Modules of the 2025 course

Topics covered	No	Lecture/Date
VAT Photo polymerization (history) – DLP printer – light engine – part I	5	20.03.2025
DLP printer – chemical components in a photoresin – role of oxygen – CLIP method– part II	6	27.03.2025
Tomographic Volumetric Additive Manufacturing (TVAM): principles and applications	7	03.04.2025
Two photon Polymerization : nanoscale printing	8	10.04.2025
Two photon Polymerization : applications	9	17.04.2025
EASTER BREAK		22.04.2025
Prof. Paul Dalton, University of Oregon: Met Electro Writing (nanoscale)	10	1.05.2025
Gari Arutinov, Holst Center for AM: Mass transfer of microcomponents	11	08.05.2025
Julian Schneider: Scrona	12	15.05.2025
Patrizia Richner: Sonova (hearing aids). // **Design Competition**	13	22.05.2025

QUIZZ #2

Role of oxygen

Photo-initiation

$$PI \xrightarrow{h\nu} 2R\bullet$$

Propagation
Polymer chain growth

$$R\bullet + M \rightarrow M\bullet$$

$$M_n\bullet + M \rightarrow M_{n+1}\bullet$$

Oxygen radical scavenging

$$R\bullet + O_2 \rightarrow R-O-O-$$

$$M_{n+1}\bullet\ O_2 \rightarrow \text{dead polymer}$$

Reaction kinetics

Photoinitiator molecule

$$\mathrm{In} \xrightarrow{k_\mathrm{d}} 2R\cdot$$

Kd: rate of decomposition

Photo initiator

$$\frac{\mathrm{d}[\mathrm{In}]}{\mathrm{d}t} = -k_\mathrm{d} I(z)[\mathrm{In}]$$

Radical Chain Polymerization

$$R\cdot + \mathrm{DB} \xrightarrow{k_\mathrm{p}} R\cdot$$

Kp: rate of propagation

Radicals

$$\frac{\mathrm{d}[R\cdot]}{\mathrm{d}t} = 2k_\mathrm{d} I(z)[\mathrm{In}] - 2k_\mathrm{t}[R\cdot]^2 - k_{\mathrm{t},\mathrm{O}_2}[R\cdot][\mathrm{O}_2]$$

$$R\cdot + R\cdot \xrightarrow{k_\mathrm{t}} R_\mathrm{dead}$$

Kt: rate of termination

Monomer Double bond

$$\frac{\mathrm{d}[\mathrm{DB}]}{\mathrm{d}t} = -k_\mathrm{p}[R\cdot][\mathrm{DB}]$$

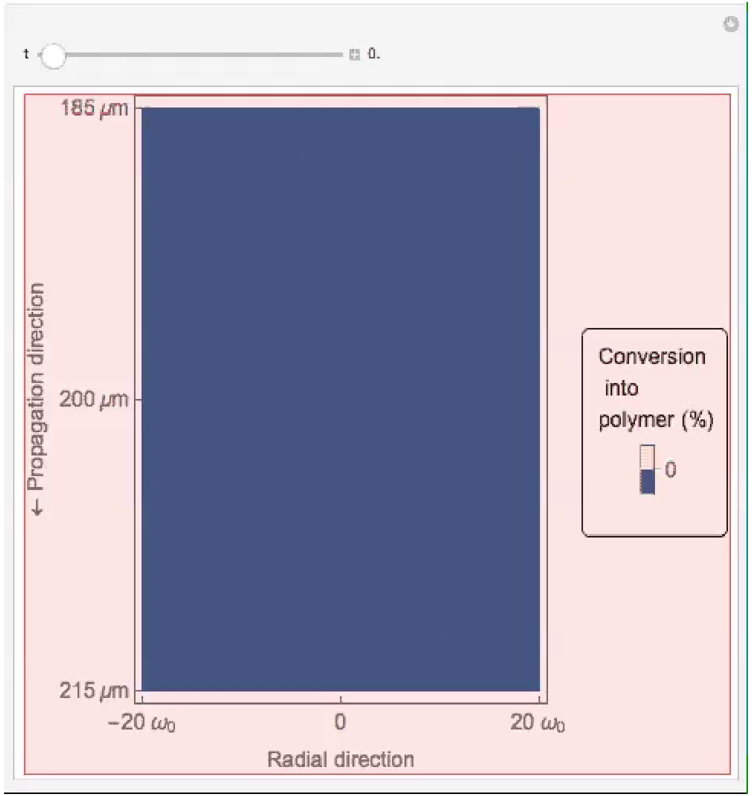
$$R\cdot + \mathrm{O}_2 \xrightarrow{k_{\mathrm{t},\mathrm{O}_2}} R_\mathrm{dead}$$

Kt,o2: rate of termination

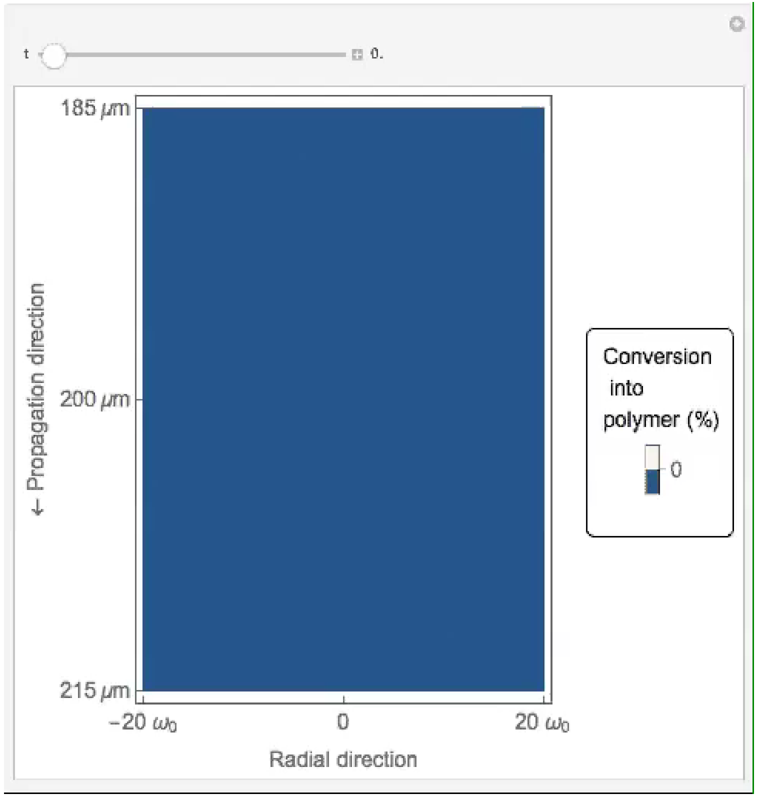
Oxygen

$$\frac{\partial[\mathrm{O}_2]}{\partial t} = -k_{\mathrm{t},\mathrm{O}_2}[R\cdot][\mathrm{O}_2] + D_{\mathrm{O}_2}\frac{\partial^2[\mathrm{O}_2]}{\partial z^2}$$

Simulation without oxygen inhibition



Simulation with oxygen inhibition



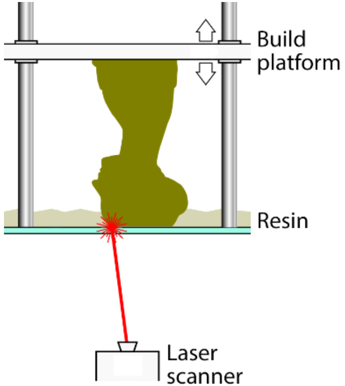
P = 250 nW, polymer: PEG-DA

Existing 3D printers are actually 2D printers.

EPFL

1^{st} generation

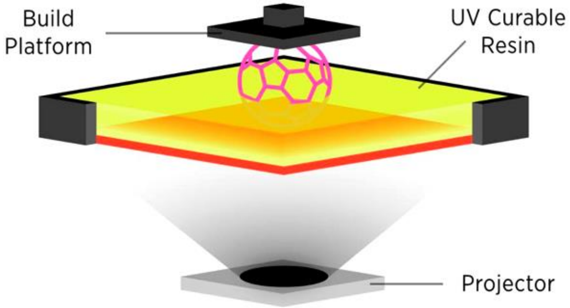
Point-by-point



10 - 50 mm per hour

2^{nd} generation

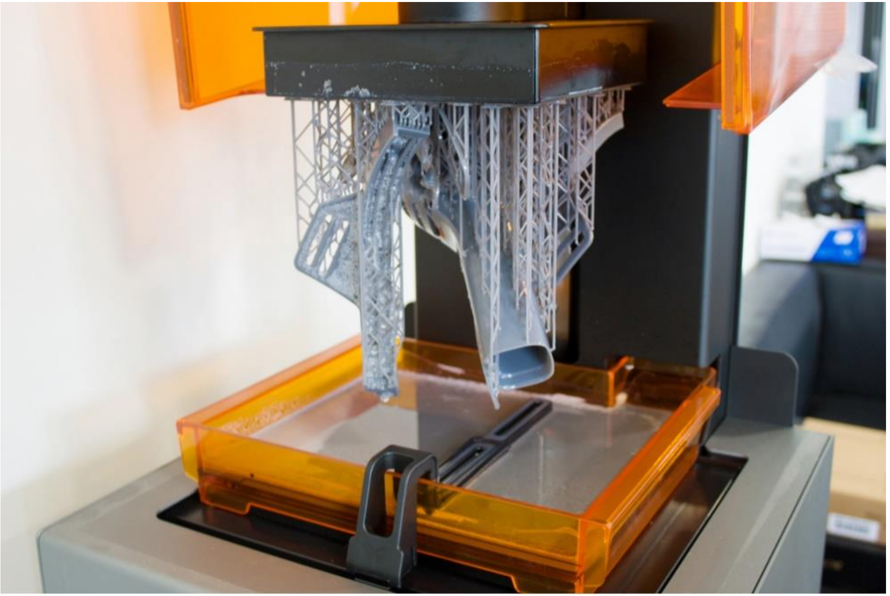
Layer-by-layer



300 - 1200 mm per hour

Existing 3D printers are actually 2D printers.

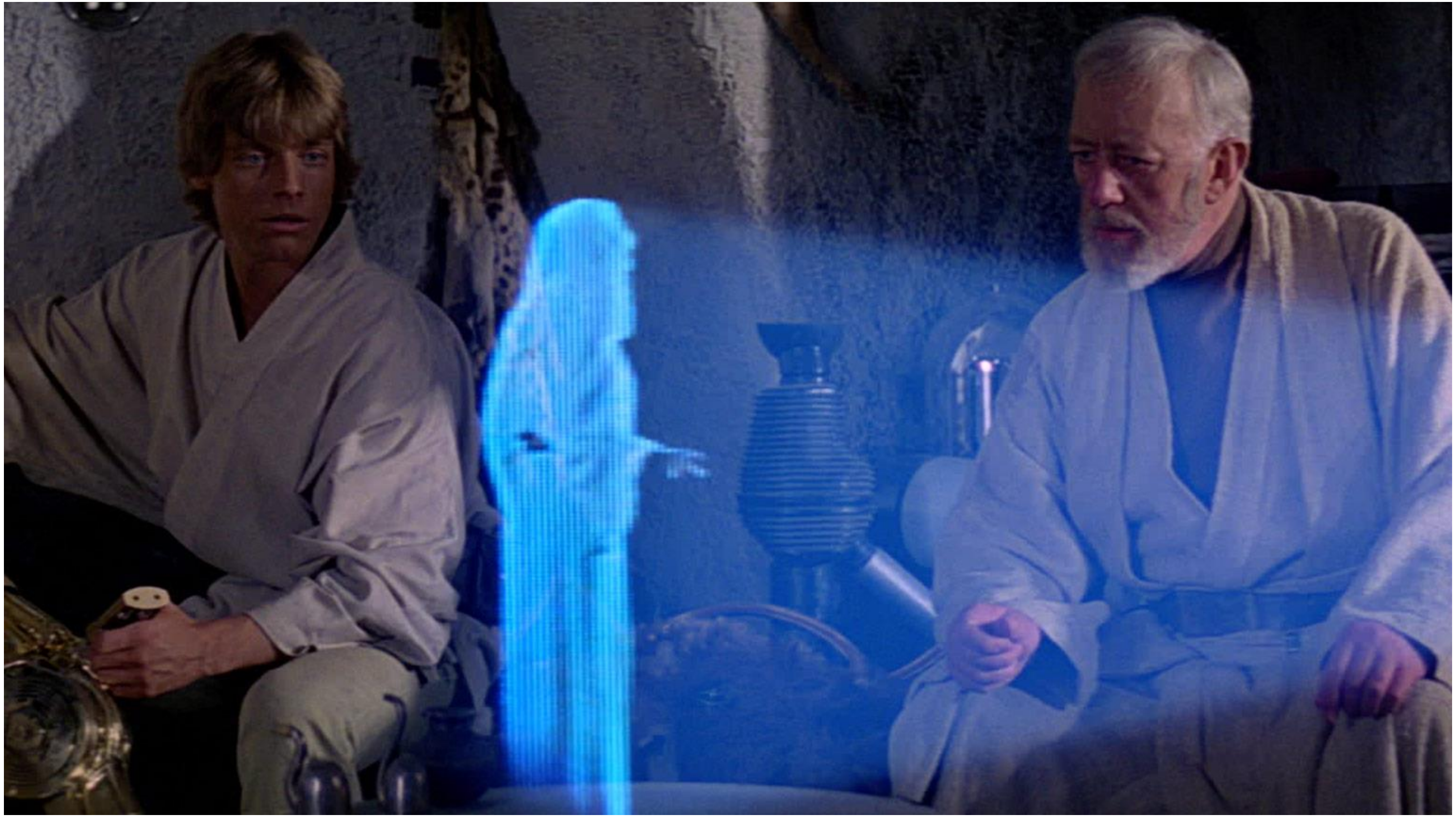
EPFL



Main limitations

- Layer-by-layer
- Needs support structure
- Still slow
- Does not work for soft materials

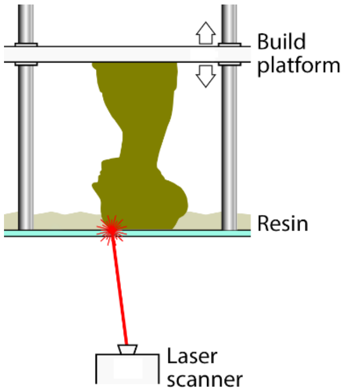
Can we do fully volumetric printing?



Can we do fully volumetric printing?

1st generation

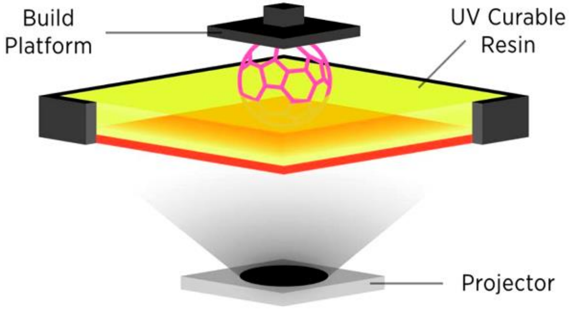
Point-by-point



10 - 50 mm per hour

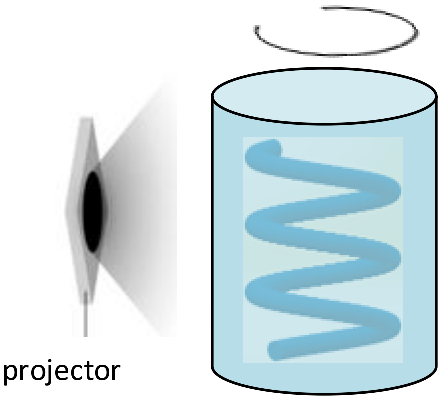
2nd generation

Layer-by-layer



300 - 1200 mm per hour

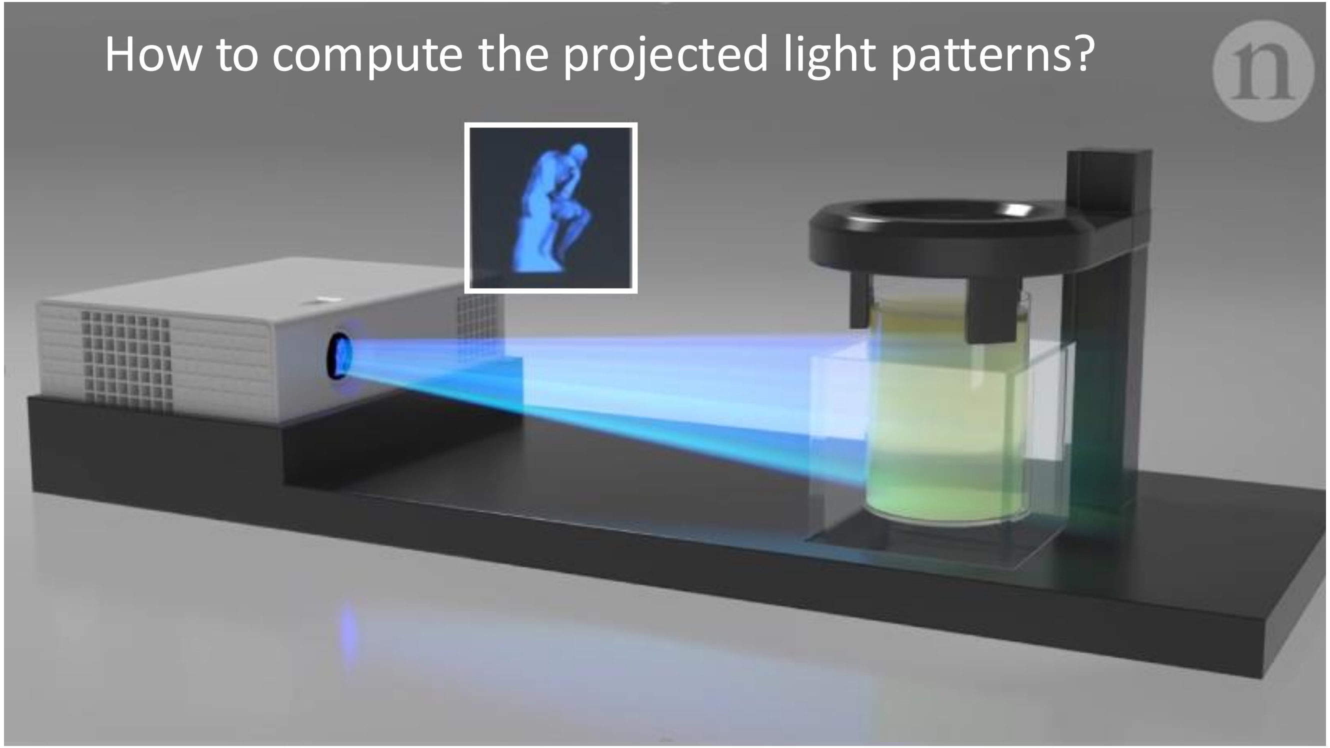
3rd generation



50 mm^3 per **seconds**

Volumetric 3D printing
By Tomographic projections

Tomographic 3D printing with light



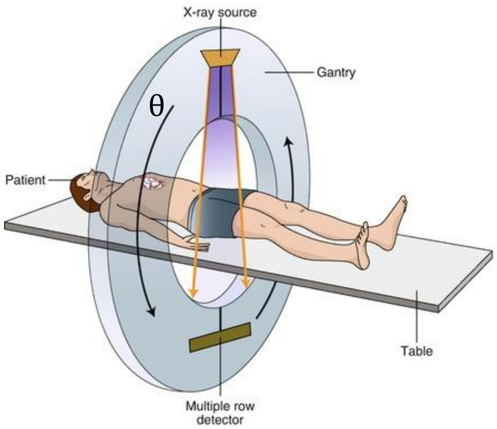
Nature Video | 31 January 2019

3D printing with light https://www.nature.com/articles/d41586-019-00410-8

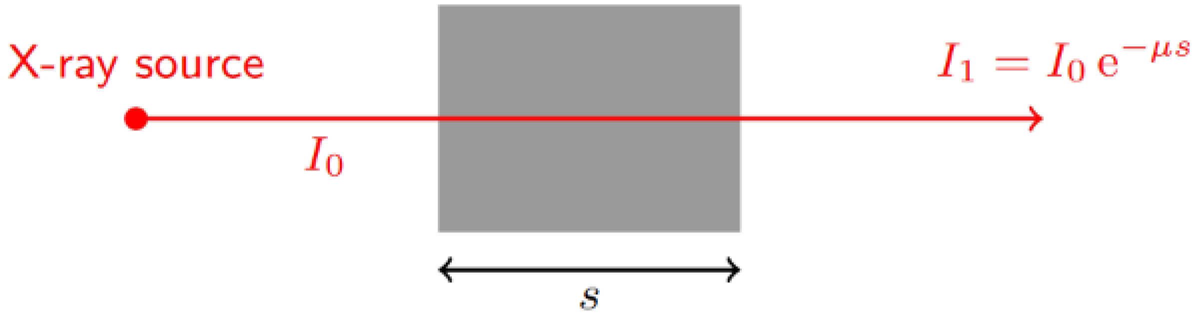
Computed Tomography (CT) imaging

CT is a **non-invasive** device that provides information about the inside of an object by taking measurements from the outside (indirect information)

