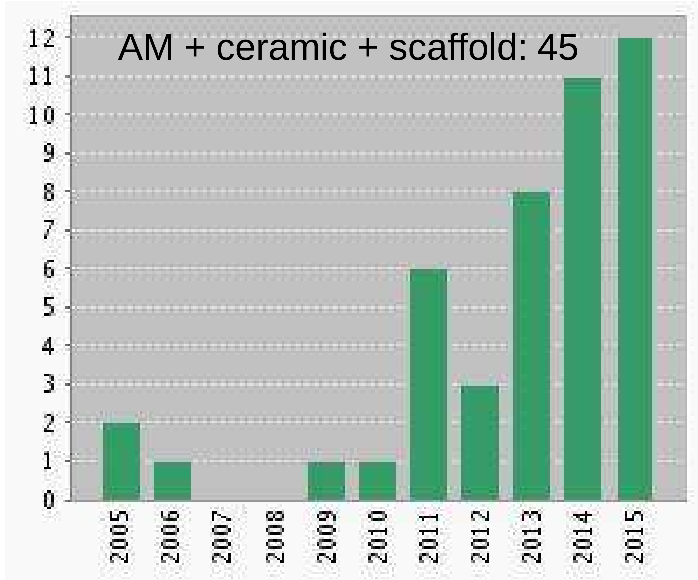
M Lasgorceix, PhD, SPCTS Limoges
collaboration Dr U Rudrich & Dr A Magnaudeix

LABEX LIM

Concluding remarks

- AM of ceramic scaffolds: very young technologies





Few of them have reached the clinic and led to commercially available products

Processing requirements are still very challenging (feedstock, sintering…)

- Promising technologies to the reliable production of bioceramics:

