Drug-eluting Stent Platform
(Stent Material, Design, Mechanics)

최락경
Buchen Sejong Hospital, Korea
History of Stenting

1912
Paraffin-coated glass & metal tubes implanted in canine thoracic aorta

1969
Non-surgical endovascular placement of guide wire mounted spiral springs

1985
Balloon mounted stainless steel graft implanted in canine aorta & peripheral vessels

1986
First human coronary stent implanted: Self-expanding stainless steel wire mesh implanted in canine coronary arteries

1994
FDA approval of coronary stents: STRESS & BENESTENT show reduced restenosis with stenting vs. PTCA

1998
EPISTENT shows significant benefit of ReoPro® with stenting

1999
First drug eluting stent implanted in humans

2006
First fully bioabsorbable drug eluting stent implanted in humans

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Current commercially available DES

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<tbody>
<tr>
<td>Sirolimus-eluting Cypher stent</td>
<td>TAXUS™ Stent</td>
<td>Endeavor™ Stent</td>
<td>TAXUS™ Element™ Stent</td>
<td>Metal &amp; Polymer Bioabsorbable stents</td>
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<tr>
<td>TAXUS™ Express™ Stent</td>
<td>TAXUS™ Liberté™ Stent</td>
<td>XIENCE™ V Stent</td>
<td>PROMUS™ Element™ Stent</td>
<td>Nobori</td>
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<td>Cypher select</td>
<td>XIENCE™ Prime Stent</td>
<td>Genous EPC capture stent</td>
<td>everolimus-eluting PLLA stent (BVS)</td>
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<td>NEVO™ Stent</td>
<td>Biomatrix</td>
<td>tyrosine-derived polycarbonate REVA stent</td>
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<tr>
<td>PROMUS™ Stent</td>
<td>Axxess Plus stent</td>
<td>Xtent custom NX stent</td>
<td>Sejong General Hospital</td>
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1st Generation Stainless Steel

2nd Generation Cobalt Chromium, Platinum Chromium Alloy

Bioabsorbable Polymer

Fully Bioabsorbable Metal & Polymer
Design criteria for the Ideal DES

DELIIVERABILITY
Flexible material, design
Thin strut thickness
Small device profile
Self-expanding

Biocompatibility

SAFETY
Biodegradable stent
Biomimetic coating
Biodegradable coating
No-polymer drug application
Cell-specific drug action

Efficacy
Uniform drug delivery
Required radial force / less recoil
Lesion-specific stent configuration
Disease-specific application

Biofunctionality

Am J Cardiol 2007;100[suppl]:3M–9M
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Conditions of the Ideal platform material

- Deliverability: ↑
- Radial strength: ↑
- Stent recoil: ↓
- Foreshortening: ↓
- Scaffolding: uniform
- Radio-opaque: ↑
- Thrombogenicity: ↓

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Metals used in stent designs

- **Stainless Steel** - iron based alloys, 1\textsuperscript{st} generation DESs
- **Nitinol** (Nickel + Titanium) - self expanding, shape memory
  - low thrombogenicity, Radius stent
  - guidewire
- **Cobalt Chromium** - 2\textsuperscript{nd} generation DESs, safe
- **Tantalum, Platinum, Gold** - good radiopacity, marker for stents
- **Platinum Chromium** - new generation DESs
- **Magnesium** alloy - biodegradable, low strength
Typical values for conventional stent materials

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Elastic Modulus (GPa)</th>
<th>0.2% Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Elongation (%)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt–Cr</td>
<td>203</td>
<td>480</td>
<td>834</td>
<td>45</td>
<td>9.9</td>
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<tr>
<td>316L</td>
<td>193</td>
<td>275</td>
<td>595</td>
<td>60</td>
<td>8.0</td>
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<tr>
<td>MP35N</td>
<td>233</td>
<td>414</td>
<td>930</td>
<td>45</td>
<td>8.4</td>
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<tr>
<td>L605</td>
<td>243</td>
<td>500</td>
<td>1000</td>
<td>50</td>
<td>9.1</td>
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</tbody>
</table>


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# Mechanical properties of stent materials