2D + θ measurements



Simple example: a line in an homogeneous medium

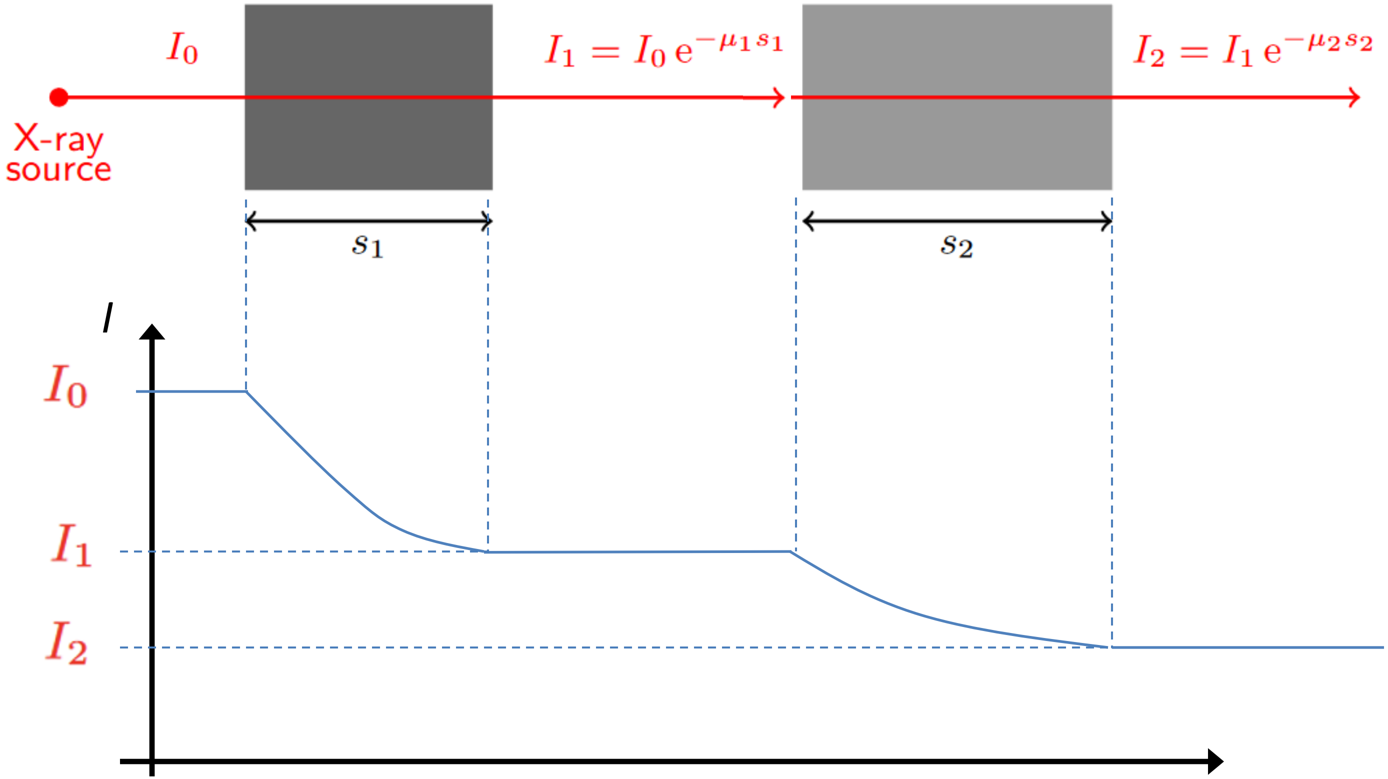


I_0: initial intensity of the X-ray

s: length of the path of the X-ray inside the body

$\mu > 0$: X-ray attenuation coefficient

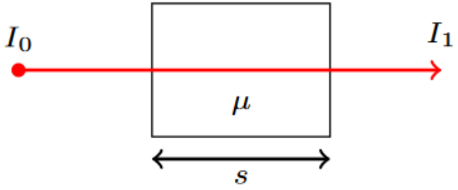
Simple example: two homogeneous blocks



The Beer-Lambert law

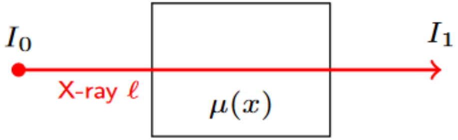
Homogeneous material:

$$I_1 = I_0 \; e^{-\mu s}$$



Non-homogeneous material:

$$I_1 = I_0 \; e^{-\int_\ell \mu(x)\, dx}$$



so-called **line integral**:

$$I_1 = I_0 \; e^{-\int_\ell \mu(x)\, dx} \quad \Longleftrightarrow \quad -\log\left(\frac{I_1}{I_0}\right) = \int_\ell \mu(x)\, dx$$

The Beer-Lambert law and Radon transform

The Beer-Lambert law connects the initial and final intensities of an X-ray:

$$I_1 = I_0 \, e^{-\int_\ell f(x)\, dx} \qquad \Longleftrightarrow \qquad -\log\left(\frac{I_1}{I_0}\right) = \int_\ell f(x)\, dx$$

and it is connected to the Radon transform

$$\mathcal{R}(f) = \int_\ell f(x)\, dx$$

through the identifications:

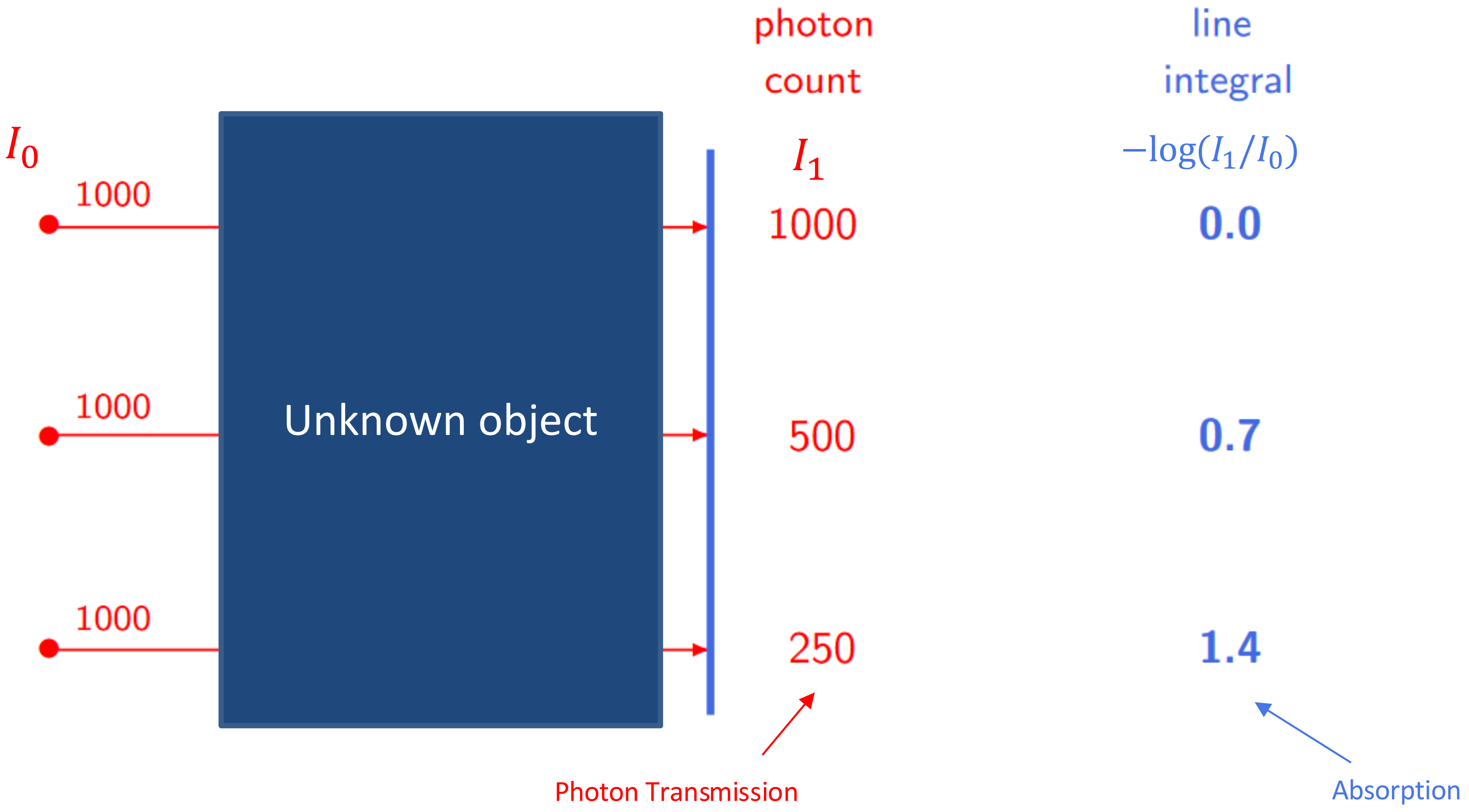
$$f(x) = \mu(x) \qquad \text{and} \qquad \mathcal{R}(f) = -\log\left(\frac{I_1}{I_0}\right).$$

The Beer-Lambert law and Radon transform

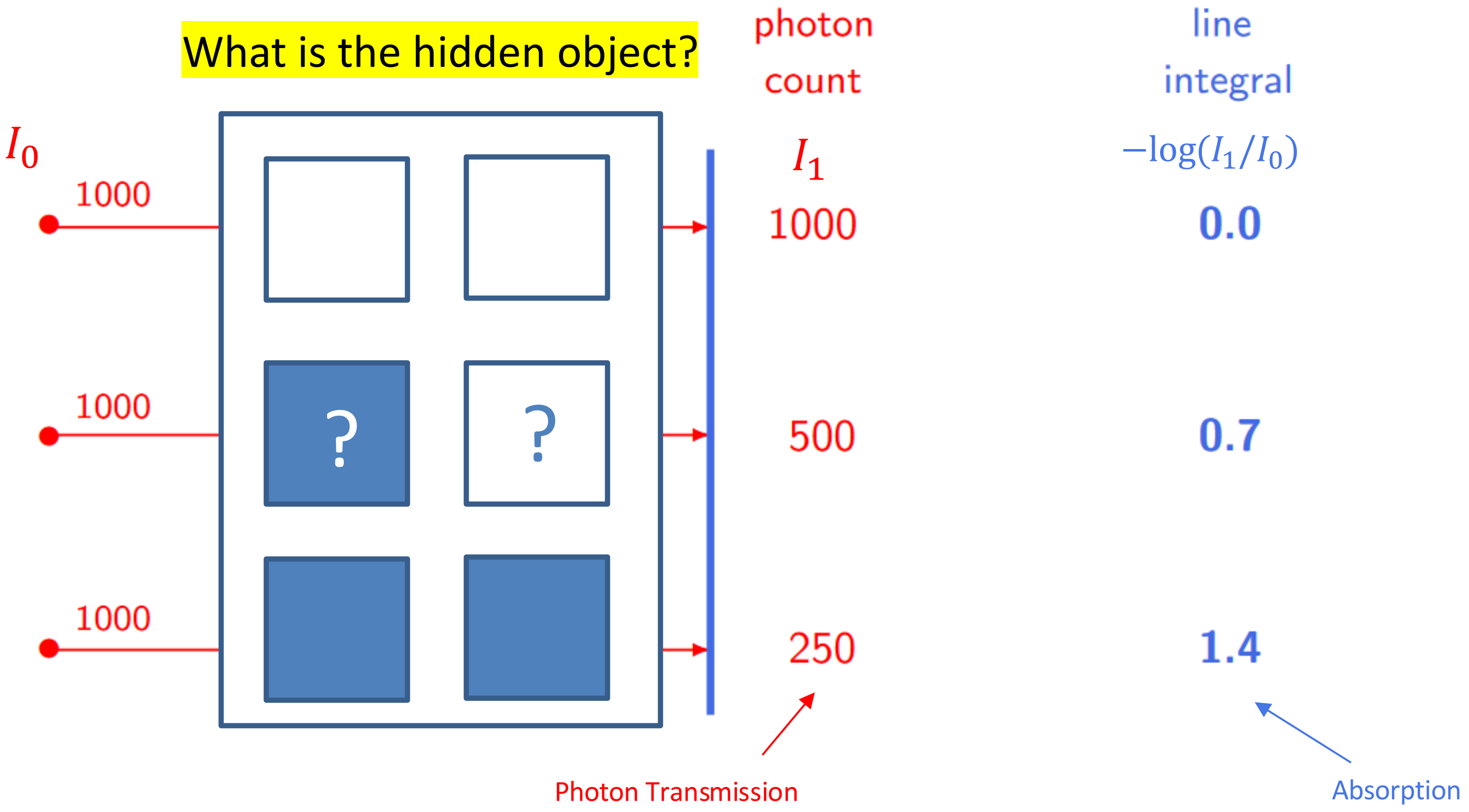
In general, during a tomographic scan:

- I_0 is known from calibration and I_1 from measurement.
- I_1 is measured along many lines $\ell_{(\theta,\tau)}$ to get many line integral values through the object from which to determine $f(x)$.
- The intensity I_1 is called the *transmission*, while the corresponding $-\log(I_1/I_0)$ is called absorption or **projection**. A collection of projections is called **sinogram**.

In practice: from transmission to absorption

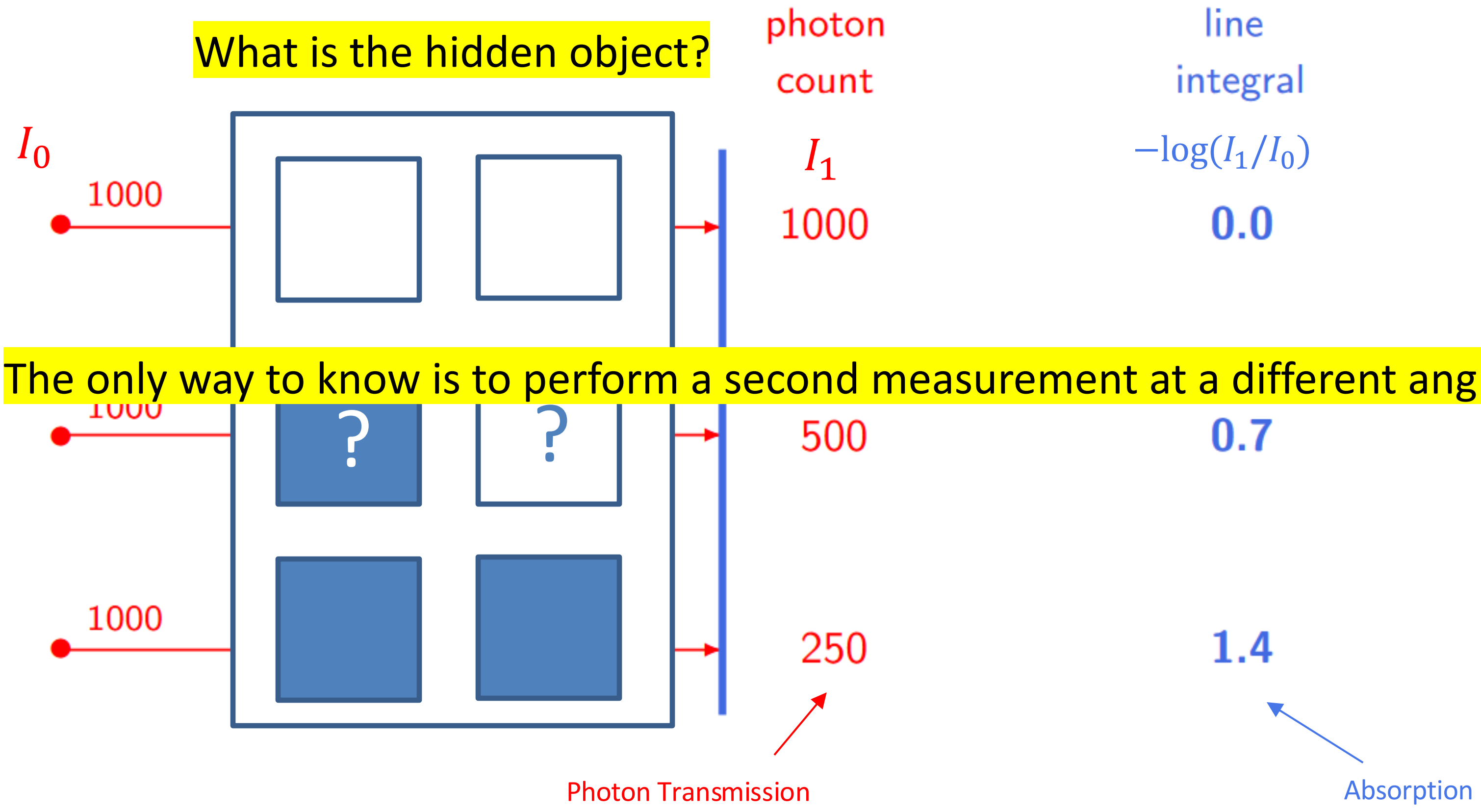


In practice: from transmission to absorption



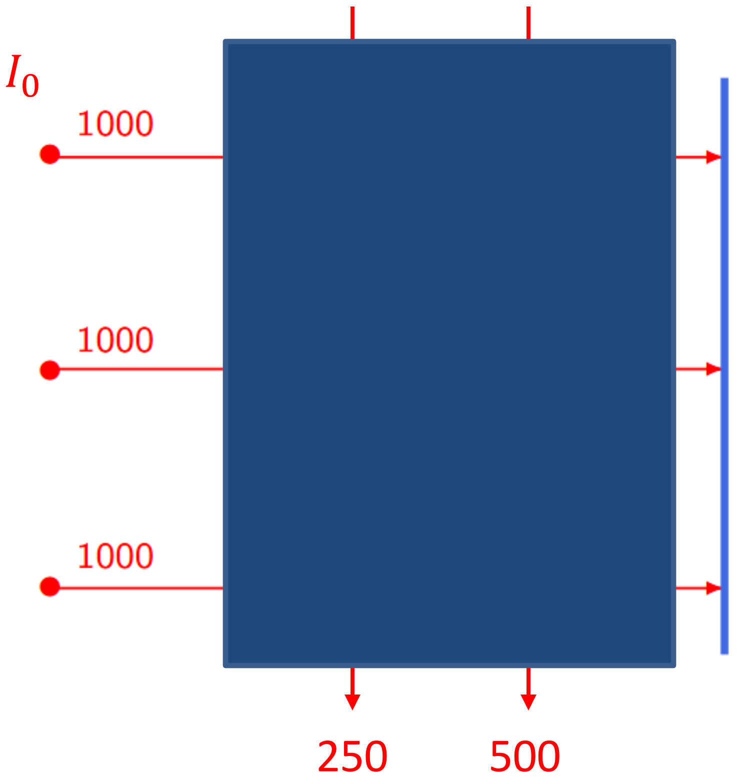
In practice: from transmission to absorption

What is the hidden object?



