Measurement of Porosity in the Context of Fiber-Based Tissue Scaffolds

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Solving the Inverse Problem

How far can I shoot

vs.

How big does my trebuchet need to be

Which scaffold properties will lead to fast fusion?

• Stiffness, strength
• Pore size, porosity
• Chemistry
Why Structure Matters

- Stiffness
- Strength
- Permeability
- Interconnectivity
- Homogeneity
- Neck radius
- Pore shape
- Specific surface area
- Periodicity
- Absorption rate
- (An)isotropy
- Cell proliferation
- Dissolution rate

Porosity & Pore Size Distribution

\[
\text{Porosity} = \frac{\text{Volume}_{\text{pore}}}{\text{Volume}_{\text{bulk}}}
\]

Which structural parameters will describe their properties sufficiently for tissue engineering applications.
Definitions

Porosity is a dimensionless number that describes the fraction of empty space in a material.

**Volume based calculation:**

\[ \varepsilon = \frac{V_v}{V_b} \]

- \( \varepsilon \) ... porosity
- \( V_v \) ... void volume
- \( V_b \) ... apparent total bulk volume

**Density based calculation:**

\[ \varepsilon = \frac{\rho_s - \rho_b}{\rho_s - \rho_{fl}} \]

- \( \varepsilon \) ... porosity
- \( \rho_s \) ... skeleton/fiber density
- \( \rho_b \) ... bulk density
- \( \rho_{fl} \) ... fluid density

**Pore size:**
- Smallest dimension within a pore
- Largest inscribable sphere (suggestion)

**Throat size:**
- Smallest dimension between two pores

Figure 5. Schematic cross-section of a porous solid (Globes et al., 2006).
Dimension and Mass Measurement

• Conceptually simple
• Dimensional measurement not trivial
  • Optical
  • Contact
• Weighing is simple
• Need to know true density to determine porosity
  • Closed porosity
  • Phase changes due to processing
Gravimetric Approach

\[ \varepsilon = \frac{w_{sat} - w_{dry}}{w_{sat} - w_{im}} \]

\[ V_b = \frac{w_{sat} - w_{im}}{\rho_{fl}} \]

\[ V_p = \frac{w_{sat} - w_{dry}}{\rho_{fl}} \]

\( \varepsilon \) ... porosity
\( V_b \) ... bulk volume
\( V_p \) ... pore volume
\( w_{sat} \) ... saturated weight
\( w_{dry} \) ... dry weight
\( w_{im} \) ... immersed weight
\( \rho_{liq} \) ... fluid density

Challenges
- Trapped air
- Saturated measurement
- Water absorption
- Buoyancy

3 measurements:
- Dry
- Saturated
- Immersed
Volumetric Approach - Pycnometer

\[ V_s = V_c \frac{V_r}{1 - \frac{P_1}{P_2}} \]

- \( V_s \) ... sample volume
- \( V_c \) ... empty chamber volume
- \( V_r \) ... reference chamber volume
- \( P_1 \) ... initial pressure
- \( P_2 \) ... final pressure

- Based on Boyle’s law
  - Independent bulk volume measurement required
  - Simple principle
  - Accurate volume measurement
  - No swelling
Porosimetry

\[ D = \frac{-4\gamma \cos\theta}{P} \]

- \( D \) ... pore diameter
- \( \gamma \) ... surface tension
- \( \theta \) ... contact angle
- \( P \) ... pressure

- Requires non-wetting liquid
- Mercury toxicity
- Pore shape assumption
- Cumulative pore volume also give the porosity
Structure Analysis Bases Approaches

2D (microscopy) or 3D (tomography) images used to measure the porosity and pore size

• 2D methods (challenges)
  • pore infiltration
  • serial sectioning
  • 3 orientations

• 3D methods (challenges)
  • Cost, time
  • Resolution
  • Automatic image analysis

\[
\varepsilon = \frac{P}{P_0} = \frac{L}{L_0} = \frac{A}{A_0} = \frac{V}{V_0}
\]

Figure 1. Schematic illustrations with corresponding calculations for area-, line- and point fraction for (a), (b) and (c) respectively showing only a slight variation between the different methods.
Round Robin’s and Control Samples

• Think of effective ways to conduct round robin tests?
• How would control sample look like?
• How would controls be manufactured?
• Use of challenge samples
Literature