<table>
<thead>
<tr>
<th>Capability to Enable Stent Performance in Relation to:</th>
<th>Stainless Steel (316L)</th>
<th>Cobalt Chromium (L605)</th>
<th>Platinum Chromium(PtCr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vascular Compatibility(^3)</td>
<td>More capable</td>
<td>More capable</td>
<td>More capable</td>
</tr>
<tr>
<td>Level of Visibility</td>
<td>Capable</td>
<td>More capable</td>
<td>Capable</td>
</tr>
<tr>
<td>High Radial Strength(^2)</td>
<td>More capable</td>
<td>More capable</td>
<td>More capable</td>
</tr>
<tr>
<td>Minimal Recoil(^2)</td>
<td>More capable</td>
<td>Capable</td>
<td>More capable</td>
</tr>
<tr>
<td>High Conformability(^2)</td>
<td>More capable</td>
<td>More capable</td>
<td>More capable</td>
</tr>
<tr>
<td>Use for Thin Strut Design</td>
<td>Capable</td>
<td>More capable</td>
<td>More capable</td>
</tr>
</tbody>
</table>

\(^{2}\) More capable, \(^{3}\) Capable, \(^{4}\) Less Capable

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Nominal Metal Composition

- **316L Stainless Steel**: Molybdenum 3%, Chromium 18%, Nickel 14%, Iron 65%
- **L-605 Cobalt Chromium**: Tungsten 15%, Chromium 20%, Cobalt 35%
- **MP35N Cobalt Nickel**: Cobalt 34%, Nickel 25%, Chromium 29%, Molybdenum 18%
- **PROMUS™ Stent & Xience™ V Stent**: Cypher Neo, PicoElite stent, Costar stent
- **Endeavor® Stent**
- **PROMUS™ Element™ Stent**

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Approach to Stent Materials

- New Alloy Technology
- Thin Struts, low profiles
- Superb Deliverability
- Excellent Clinical Results
basic terms and designs of stents
Element Length

Shorter
  • Better scaffolding
  • Higher radial strength

Wider
  • Poorer scaffolding
  • Lower radial strength
Element Length

(ML VISION) Consistent element length

(EXPRESS) Inconsistent element length

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Crests per Ring

**Less Crests**
- Less Scaffolding
- less profiles
- Less Expansion Range

**More Crests**
- More Scaffolding

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Connections per Ring

**Less**
- More Flexible
- Less Scaffolding

**More**
- Less Flexible
- More Scaffolding

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Connection Design

Single-curved link (ML VISION)

Welded (ENDEAVOR)

Straight link (TAXUS)

Double-curved link (CYPHER)

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Flexibility & Conformability

More
Crimped stent: flexibility

Expanded stent: conformability

Less

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Stent Pattern

In Phase (repeating)
• Better Scaffolding

Out of Phase
• Less metal volume

ZETA (in phase)
S7 (out of phase)
In Phase vs. Out of Phase

In Phase 14 rings (18 mm stent)

Out of phase 8 rings (18 mm stent)

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Radiopacity

- Visibility of the stent using fluoroscopy
- Impacted by strut thickness / or stent material / alloy
Strut Thickness

**Thinner**
- Less Visible
- Less Metal in the Vessel
- Less stress to vessel walls
- Less radial strength

**Thicker**
- More Visible
- More Metal in the Vessel
- More stress to vessel walls
- More radial strength

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Tubular vs. Coil-type stents

- Stent deployment pressure: CS < TS
- Elastic recoil: CS > TS
- Radial strength: CS < TS
- Stent shortening: CS < TS
- Stent metal coverage area: CS < TS
- Flexibility: TS < CS
Stent configuration

Closed-cell stent designs

Advantages – more uniformity of drug delivery
Disadvantages – less conformability, and deliverability

Open-cell stent designs

Advantages – good trackability, delivery, and conformability
- better access to side branches
Disadvantages – inhomogeneous drug delivery
Mechanical properties of stents
Stent recoil

Stent+Balloon deployment (balloon inflation)

Intrinsic elastic recoil (balloon deflation)

Compressive arterial forces (unknown parameter)

Final stent deployment diameter

Angiographic recoil
Post Expansion Stent Diameter Recoil

Percentage the stent diameter decreases after balloon deflation

2.5mm Stent Products

- Endeavor™ TAXUS™ Liberté™: 5.0%
- Xience PRIME™: 4.9%
- Xience V™: 4.7%
- Cypher™: 3.0%
- Promus™ Element™: 3.0%