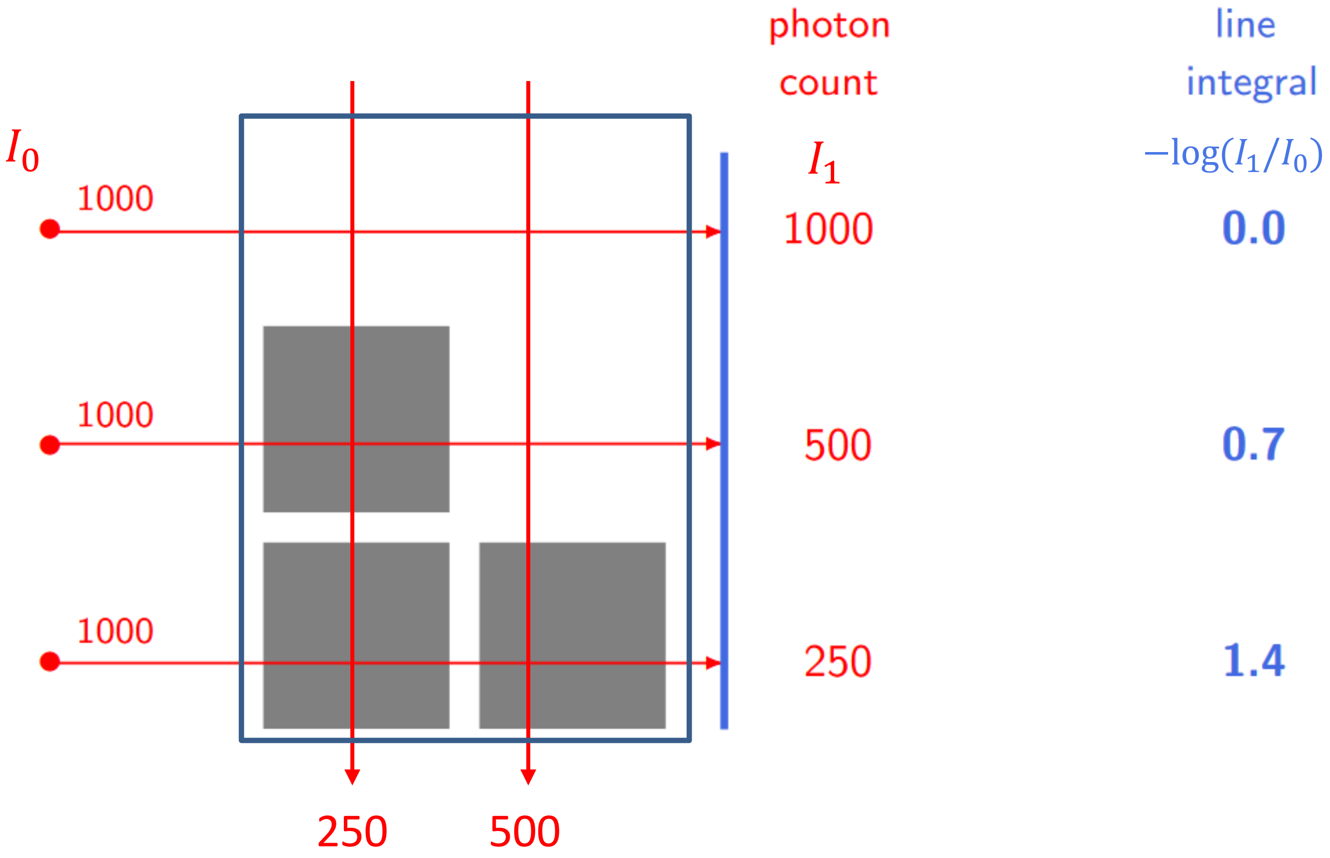
The only way to know is to perform a second measurement at a different angle

The Beer-Lambert law and Radon transform



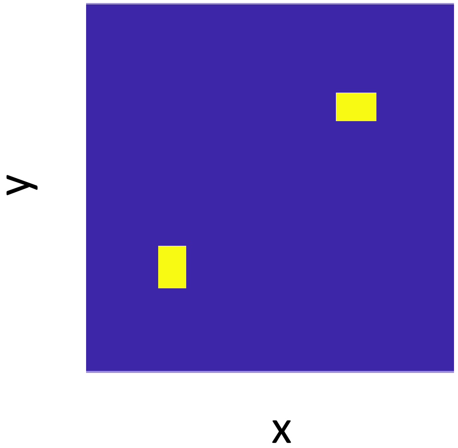
photon count I_1	line integral $-\log(I_1/I_0)$
1000	0.0
500	0.7
250	1.4

The Beer-Lambert law and Radon transform

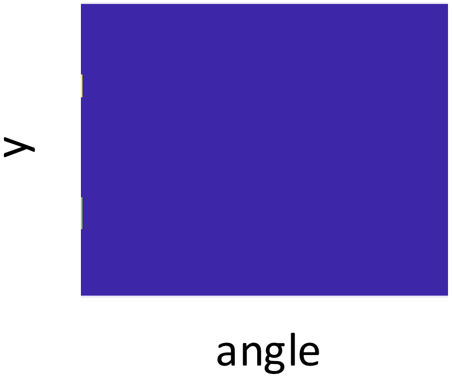


Tomography: principle

object



Sinogram



Tomography: reconstruction principle

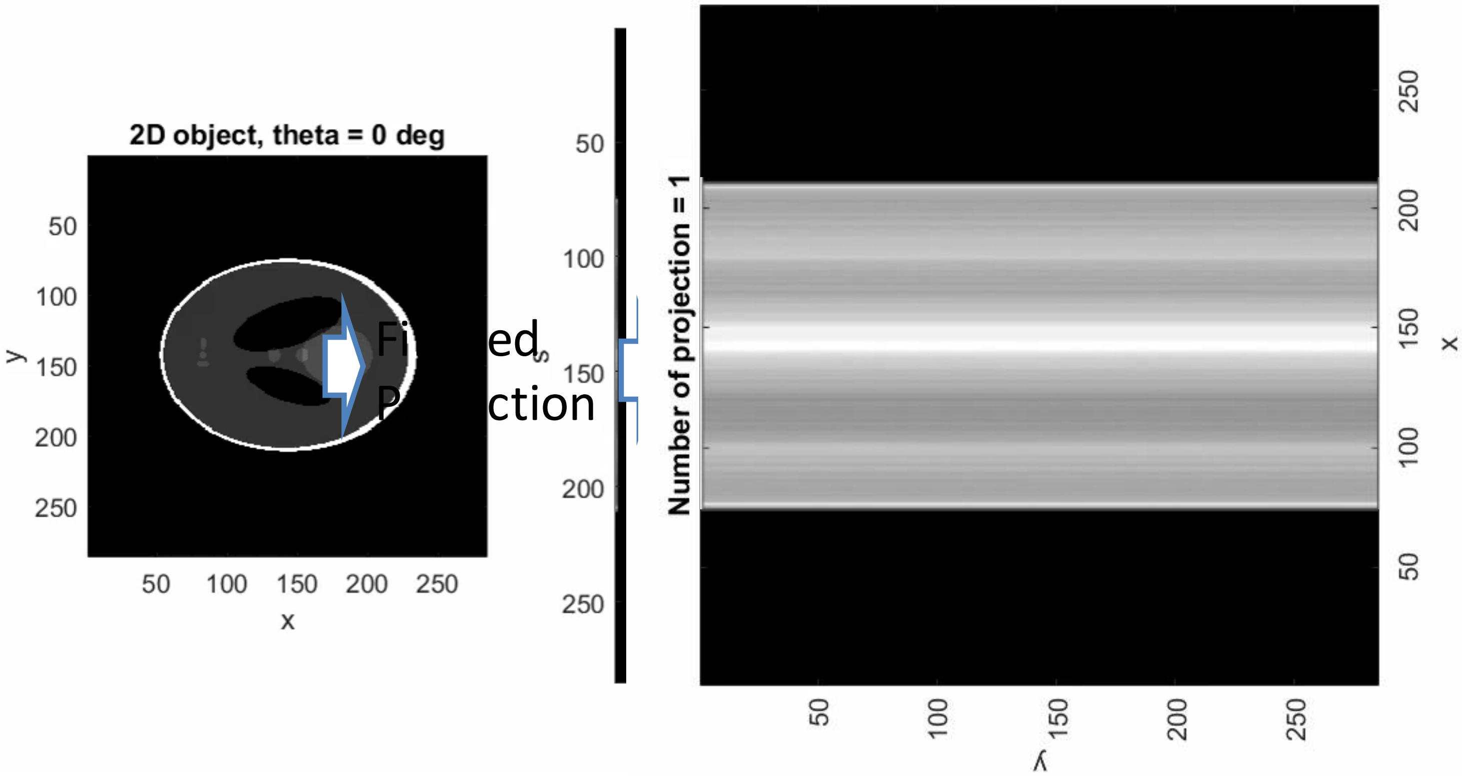
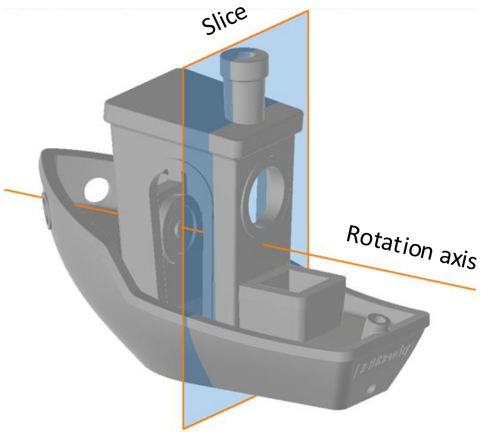
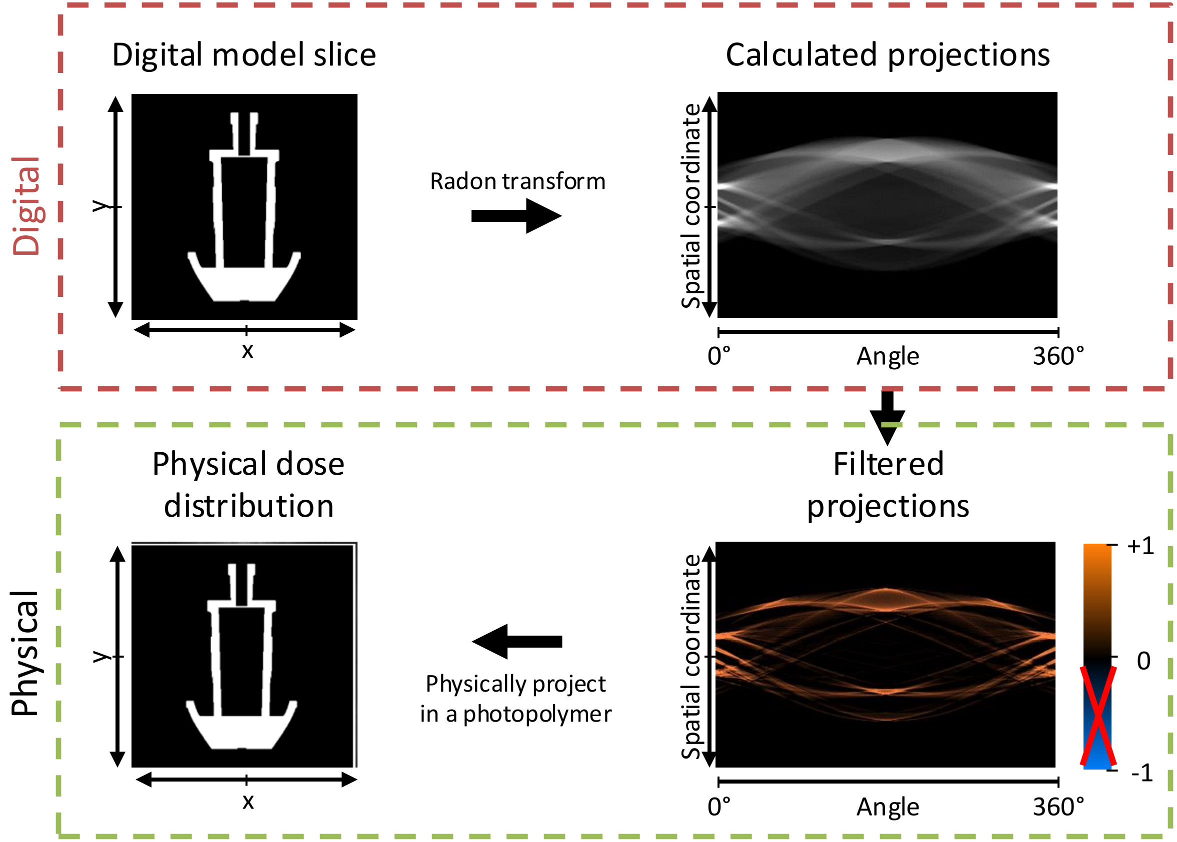


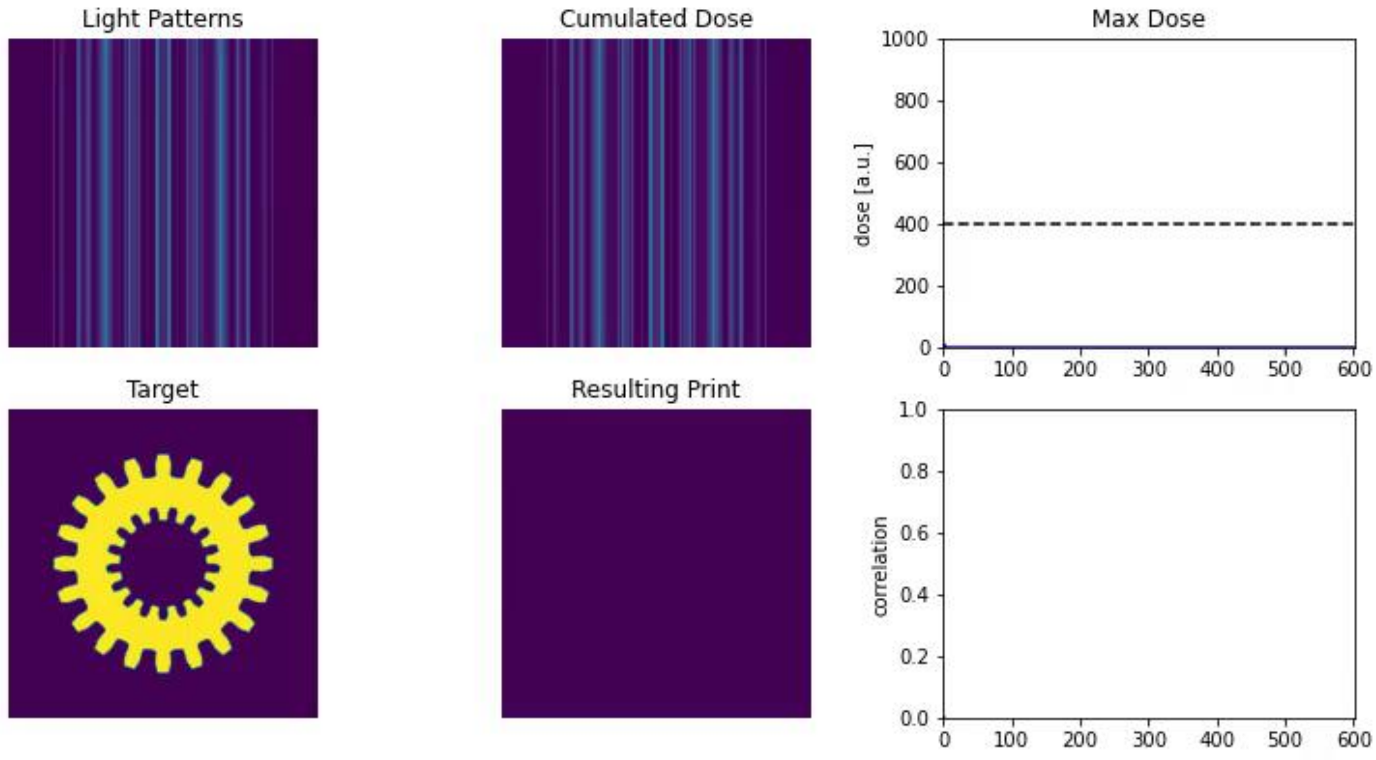
Illustration of the Radon transform in ***3D printing***



3D object
(3DBenchy by Creative Tools, license CC BY ND 4.0)

