Medical Catheters and Plastics – Properties Critical to Performance

Medical catheters are indispensable devices in modern healthcare, serving critical roles in diagnostics, interventions, and therapy delivery. Their ability to perform efficiently inside the human body depends on a variety of mechanical and functional properties that dictate their navigation, control, and visibility.

This article combines key aspects of catheter performance, focusing on **pushability, torque ability, and radio-opacity**—three of the most important parameters determining their safe and effective use in clinical practice.

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1. Pushability of Catheters

Pushability refers to the ease with which a catheter can be advanced through the vascular system. It expresses the degree of force required to transmit a longitudinal push from the proximal (near insertion) end to the distal (farthest) end of the catheter.

In engineering terms, pushability is linked to **columnar stiffness**, which defines the ability of the catheter to transmit force or displacement along its axis. For small deflections, a catheter can be approximated as a spring system, with its longitudinal stiffness defined by:

$$k_{long} = \frac{EA}{L}$$

Where

k_{long} is the longitudinal spring constant,

E is the modulus of elasticity of the material of the catheter,

A is the cross-sectional area

L is the length of the catheter shaft.

Implications:

- Increased catheter size (larger cross-sectional area) → **higher pushability.**
- Higher material stiffness (elastic modulus) → **improved force transmission.**
- Shorter catheter length → **better pushability.**

Limitations in practice:

- Catheter size is restricted by vessel diameter.
- Stiffer materials risk vascular injury.
- Length is dictated by procedure and anatomical access point.

Thus, pushability must be carefully balanced between mechanical performance and patient safety.

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2. Torqueability of Catheters

Another crucial property for catheter navigation is **torqueability**, or the ability to transmit rotational force (torque) from the proximal to distal end. Torque allows physicians to steer and maneuver catheters through complex vasculature.

The **torque ratio**—the degree of distal rotation divided by proximal rotation—indicates performance. Sometimes, a slightly lower torque ratio may improve fine steering control.

For small deflections, torsional stiffness (torqueability) can be expressed as:

$$k_{torq} = \frac{GJ}{L} \qquad (2)$$

Where

k_{torq} is the torsional spring constant

G is the shear modulus

J is the polar moment of inertia

L is the length of the catheter shaft

Maximizing the transmission of torque means an increase in the torqueability of the catheter and this can be achieved by maximizing the torsional stiffness value, k_{torq}. One of the ways of increasing the k_{torq} value can be through maximization of the material polar moment of inertia, J.

For a tube, the governing equation for J is:

$$J = \frac{\pi}{32}(d_o^4 - d_i^4) \qquad (III.6)$$

Where,

d_o = outer diameter of the catheter

d_i = inner diameter of the catheter

Maximization of J can be achieved through the maximization of the catheter's outside diameter as well as its wall thickness.

As the shear modulus is also directly proportional to the torqueability, an increase in the shear modulus can also result in an increase in the k_{torq} value. The shear modulus is directly related to the elastic modulus of a polymer and generally expressed as:

$$E = 2G(1 + \upsilon) \quad (3)$$

Where,

E = Material elastic modulus

G = Shear modulus

ν = Poisson's ratio

Poisson's ratio is a dimensionless quantity and is generally between 0.3 – 0.5 for most plastics.

An increase in torqueability can also occur with a corresponding decrease in the part length, L, as it is inversely proportional to k_{torq}. However, as with pushability, the degree of freedom with these variables in increasing the torqueability is limited by the application site and the potential of injury to the blood vessels.

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3. Radio-Opacity of Catheters

Beyond mechanical properties, visualization of catheters during procedures is critical. This is achieved through **radio-opacity**—the ability of the catheter material to block X-rays. Radio-opacity (or radiodensity) enables clear imaging under fluoroscopy, a real-time X-ray imaging technique widely used in cardiovascular interventions.

3.1 Physics of X-ray Interaction

X-rays are high-energy electromagnetic waves (wavelength 0.1–1 Å) with photon energies of 5–10 keV for medical imaging. Their attenuation within the body depends on tissue composition: bones (rich in calcium, high atomic number) appear clearly, while soft tissues do not. To distinguish catheters, **radio-opaque fillers** are added to polymers to increase contrast.

3.2 Common Radio-Opaque Fillers

- **Barium sulfate ($BaSO_4$):**
  - Specific gravity: 4.5
  - Typical loading: 20–40 wt%
  - Low cost, white in color, easily colored with pigments
  - Requires higher loading for adequate opacity, which may reduce tensile strength and biological stability

- **Bismuth compounds:**
  - Almost twice as dense as $BaSO_4$
  - Allows greater loading with less compromise to plastic properties
  - More expensive, but provides clearer imaging
- **Tungsten powder:**
  - Extremely high specific gravity: 19.5
  - Enables excellent radiographic clarity at lower loadings
  - Abrasive nature can damage compounding extruders, limiting use

3.3 Design Considerations

- **Location of use:** Deeper catheters (e.g., coronary arteries) require higher filler loadings compared to superficial ones.
- **Wall thickness:** Thin-walled catheters need higher loadings.
- **Discrete vs. uniform markers:** Some catheters use localized opaque strips instead of uniformly filled tubing.
- **Filler blending:** Combining fillers can balance cost, radiographic clarity, and mechanical performance.

Compounding must be carefully controlled to prevent over-shearing, which may degrade sensitive fillers (e.g., bismuth) or damage processing equipment (e.g., tungsten).

Conclusion

The design of medical catheters is a balancing act between **mechanical performance** and **functional visibility**.

- **Pushability** ensures effective longitudinal advancement.
- **Torqueability** allows precise rotational control for navigation.
- **Radio-opacity** provides critical visualization during imaging procedures.

Each property is influenced by material selection, geometry, and processing, but ultimately limited by anatomical constraints and patient safety considerations. Understanding these interdependent parameters helps engineers and clinicians design catheters that are safe, effective, and reliable for life-saving medical interventions.
If you have any other questions or would like to suggest topics for us to write about, please feel free to contact us at info@polymerupdateacademy.com

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