On-demand large implants with accurate dimensions

Scaffolds with controlled pore size and geometries

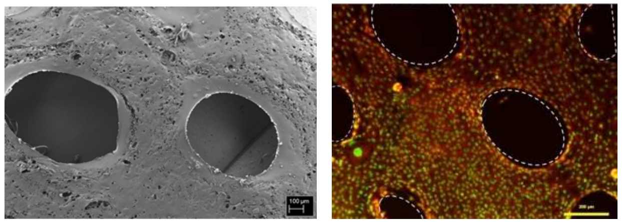
Multiscale control of architectures

Concluding remarks

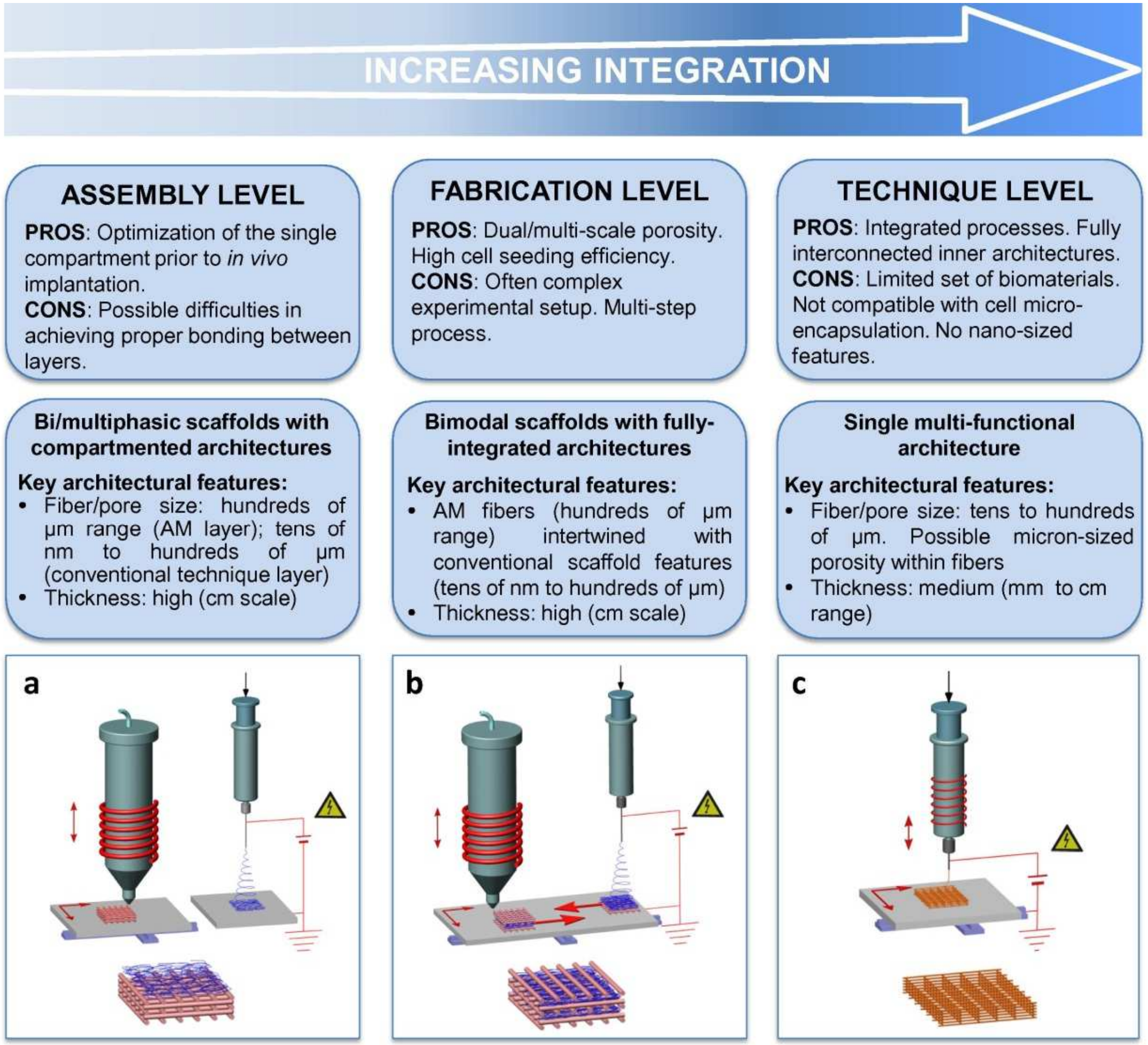
➢ Further developments

Combination of several AM technologies

Association with cells seeding using biofabrication technologies (bioprinting, robocasting..)



(T Zehnder, B Sarker, AR Boccaccini, R Detsch. Evaluation of an alginate–gelatine crosslinked hydrogel for bioplotting. Biofabrication, 2015)



(SM Giannitelli, P Mozetic, M Trombetta, A Rainer. Combined additive manufacturing approaches in tissue engineering. Acta Biomater, 2015)

Thanks for your attention

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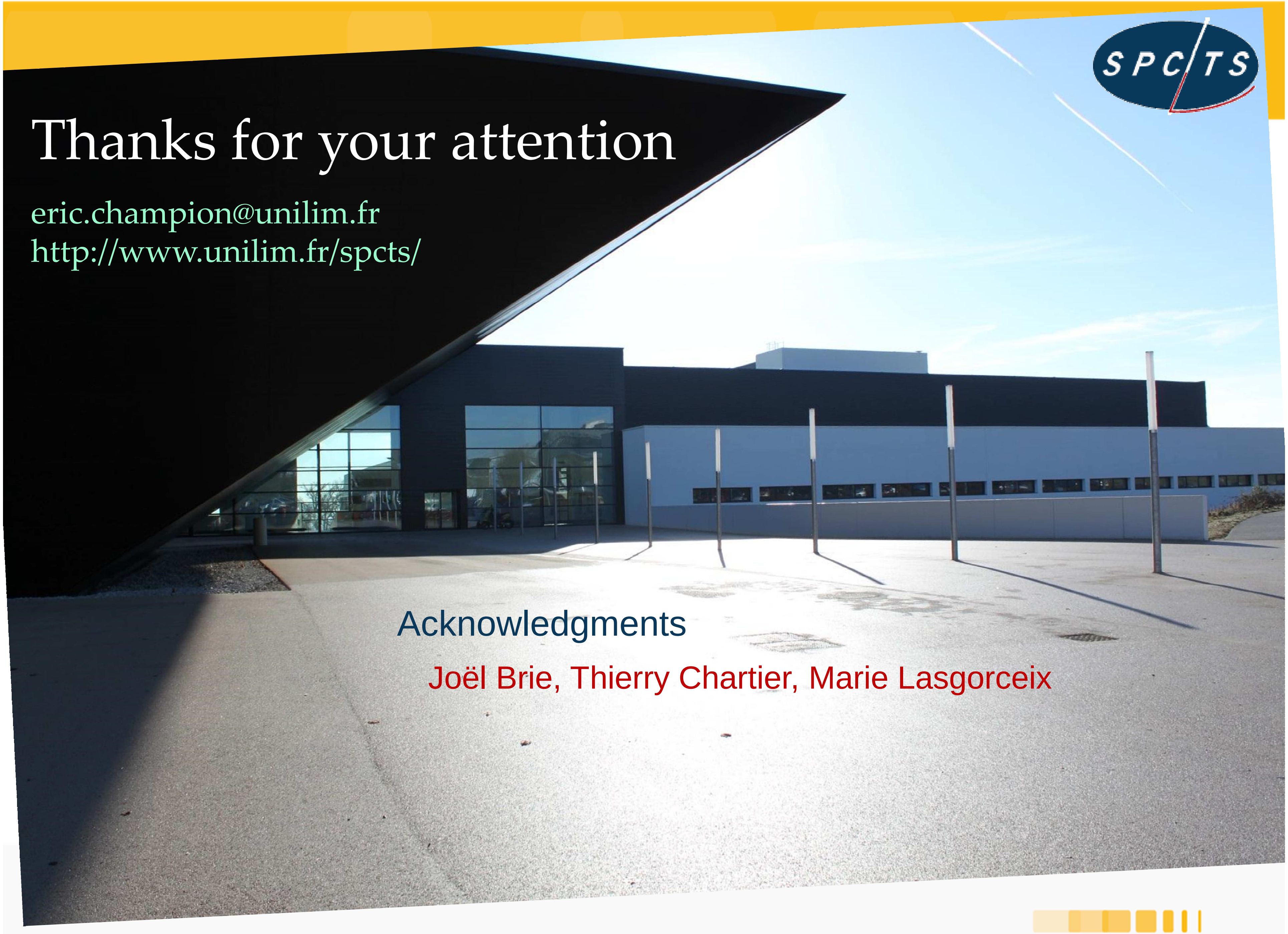

Acknowledgments

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