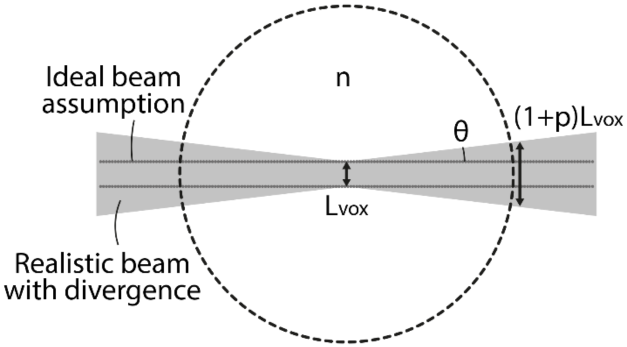


Reverse tomography for 3D printing

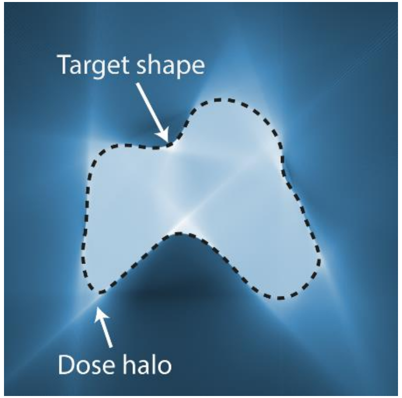


Resolution

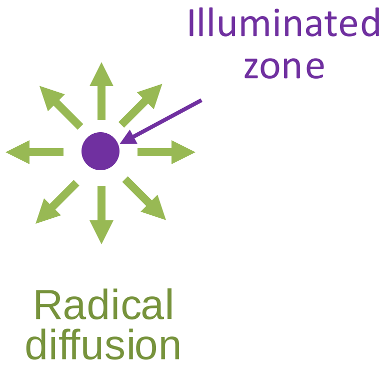
Divergence



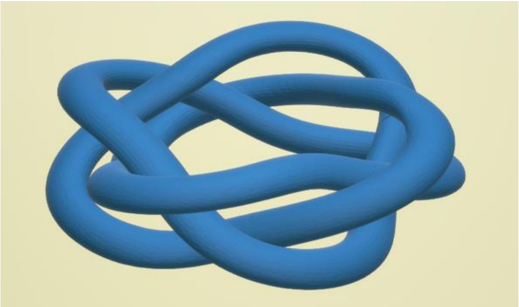
Algorithm



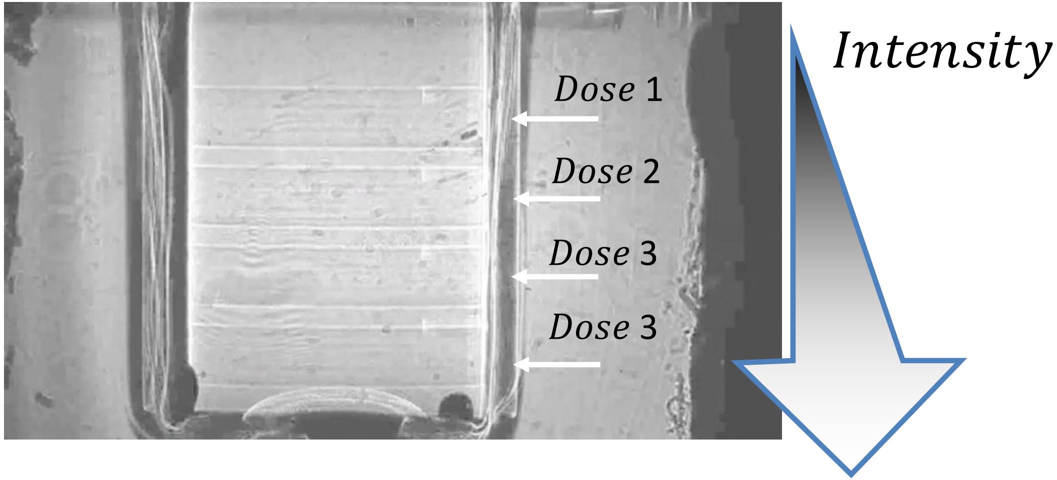
Chemical diffusion



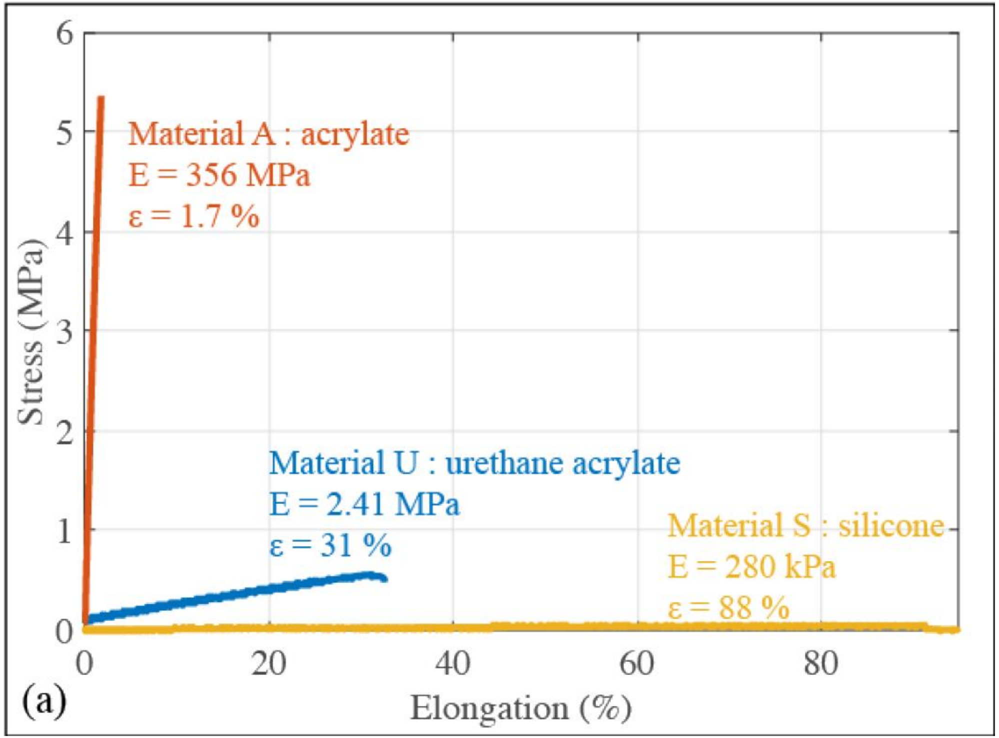
Effect of dose in volumetric printing



$$Dose[\frac{J}{cm^2}] = I \cdot time$$



Materials



Polymers

Silicones

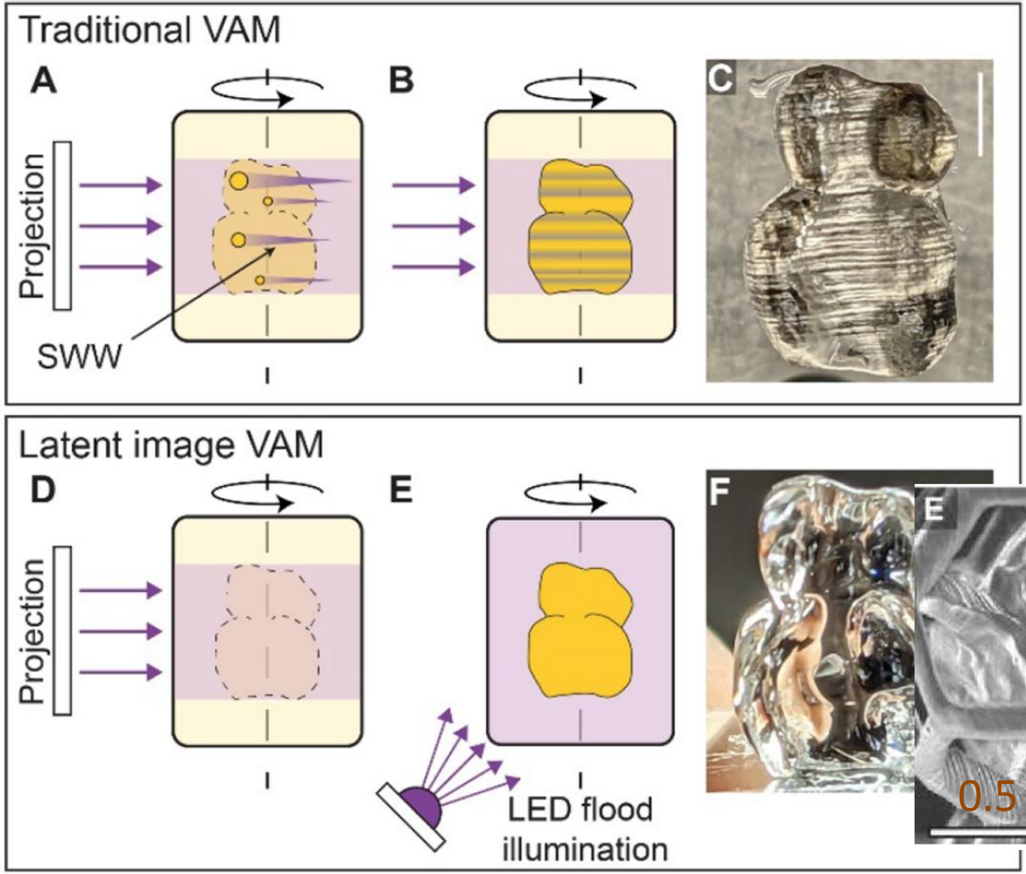
Hydrogels

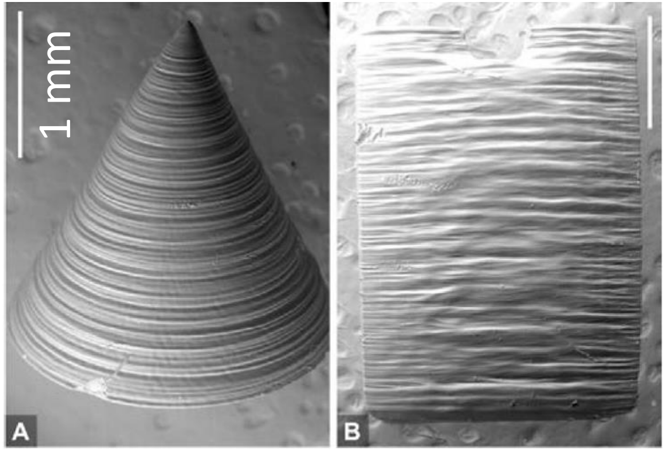
Ceramics

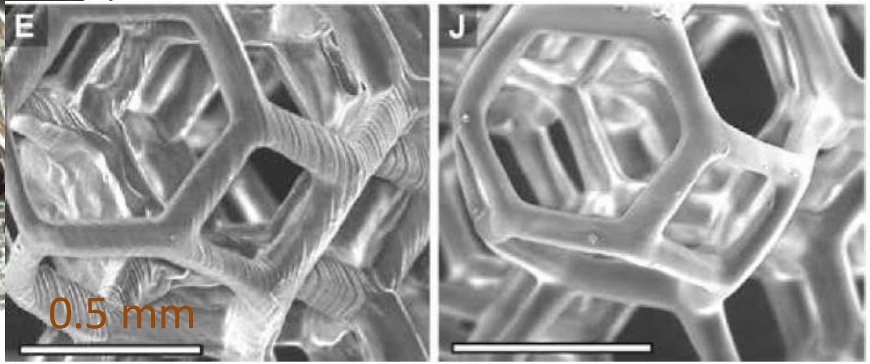
Glass

Striation effect

Rackson C, […], McLeod R., " Latent image volumetric additive manufacturing", Opt. Lett. 2022.

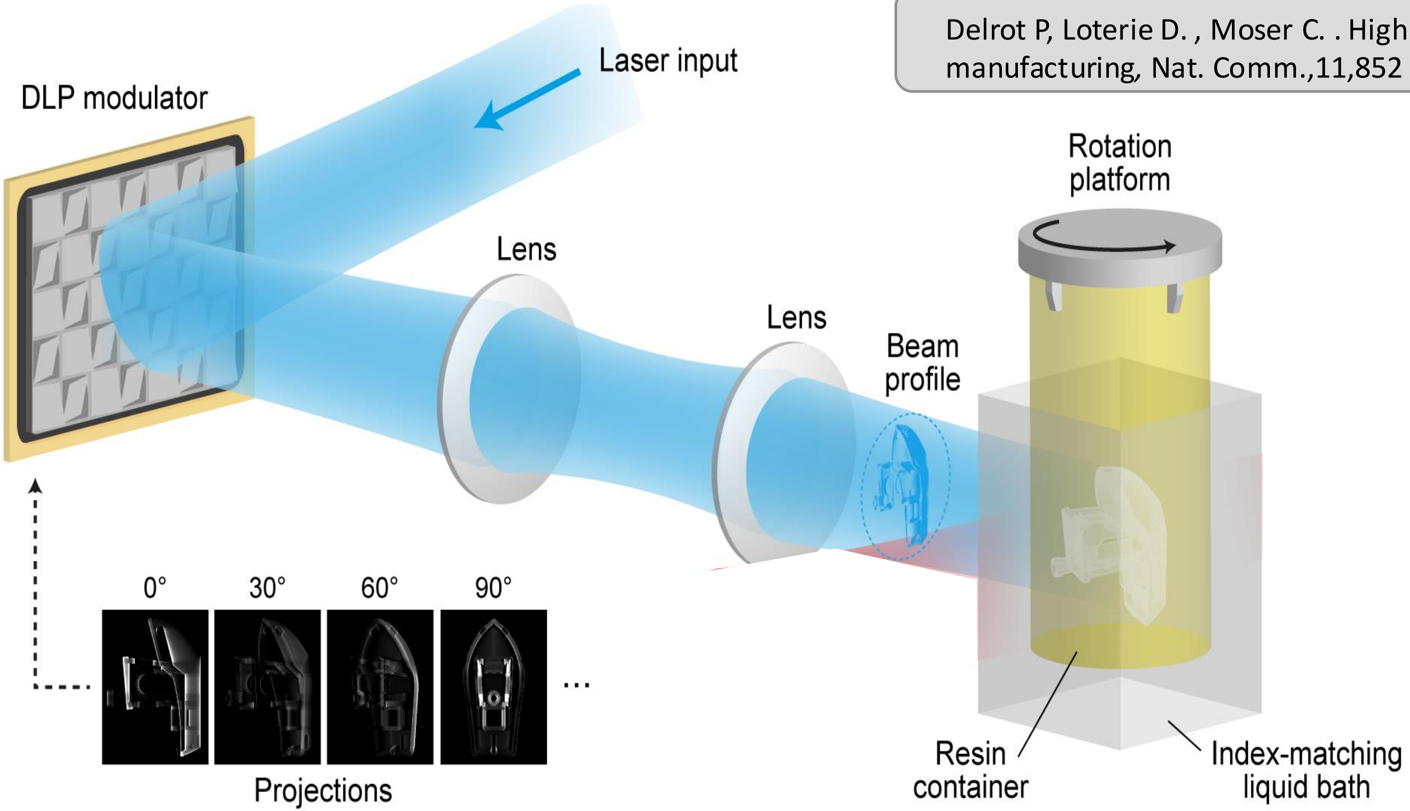


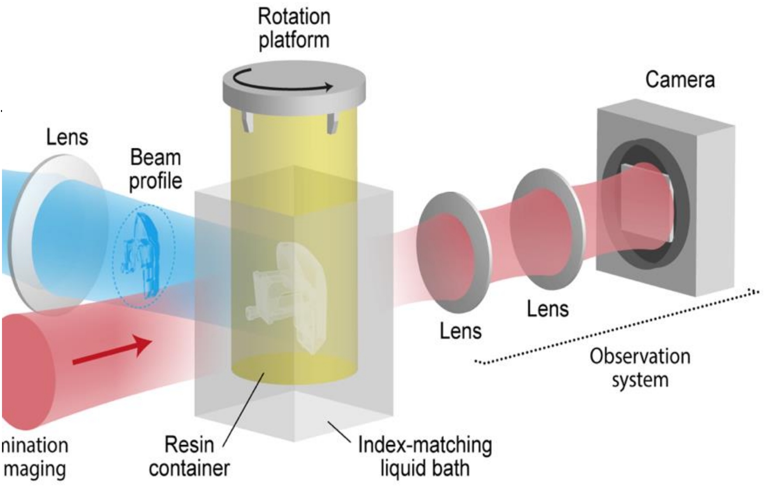


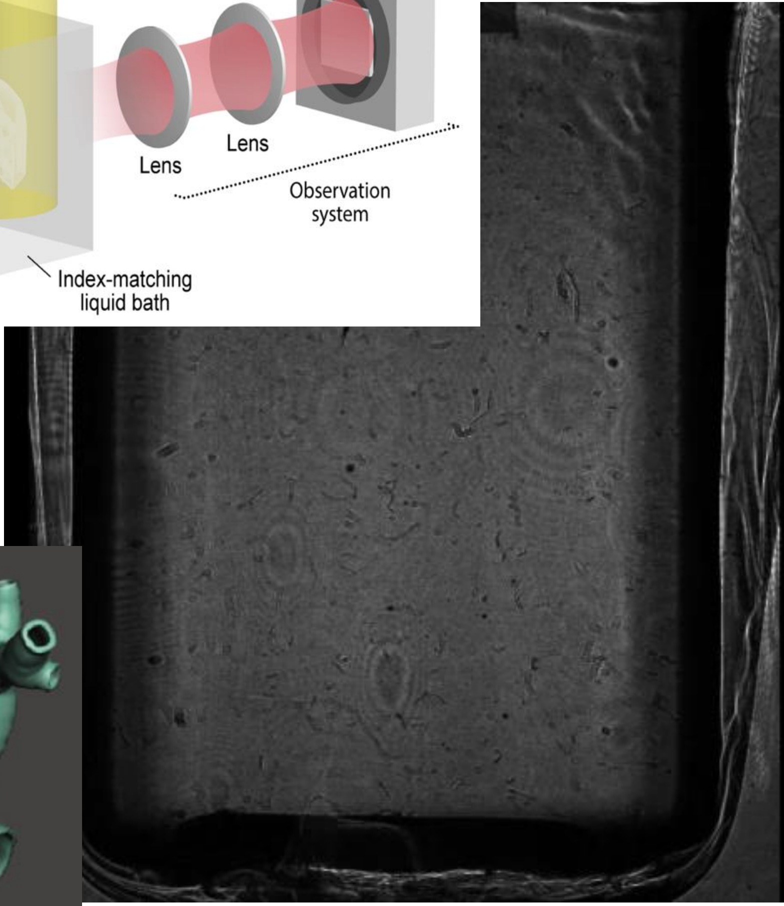


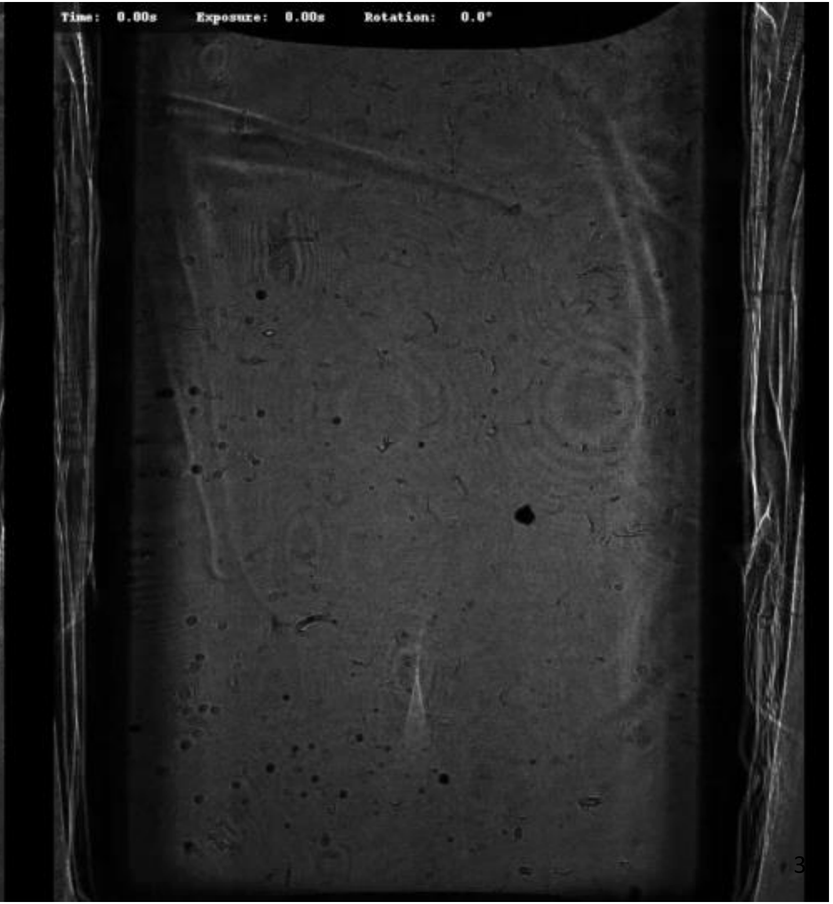
Feedback assisted volumetric printing

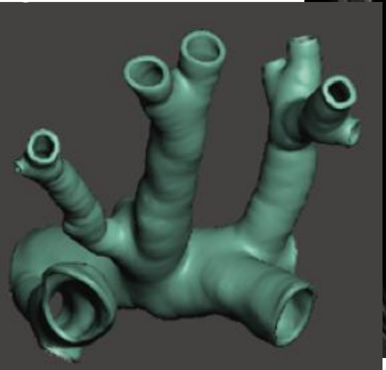
Delrot P, Loterie D. , Moser C. . High resolution volumetric additive manufacturing, Nat. Comm.,11,852 , 2020




Rotation platform
Camera
Lens
Beam profile
Lens
Lens
Observation system
Resin container
Index-matching liquid bath

