Osteochondral defects
Facts & current problems

Facts
- Affects 6% to 10% of the population
- Does not regenerate spontaneously

Issues
- Steep mechanical gradient
- Composite multiphase tissue
- Thin thickness
Osteochondral defects
A closer look at the tissue
Osteochondral defects
A closer look at the tissue

Superficial layer
Middle layer
Deep zone
Bone
Create a cellular structure
Current processes

Sc Foaming  Leaching

MEW  Emulsion  FDM

Limitations
Control
Homogeneity
Scale resolution

Pore size

Foaming of 3DP templates
Materials & methods

3D Printing  Foaming

Porosity = P_{3DP} + p_{FOAM}

Function^{1,2}

Modulus

P_{3DP}: 100% interconnected
p_{FOAM}: higher surface area

References:
1. Dalton's Lab, University of Würzburg, Germany
Foaming of 3DP templates
Fused deposition modeling

Heating block
Filament feeder
Nozzle

Supercritical CO₂ batch foaming

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P
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T

CO₂ diffusion into molten polymer

Cell nucleation

Cell growth

t [min]

- Pellets
- CO₂
- Pores

Foaming
Foaming of 3DP templates

A matter of processing windows

Batch
- Above Tm
- High pressure
- Mold

Directional
- Below Tm
- High P
- Mold-less

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Poly-lactide acid (PLA)
Natureworks d2003
1.75mm filament
E = 3.5GPa

MakerBot Replicator 2
T = 200°C
v = 60mm/s

Autoclave SITEC AG
T = 110 – 140°C
P = 120 – 200 bar
tsat = 5 – 60min
dP/dt = 1 – 50bar/s
Foaming of 3DP templates
Foam morphology

Processing windows: influence of T and P (foam/not foam)
Morphology: minor influence of P, high influence of dP/dt (porosity, distribution)

Mechanical properties

Foaming of 3DP templates

3D Printed
dP/dt = 5 bar/s
dP/dt = 50 bar/s

Increasing dP/dt

<table>
<thead>
<tr>
<th>Stress [MPa]</th>
<th>Strain [-]</th>
<th>E [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>398</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>279</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>21</td>
</tr>
</tbody>
</table>

3DF, 50b/s

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## Foaming of 3DP templates

### Expansion ratio

<table>
<thead>
<tr>
<th>3DPrint</th>
<th>dP/dt = 30bar/s</th>
<th>dP/dt = 50bar/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0 ± 0.1 mm</td>
<td>13.3 ± 0.2 mm</td>
<td>15.4 ± 0.1 mm</td>
</tr>
<tr>
<td>4.0 ± 0.1 mm</td>
<td>8.1 ± 0.1 mm</td>
<td>11 ± 0.1 mm</td>
</tr>
<tr>
<td>Expansion: x1.7 (x-y)</td>
<td>Expansion: x1.9 (x-y)</td>
<td></td>
</tr>
<tr>
<td>Expansion: x2.1 (z)</td>
<td>Expansion: x2.8 (z)</td>
<td></td>
</tr>
</tbody>
</table>

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### 3D Foaming of Biomaterials

Can it this be extended to MEDICAL-GRADE HIERARCHICAL FOAMS?
Biomaterial printing
Material selection

◊ Materials

• Food grade (model): PLA d2002
• Medical:

  Copolymers
  PLA/PCL 703s ➔ Soft & viscoelastic (E ≈ 1Gpa)
  PLGA 855s

  Blends
  PLLA-10%βTCP ➔ Composite bone-like
  PLLA-10%PEG35k

Biomaterial printing
Filament extrusion

PLL/PCL (703s)

PLL/−TCP

ϕ = 1.75 ± 0.1

ϕ = 1.45 ± 0.1
Biomaterial printing

Printability

Food grade (d2002)  
T = 200 °C  
Print time: 4min

PLLA/PCL (703s)  
T = 180 °C  
Print time: 6min

PLLA/TCP  
T = 220 °C  
Print time: 4min

Biomaterial printing

Mechanical properties

Stress [MPa] vs. Strain [-] for different biomaterials:

- PLA d2003: E modulus = 386 MPa
- PLLA/βTCP: E modulus = 428 MPa
- PLA/PCL 703s: E modulus = 19 MPa
**OBJECTIVE:**
Create a biphasic structure
Foam only a specific region
Directional foaming is selective

**CARTILAGE:** PLA/PCL 703s

**BONE:** PLLA-βTCP

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**Biphasic structure**
3D Printing of hard & soft materials

![Stress vs. Strain Graph](image)
Biphasic structure
A look at the interface

Biphasic foaming
Selective foaming of a specific material
Biphasic final scaffold
Comparison cartilage vs scaffold

Aggregate modulus (MPa)

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powdered TCP</td>
<td>1.27</td>
</tr>
<tr>
<td>Biphasic foam</td>
<td>2.44</td>
</tr>
<tr>
<td>PLA/PCL</td>
<td>1.00</td>
</tr>
<tr>
<td>PLA/PCL-PLLAβTCP</td>
<td>0.77</td>
</tr>
<tr>
<td>Articular cartilage</td>
<td>2.44</td>
</tr>
</tbody>
</table>

Resume

FDM printing and supercritical foaming can be coupled to produce tunable hierarchical foams.

The narrow processing windows allow to precisely foam only one of a multi-material structure.

The process can be applied for hybrid scaffold for osteochondral tissue engineering.
Continuous 3D foam printing

Can we produce CUSTOM MOLD-LESS CELLULAR STRUCTURES?

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