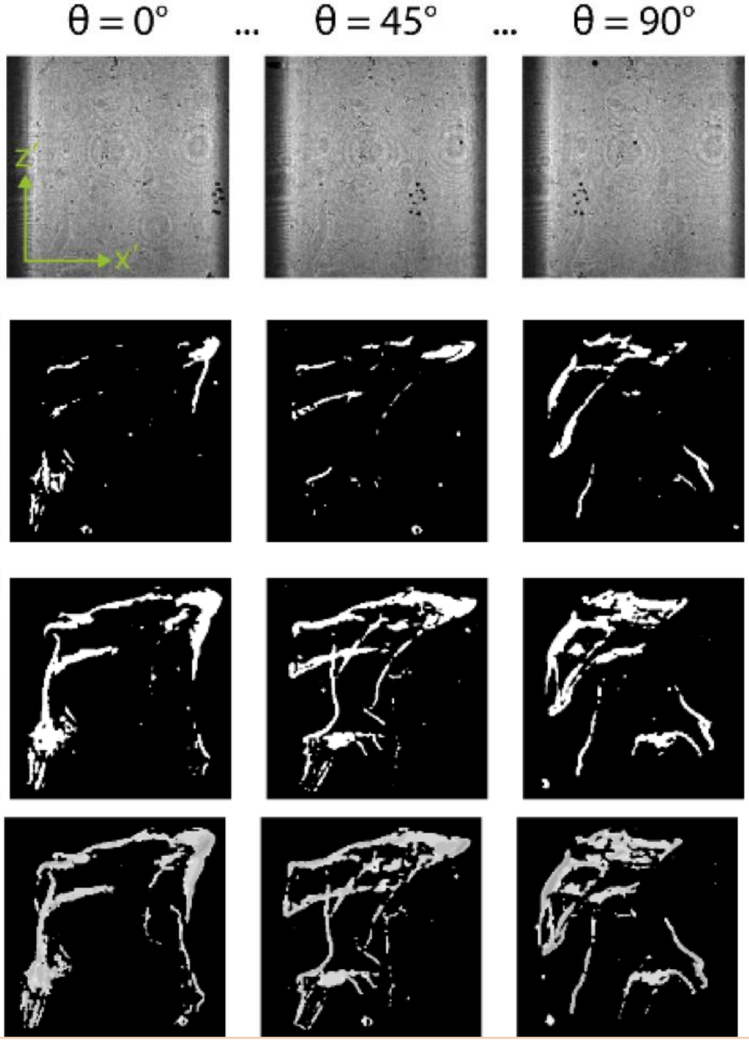


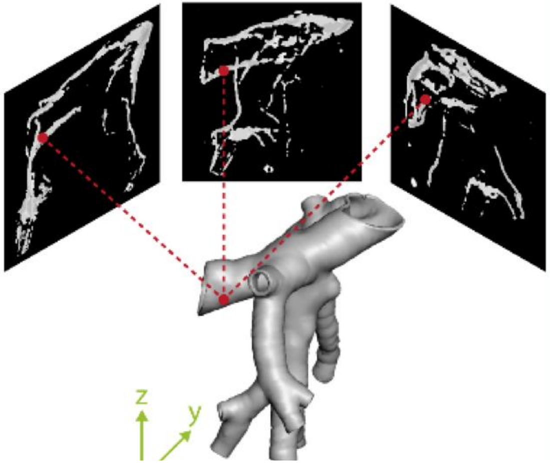

Time: 0.00s Exposure: 0.00s Rotation: 0.0°

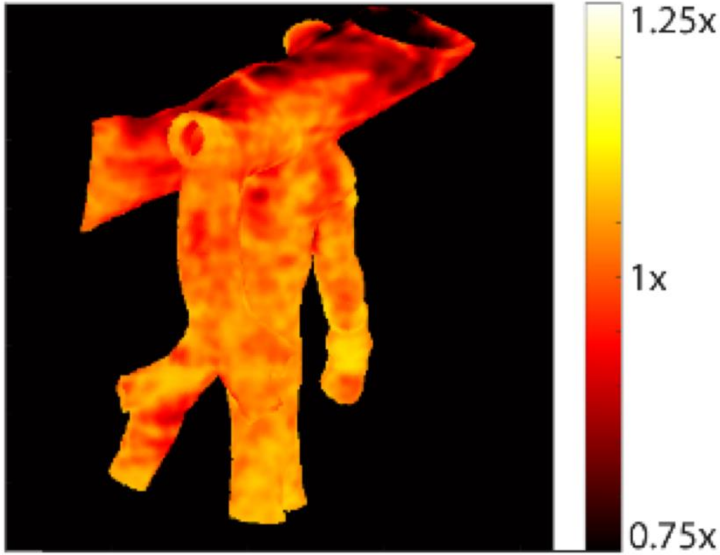


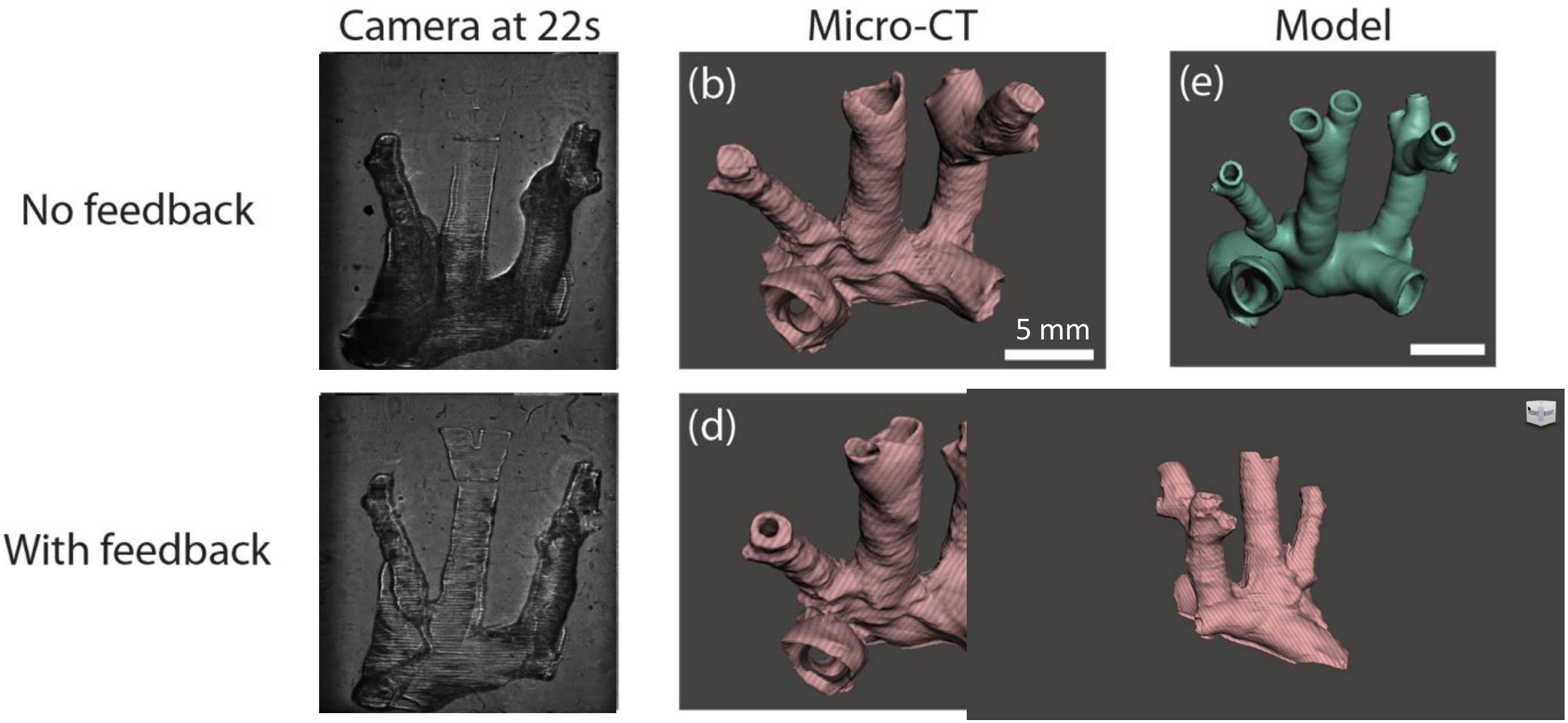
Rot. 8

Rot. 9

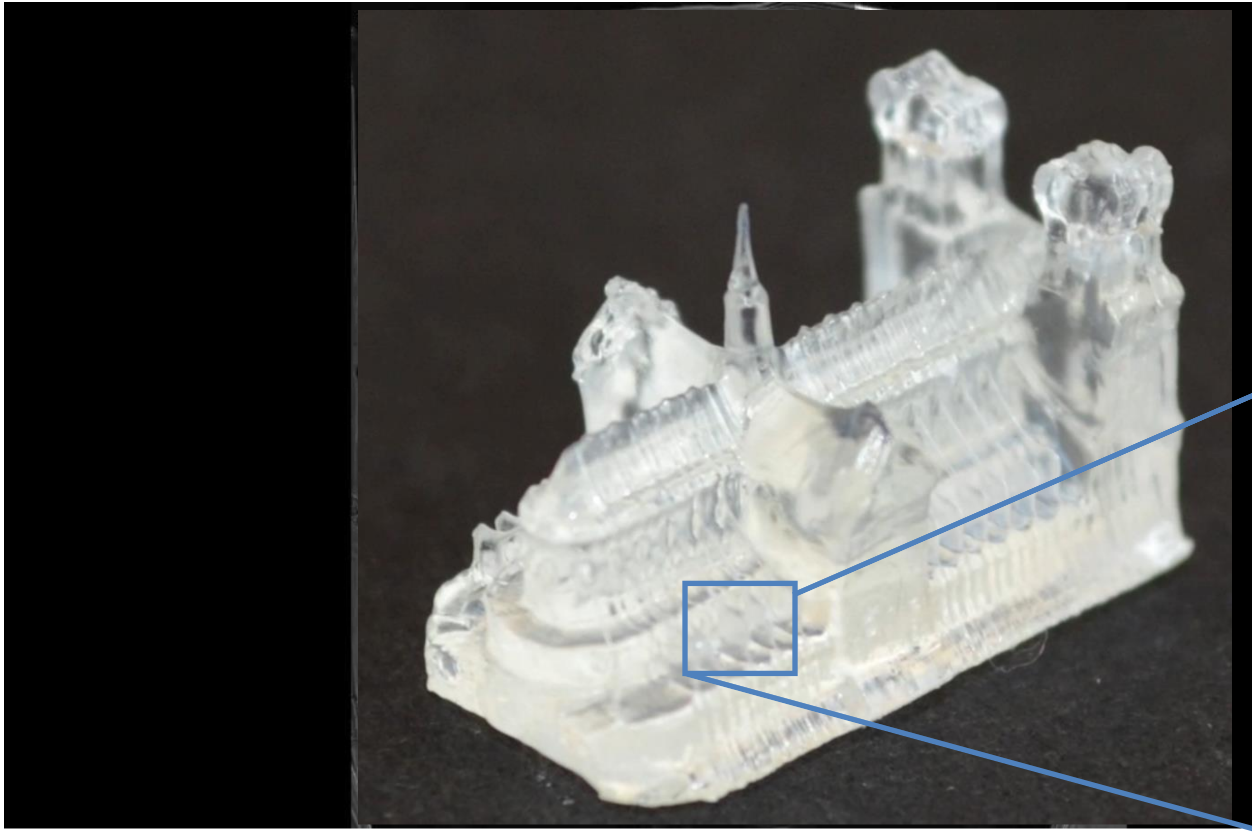


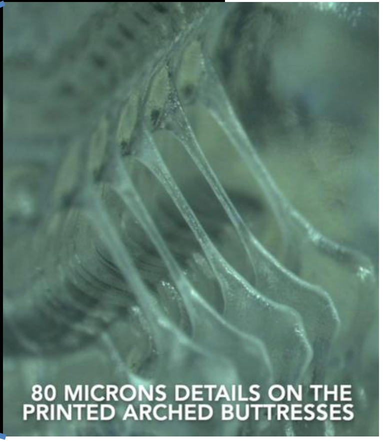


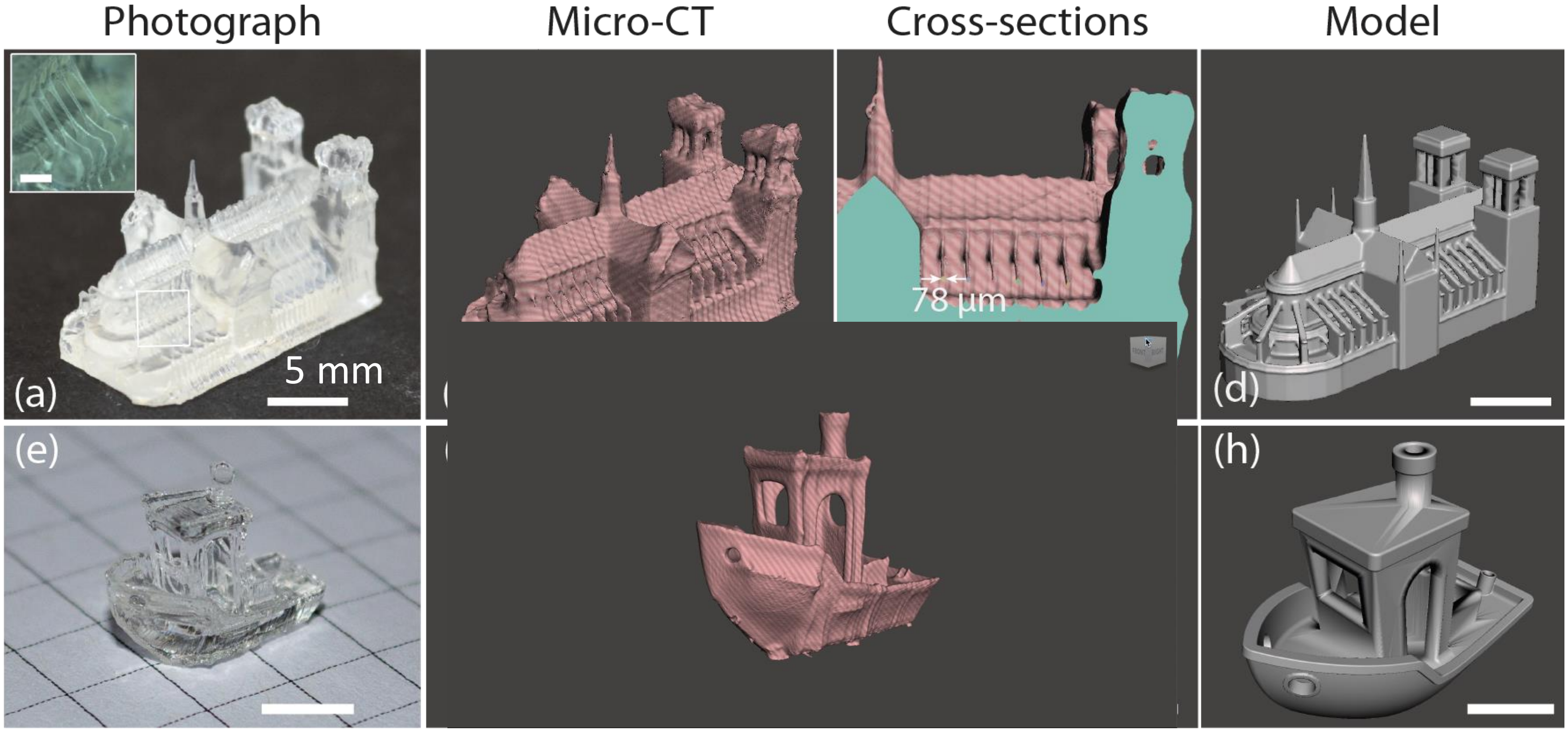


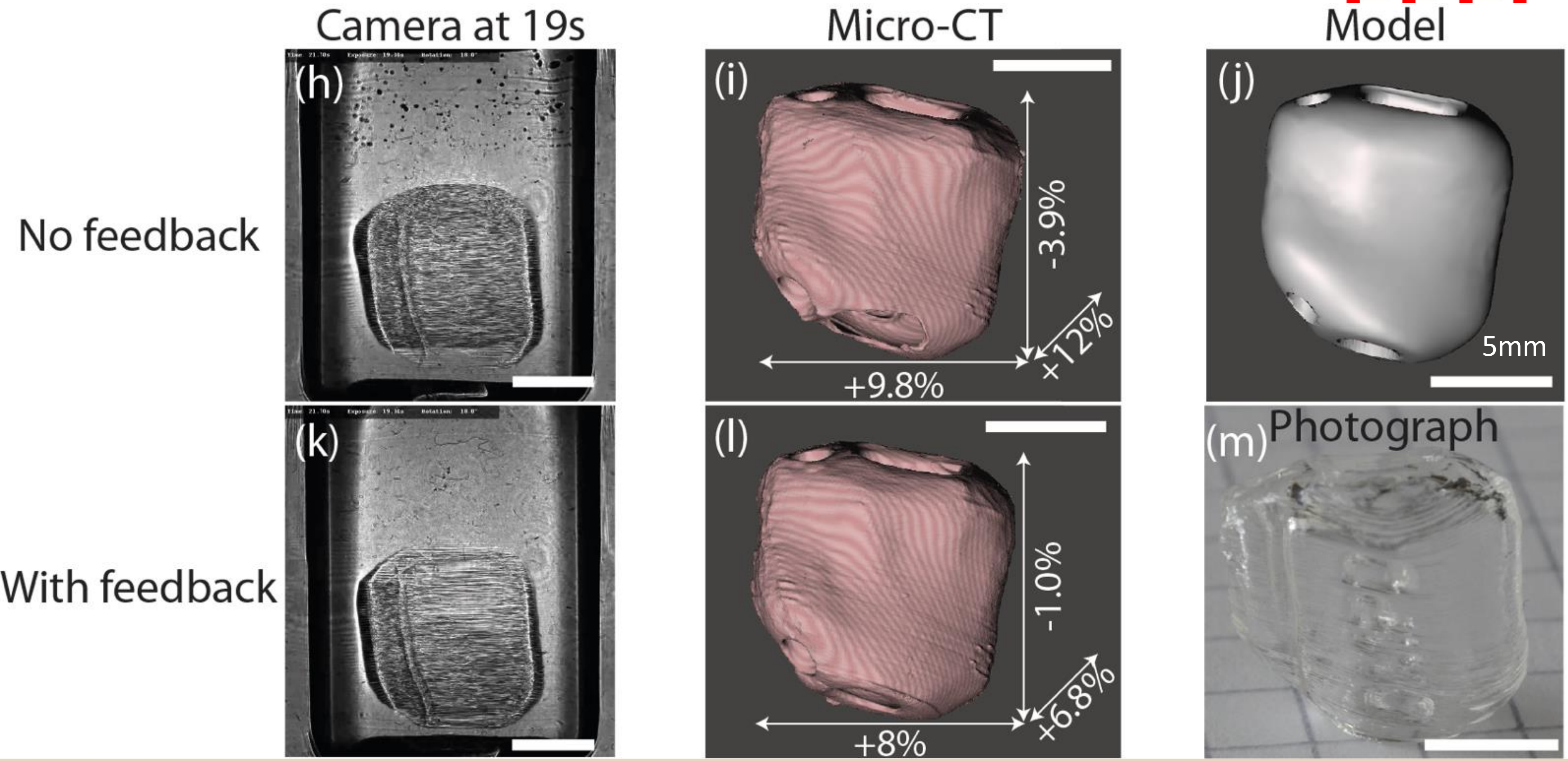


Camera at 22s
Micro-CT
Model
No feedback
With feedback
(b)
(e)
(d)
5 mm

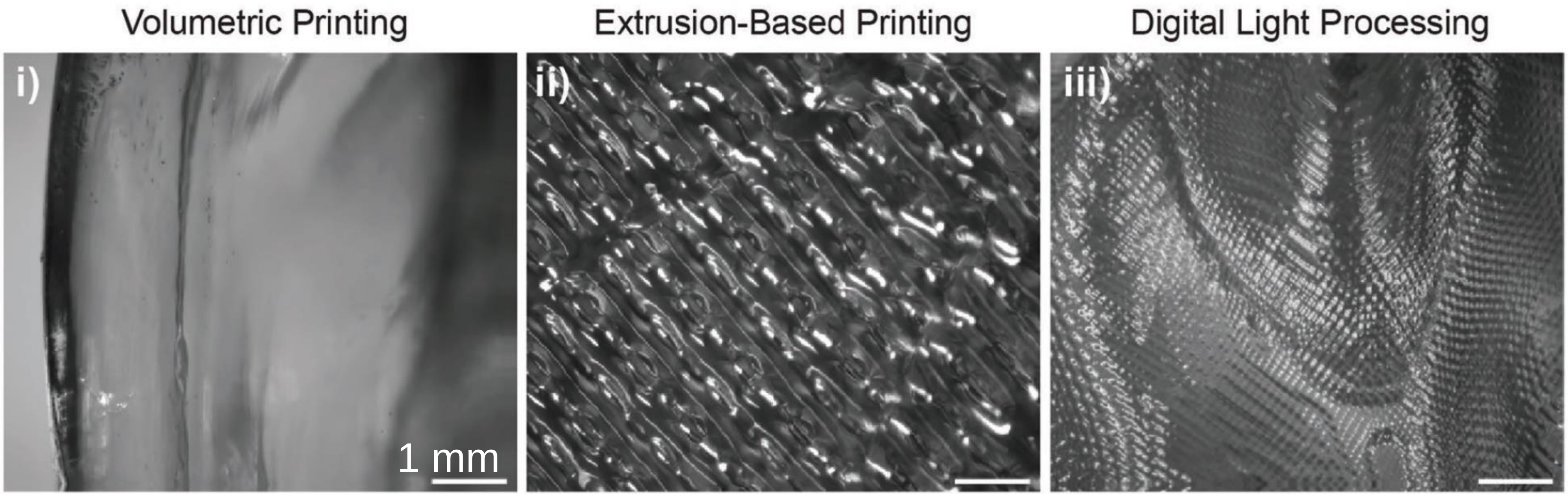



80 MICRONS DETAILS ON THE
PRINTED ARCHED BUTTRESSES

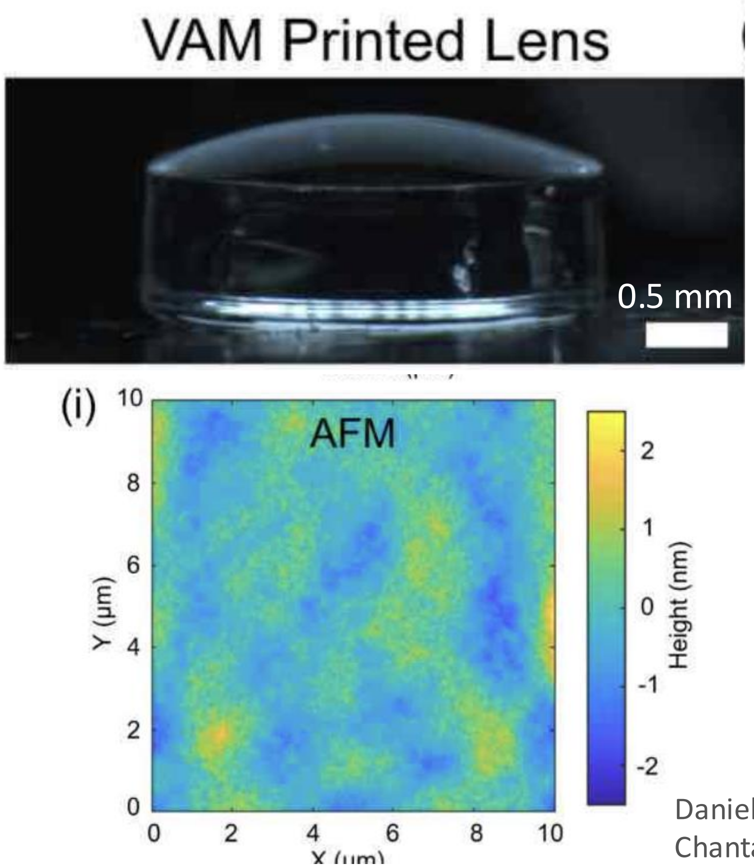

Photograph
Micro-CT
Cross-sections
Model
(a)
5 mm
78 µm
(d)
(e)
(h)

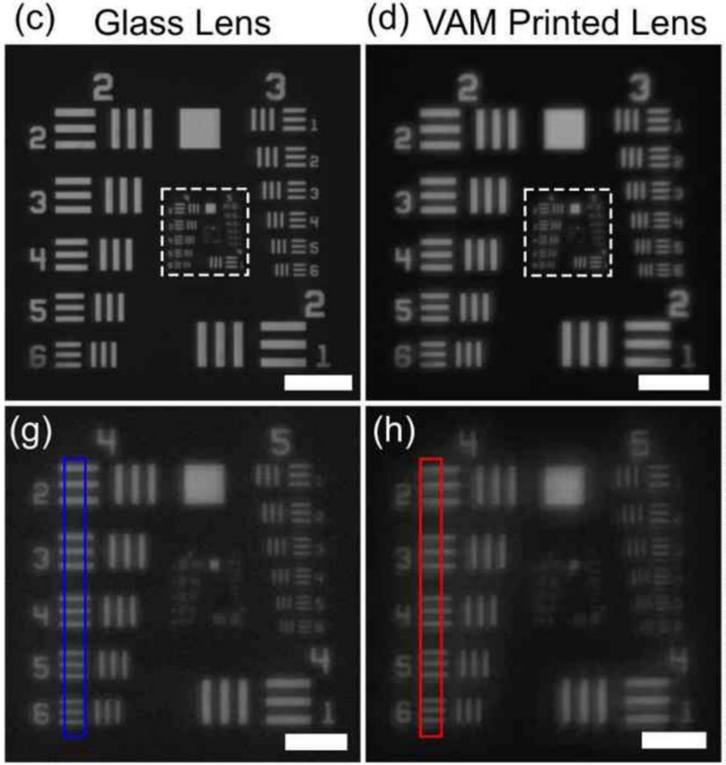

Camera at 19s
Micro-CT
Model
No feedback
With feedback
(h)
(i)
-3.9%
+9.8%
+12%
(j)
5mm
(k)
(l)
-1.0%
+8%
+6.8%
(m)
Photograph

Surface quality



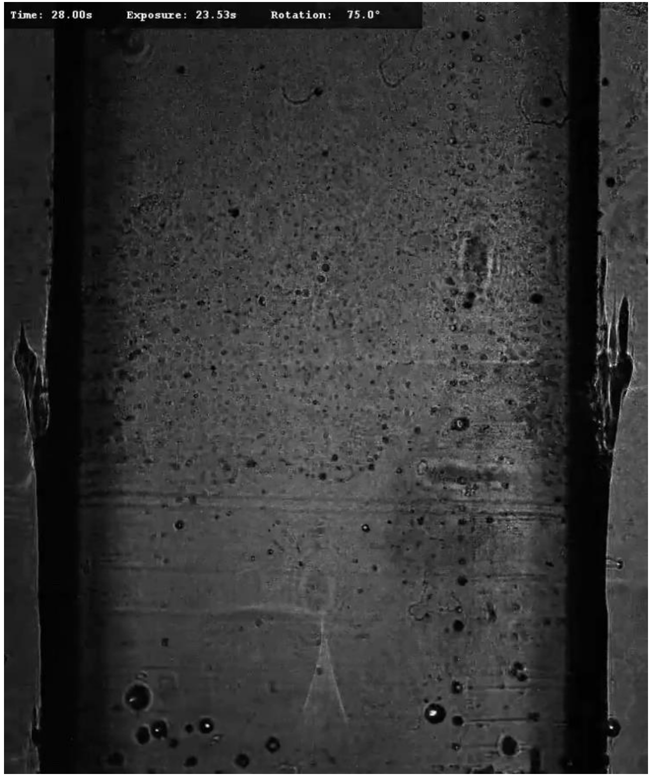
Micro optics fabrication



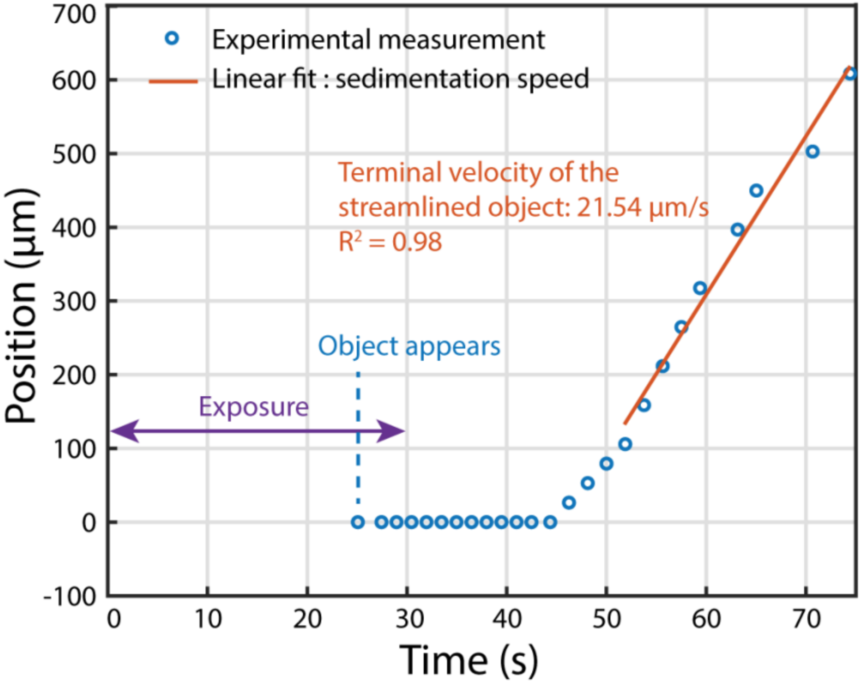


Daniel Webber, Yujie Zhang, Kathleen L. Sampson, Michel Picard, Thomas Lacelle, Chantal Paquet, Jonathan Boisvert, and Antony Orth, "Micro-optics fabrication using blurred tomography," Optica 11, 665-672 (2024)

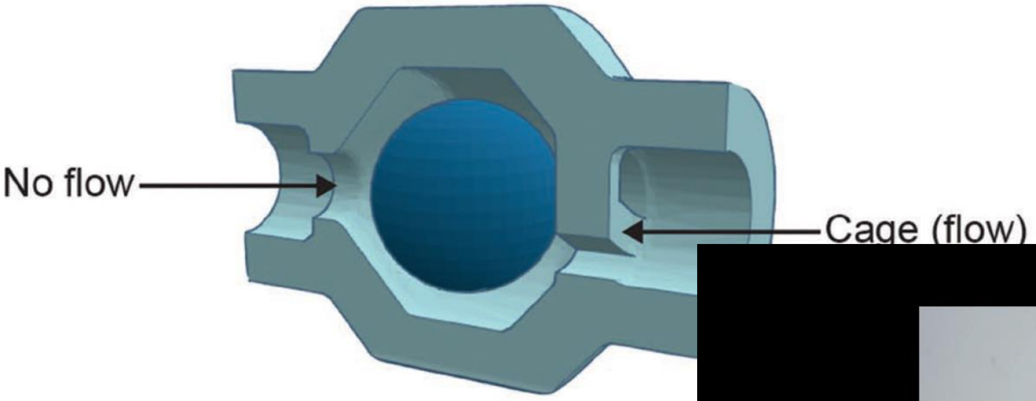
Sedimentation effect



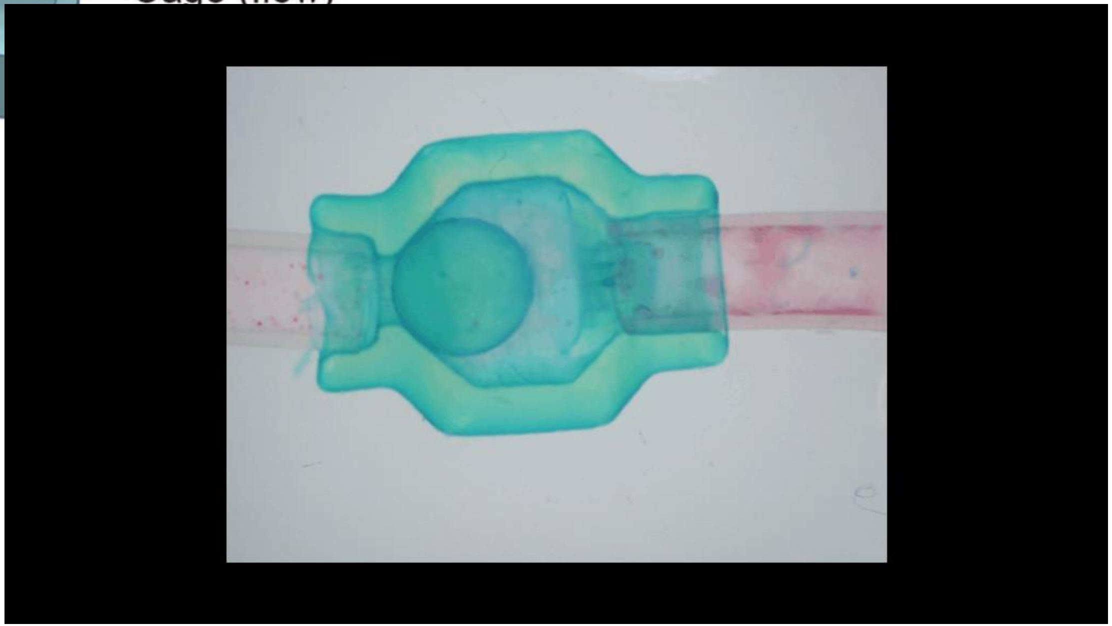
$$v \propto \Delta\rho \cdot r^2/\mu$$



Unique designs: Ball cage valve



Ball cage cardiac valve



Silicone

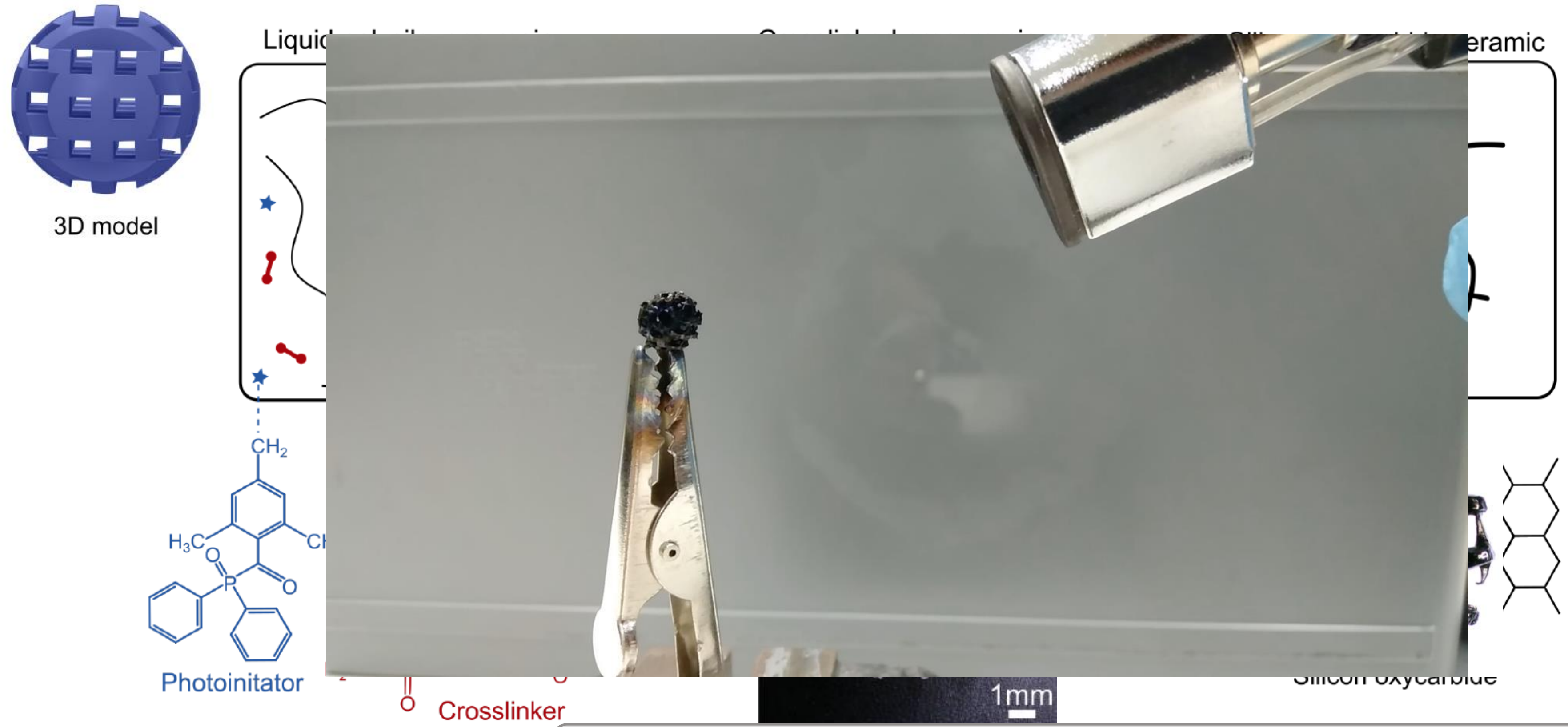
Soft hearing aid shell

Main cavity

Side vent

Arterial junction model

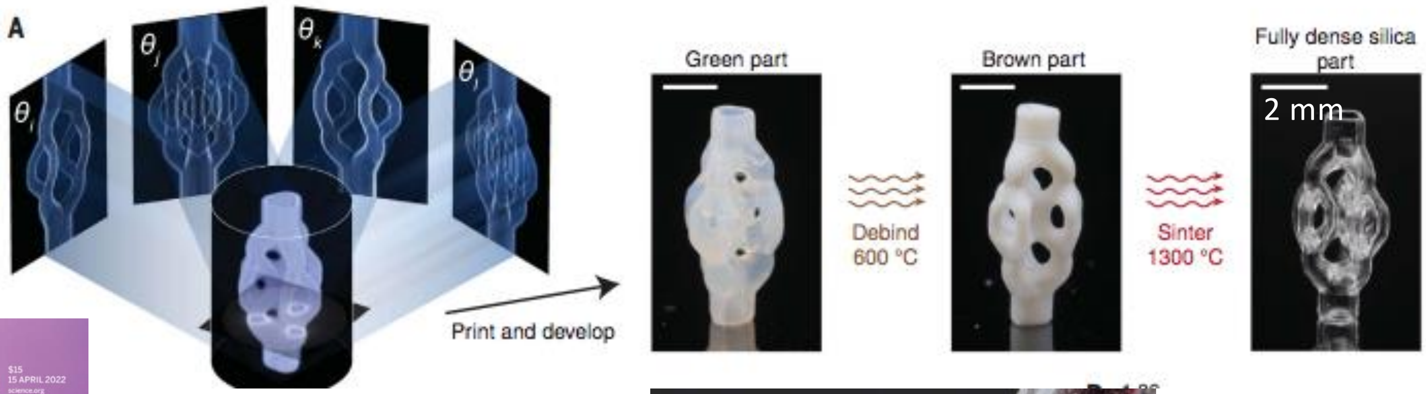
Ceramic

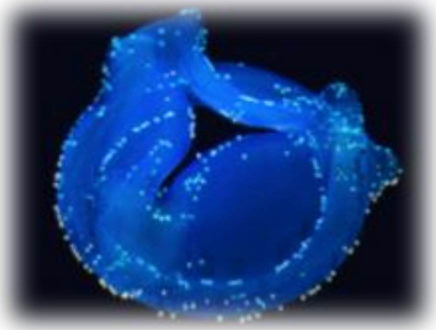


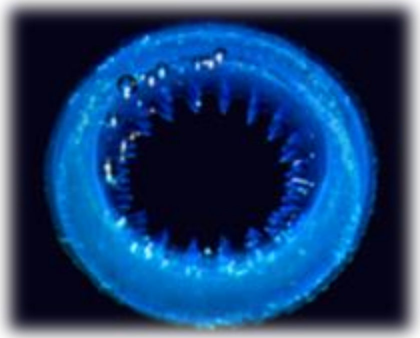
Madrid Wolff J, […], Moser C. "Tomographic volumetric additive manufacturing of silicon oxycarbide ceramics, Advanced Engineering Materials, 2101345 (2022).

Glass

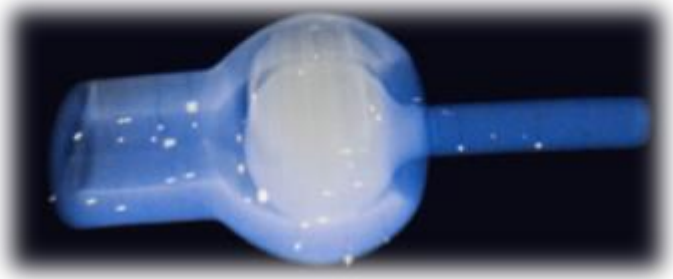
ToombsJ, […], Rapp. B. ,Taylor H. "Volumetric additive manufacturing of silica glass with microscale computed axial lithography, Science , 376 (2022).



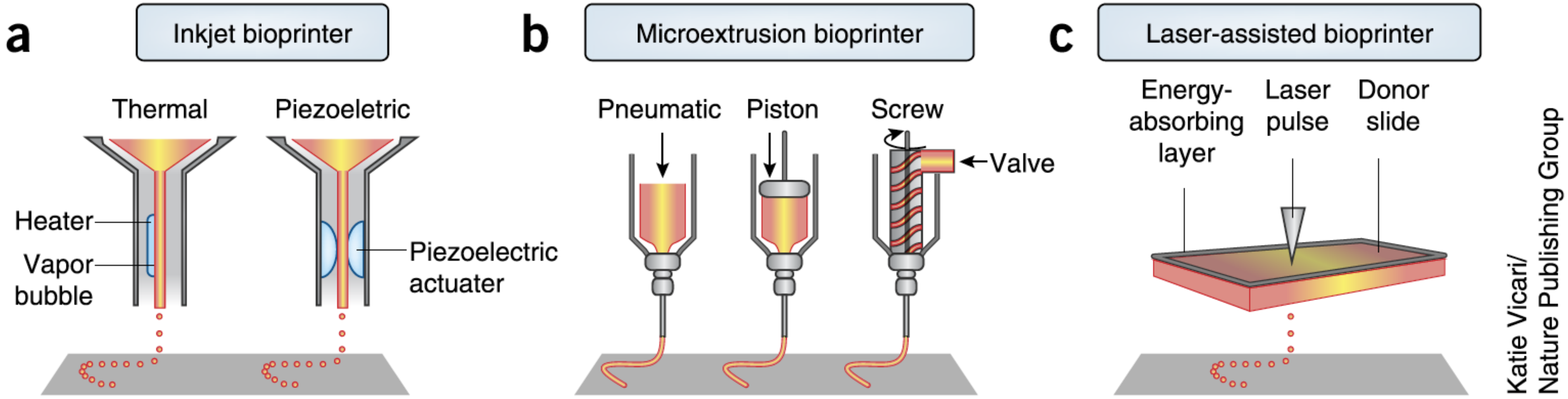




Volumetric Bioprinting with soft hydrogels



Bio Printing technologies

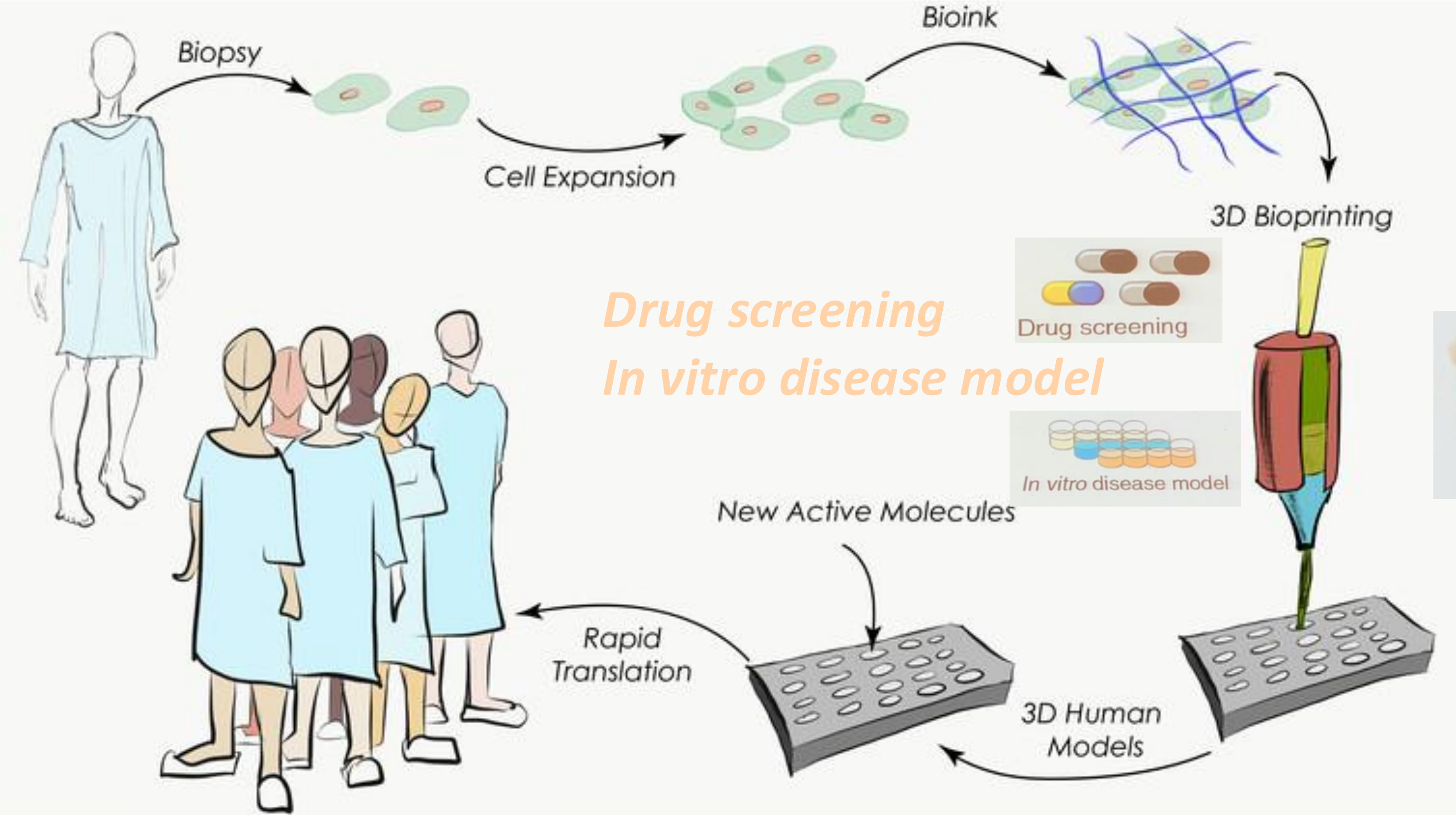


NATURE BIOTECHNOLOGY VOLUME 32 NUMBER 8 AUGUST 2014

3D bioprinting of tissues and organs

Sean V Murphy & Anthony Atala

Now

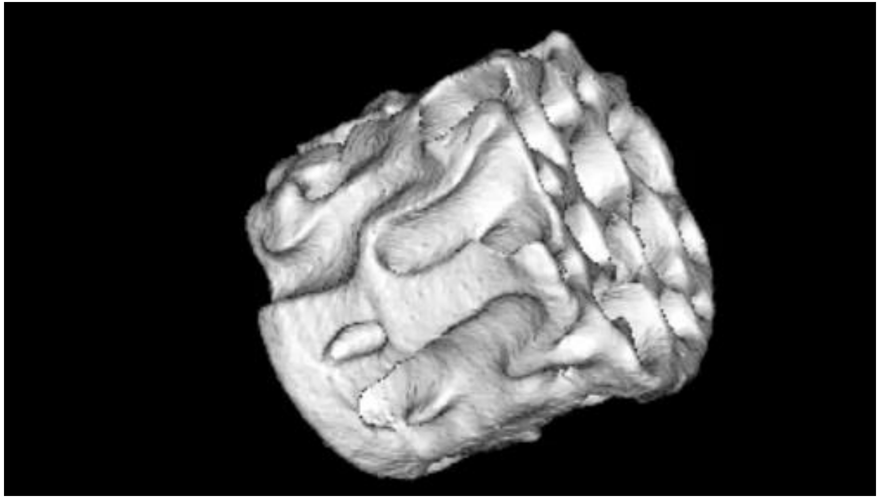


Drug screening

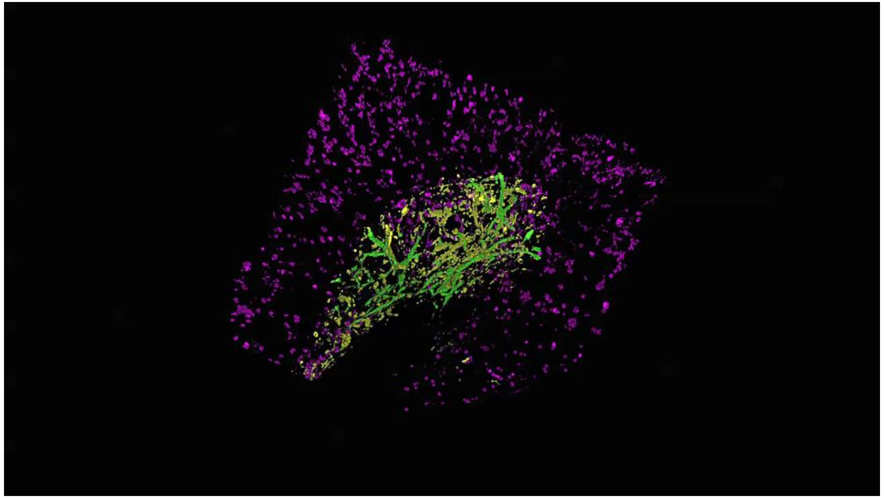
In vitro disease model

Volumetric printing of cell seeded structures

Trabecular Bone construct

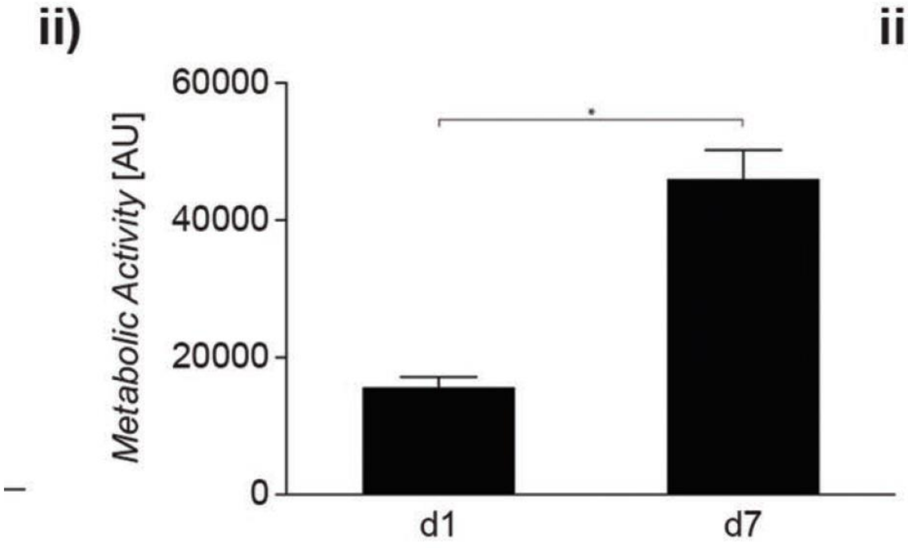


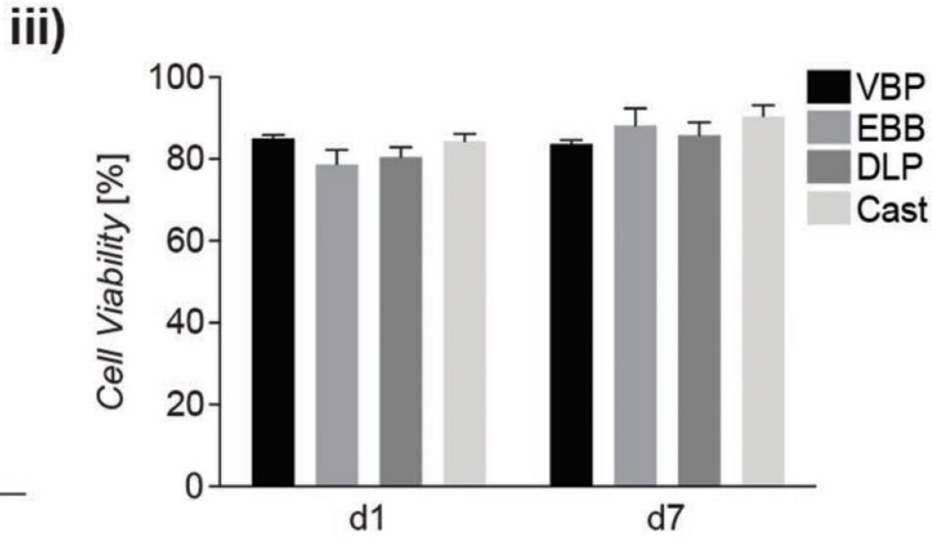
MSC cells in GelMA



Bernal P.N, […] Moser C. Levato R.. "Volumetric Bioprinting of Complex Living-Tissue Constructs within Seconds", Adv. Mat., 2019

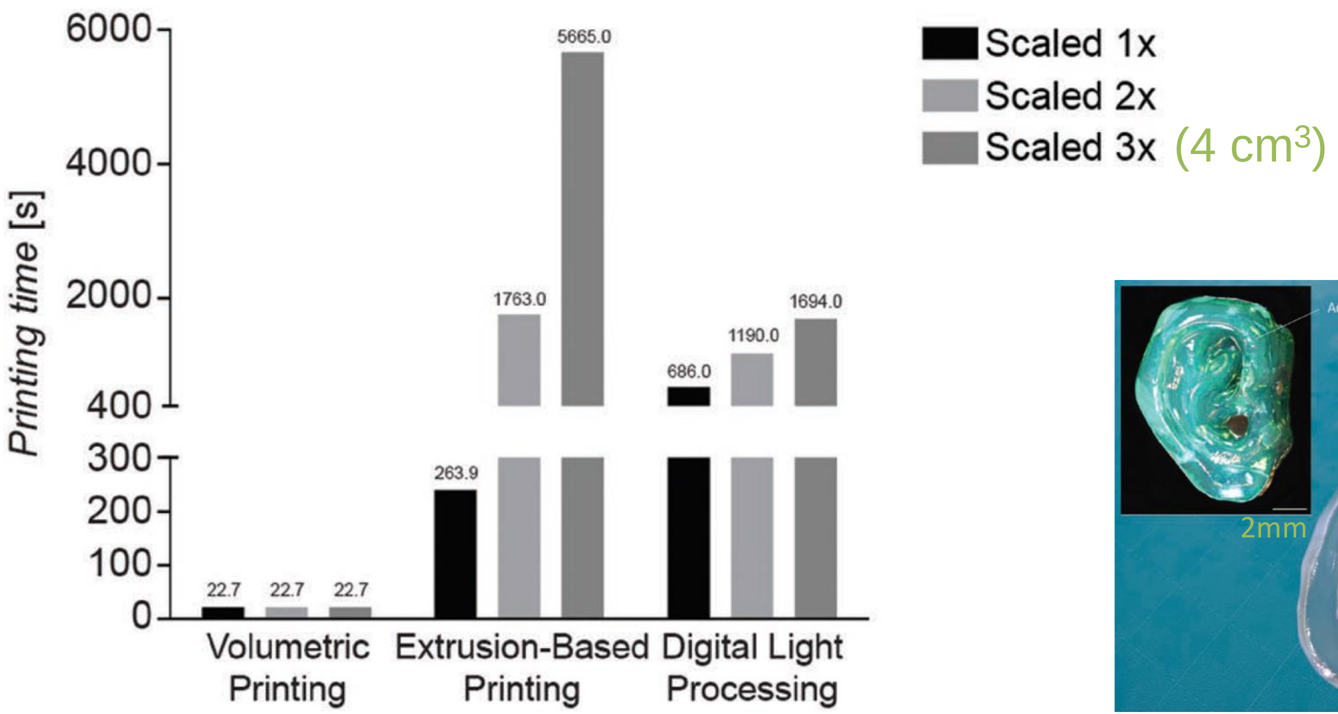
Bioprinting (GelMA)

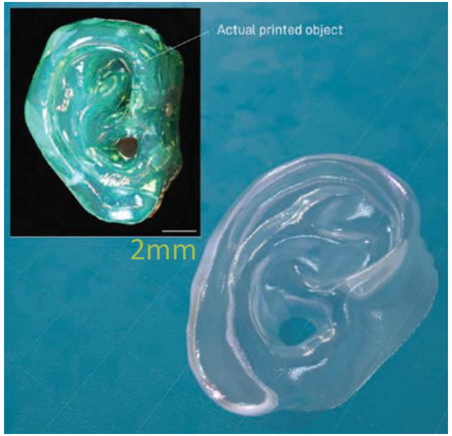




Day 1 Day 7 Day 1 Day 7

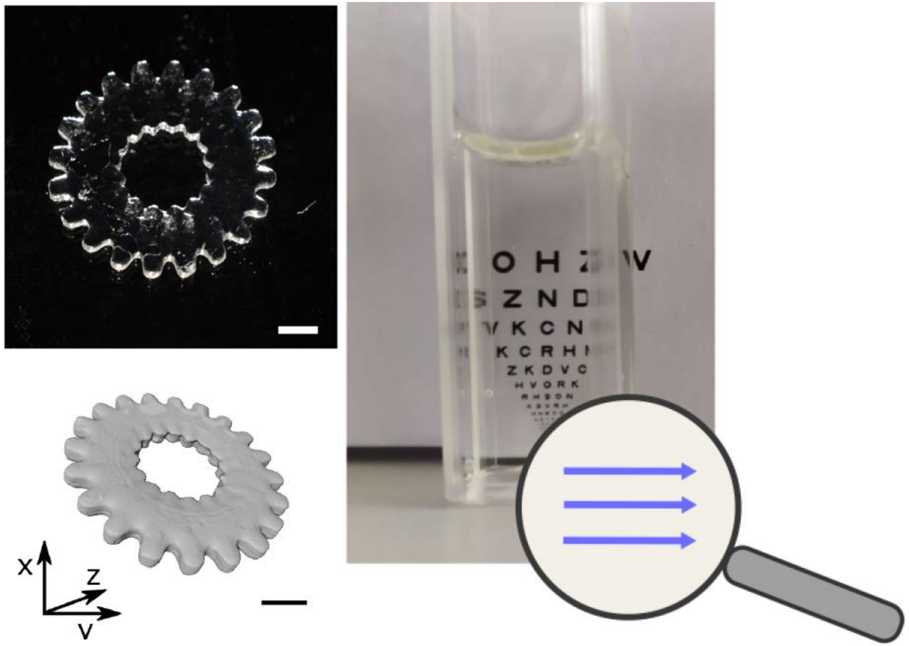
Comparative printing speed



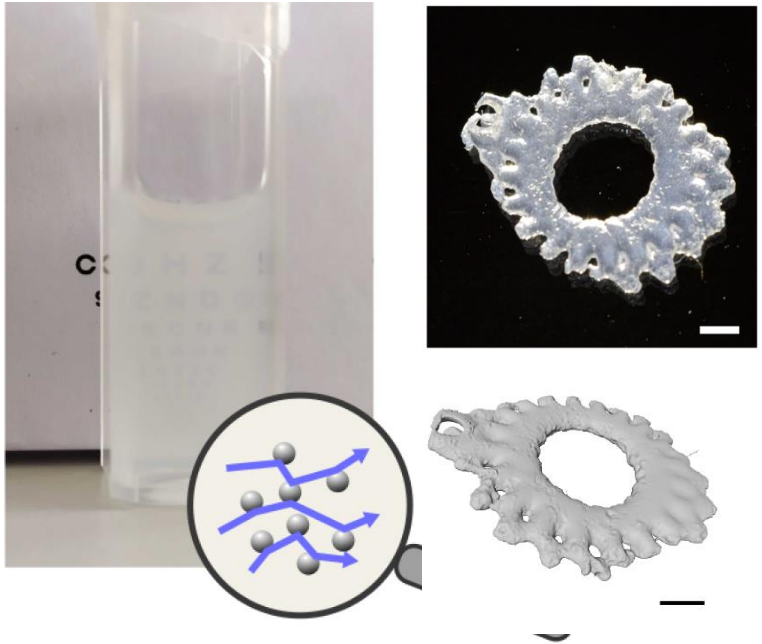


Scattering when cells are added

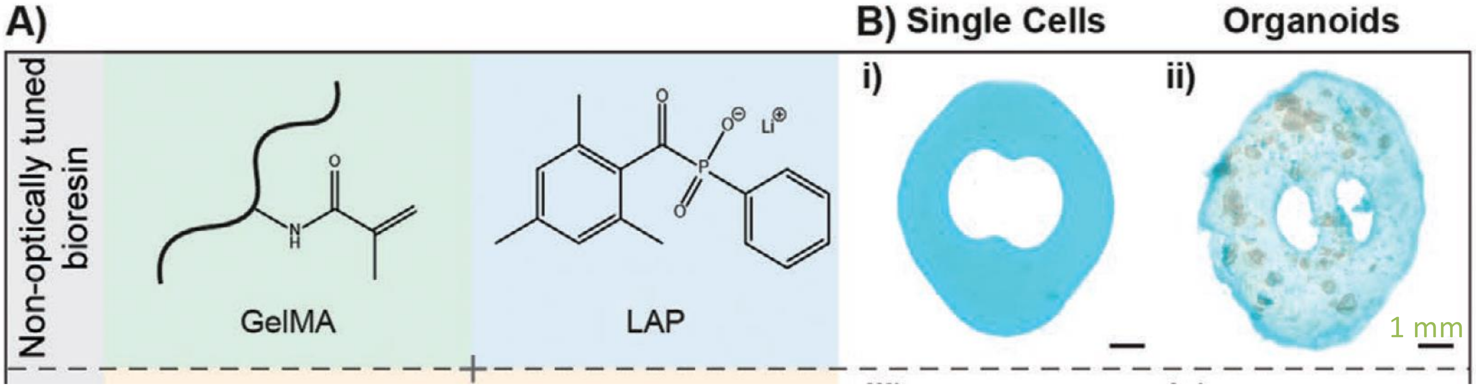
Transparent hydrogel

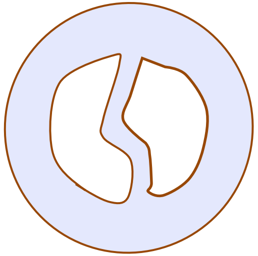


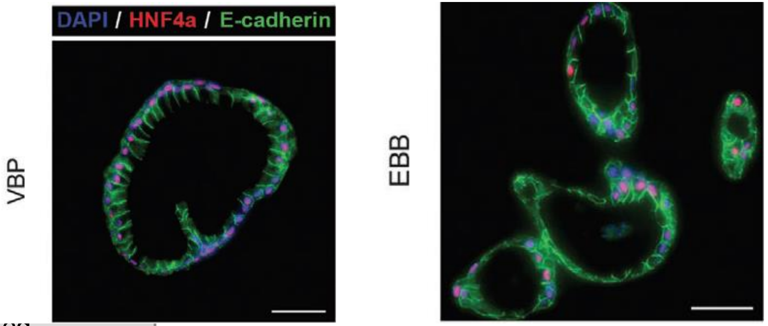
Hydrogel with cells



Printing in organoid-laden bioresins

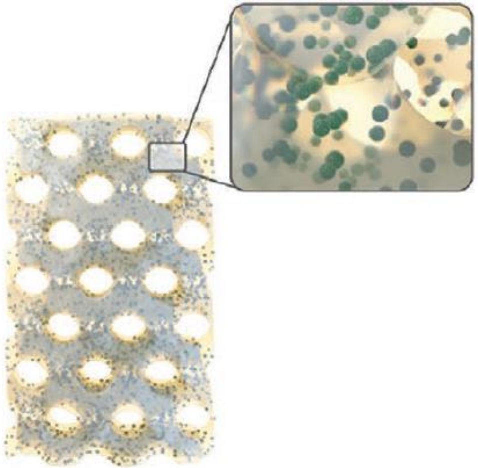




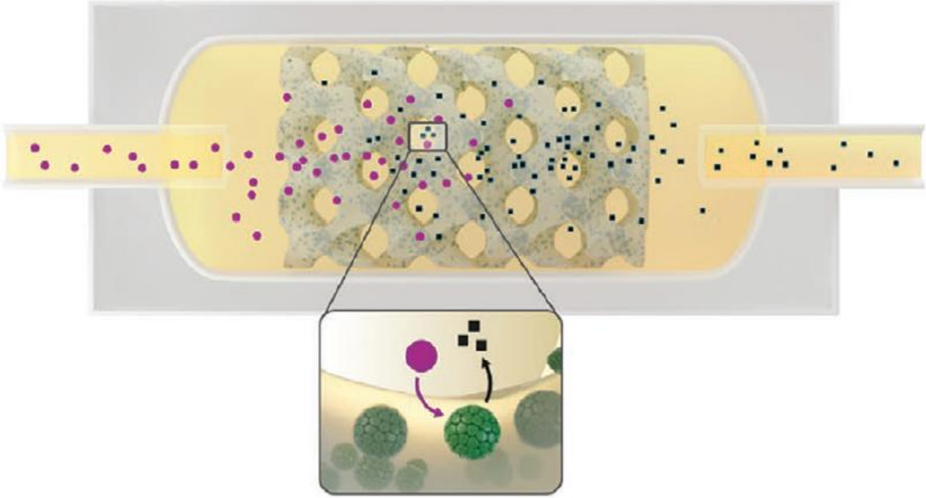


Bernal P., […] Moser C., Levato R. "Volumetric Bioprinting of Organoids and Optically Tuned Hydrogels to Build Liver-Like Metabolic Biofactories", Adv. Mat, 2022.

Printing in organoid-laden bioresins

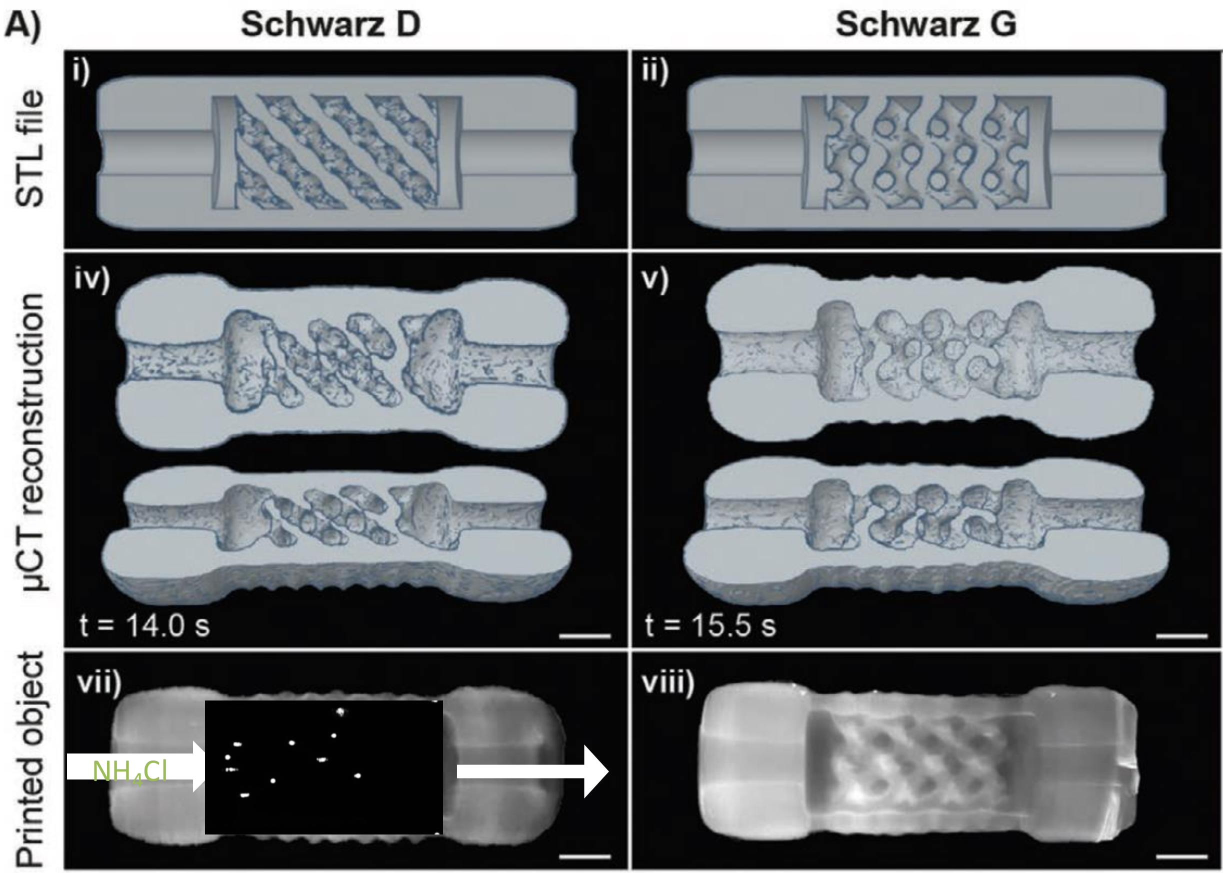


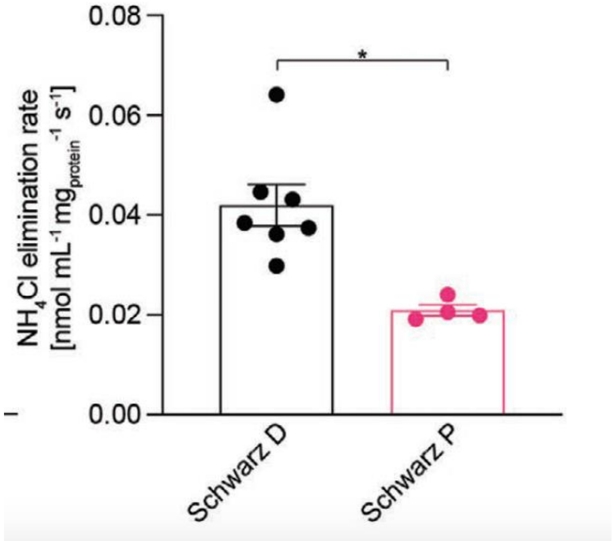
Optimized bioresin
(5% gelMA + 0.1% LAP + 10% iodixanol)
5×10^6 cells mL^{-1}



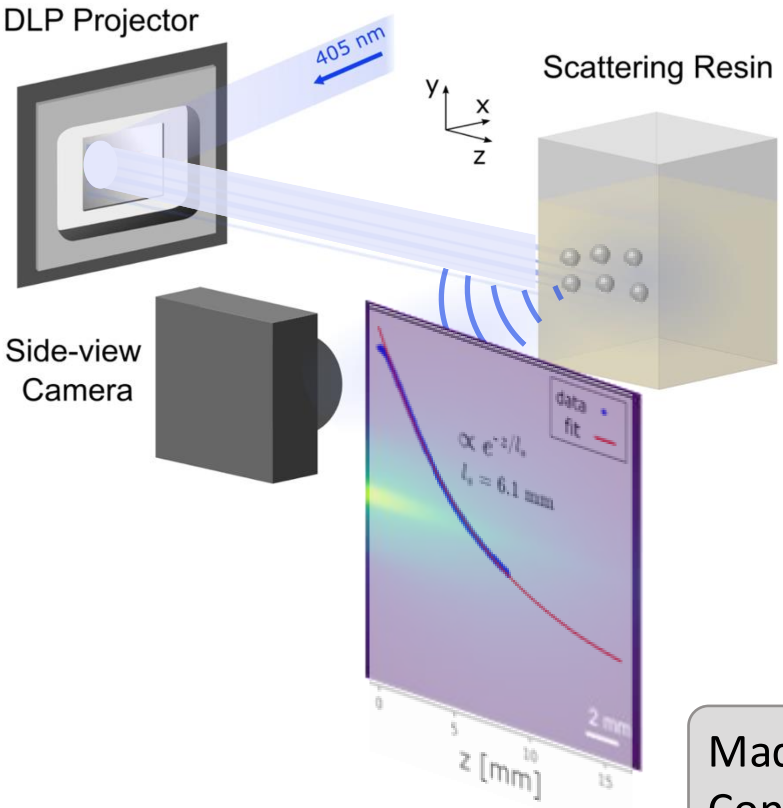
Sterile perfusion system for bioprinted constructs

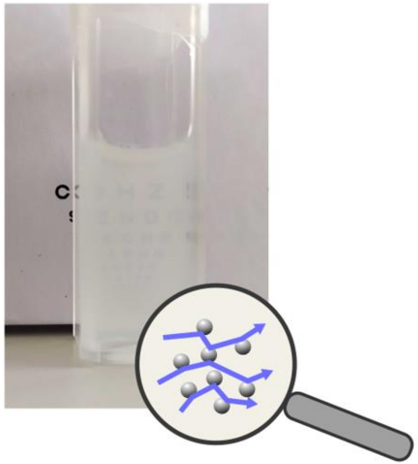
Ammonia detoxification





Printing in scattering resins

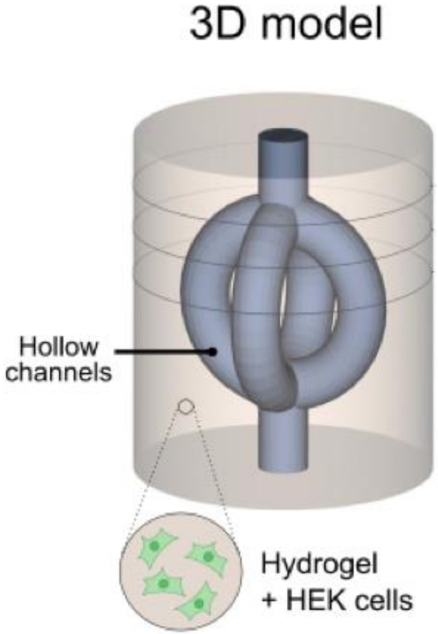


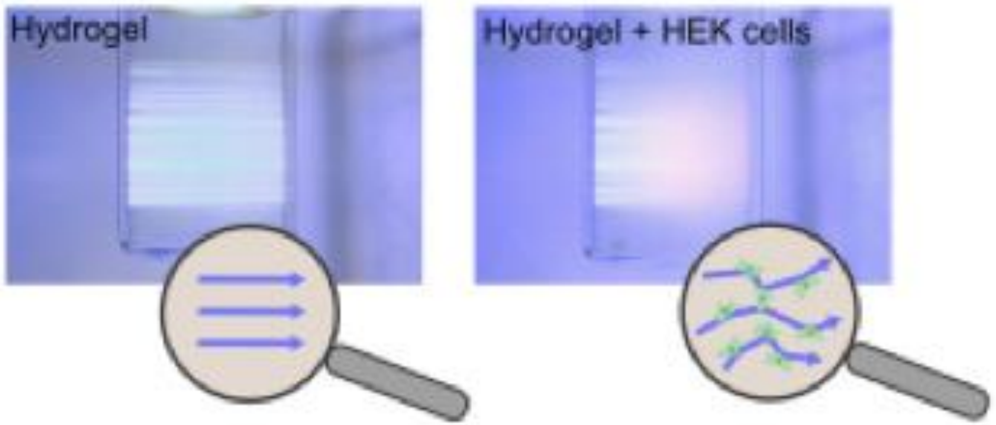


Acrylate +
100 nm **TiO2** nanoparticles

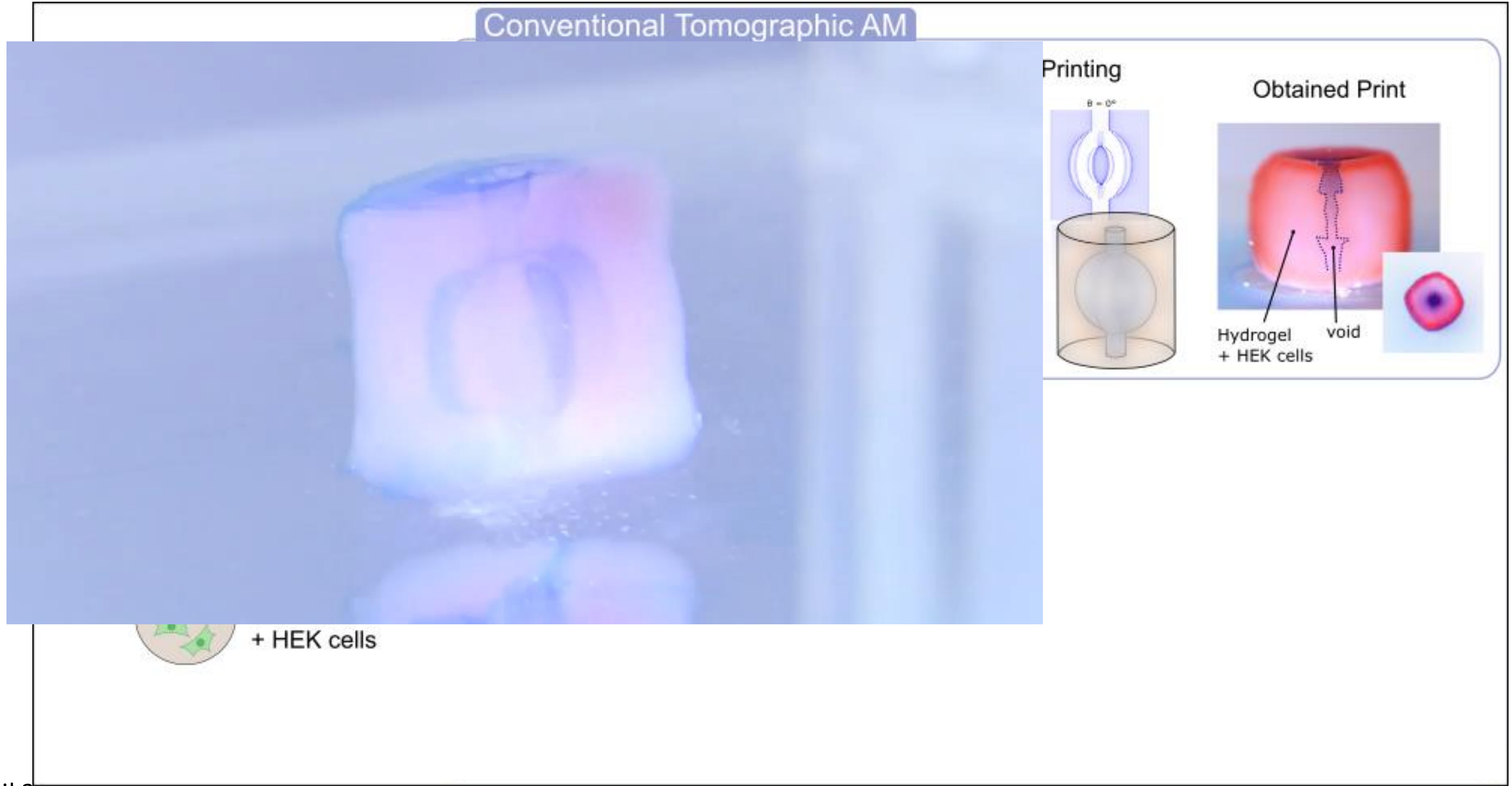
Madrid-Wolf J, Boniface A., Loterie D., Delrot P., M
Controlling light in scattering materials for volum
Manufacturing, Adv. Science, 2022

Printing in hydrogels with High cell densities





Printing in hydrogels with High cell densities



Volumetric printing by tomographic back-projections

- Principle of Reverse Tomographic Projection
- Ultra fast printing speed (30 seconds)
- No support structures
- 80 µm resolution