Sejong General Hospital
Stent Recoil

3.0mm Stent Products

<table>
<thead>
<tr>
<th>Product</th>
<th>Recoil Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cypher Select+</td>
<td>3.0</td>
</tr>
<tr>
<td>Taxus Liberte</td>
<td>2.0</td>
</tr>
<tr>
<td>Endeavor</td>
<td>5.0</td>
</tr>
<tr>
<td>Xience V</td>
<td>4.0</td>
</tr>
<tr>
<td>Nobori</td>
<td>1.0</td>
</tr>
<tr>
<td>BioMatrix</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Sejong General Hospital
Stent Shortening

3.0mm Stent Products

Cypher Select+  Taxus Liberte  Endeavor  Xience V  Nobori  BioMatrix

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Radial Strength

Amount of Radial Force Required to Reduce the Diameter of a Deployed Stent

2.5mm Stent Products

<table>
<thead>
<tr>
<th>Stent Product</th>
<th>Radial Force (Newtons/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAXUS™ Element™</td>
<td>0.26</td>
</tr>
<tr>
<td>TAXUS™ Liberté™</td>
<td>0.24</td>
</tr>
<tr>
<td>Cypher™</td>
<td>0.17</td>
</tr>
<tr>
<td>Xience PRIME™</td>
<td>0.15</td>
</tr>
<tr>
<td>Endeavor™</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Better

Sejong General Hospital
Radial Strength

3.0mm Stent Products

Radial Force (N/cm)

- Cypher Select+
- Taxus Liberte
- Endeavor
- Xience V
- Nobori
- BioMatrix

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Conformability

Measures the ability of the stent to naturally conform to the vessel

2.50mm product tested.

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Stent Design Summary

**Improve Scaffolding:**
- In phase pattern
- More crests per ring
- Shorter element length
- More connections per ring

**Profiles:**
- Thinner struts
- Less crests per ring

**Improve Flexibility:**
- Shorter element length
- Less connections per ring
- Shaped or staggered connections

**Expansion Range:**
- More crests per ring

**Visibility:**
- Thicker struts

**Metal in Vessel:**
- Thicker struts
- More crests
- Shorter element length

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Optimal stent delivery system

- Trackability
- Crossability
- Pushability
- Flexibility
Trackability

- Combined property
- **Stiffness and profile** of the stent delivery system
- Friction effects (system and GC&GW)
  - Proximal force (force-distance curve)

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Crossability test

The ability of the distal part of the stent System to pass through a narrowed vessel lesion
Stenosis model for the pushability test

The possibility to transmit a proximal push force to the distal part of the stent System

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System Flexibility

Test method

Push down

Fixation of Stent & Catheter (balloon)

7mm

stent

Measuring “Force” required to push 0.5mm down (bend)

System: 3.0mm

Sejong General Hospital
The mechanical response of coronary stent systems

<table>
<thead>
<tr>
<th>Stent system</th>
<th>Pushability (%)</th>
<th>Mean track force (N)</th>
<th>Mean cross force (N)</th>
<th>Crimped stent profile (mm)</th>
<th>Bending stiffness of cramped stent (Nmm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomatrix</td>
<td>35.89</td>
<td>0.55</td>
<td>0.09</td>
<td>1.130</td>
<td>30.06</td>
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<tr>
<td>Costar</td>
<td>38.66</td>
<td>0.76</td>
<td>0.04</td>
<td>1.088</td>
<td>22.44</td>
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<tr>
<td>Cypher Select +</td>
<td>27.34</td>
<td>1.14</td>
<td>0.08</td>
<td>1.198</td>
<td>25.90</td>
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<td>Endeavor</td>
<td>32.20</td>
<td>0.69</td>
<td>n.a.</td>
<td>1.130</td>
<td>47.20</td>
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<tr>
<td>Taxus Liberté</td>
<td>20.91</td>
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<td>0.09</td>
<td>1.124</td>
<td>17.24</td>
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<tr>
<td>Xience V</td>
<td>37.60</td>
<td>0.87</td>
<td>0.04</td>
<td>1.055</td>
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<td>Coroflex Please</td>
<td>18.53</td>
<td>0.67</td>
<td>0.10</td>
<td>1.145</td>
<td>20.16</td>
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</table>

*a Medtronic Endeavor was excluded because of stent loss.
*b Taxus Liberté was excluded because of force overload after 146-mm travel distance.
Summary of requirement for successful treatment of coronary disease by stents

<table>
<thead>
<tr>
<th>Stent property</th>
<th>Deliverability</th>
<th>Scaffolding/recoil prevention</th>
<th>Minimal vessel trauma</th>
<th>Low level of inflammation</th>
<th>Antirestenosis properties</th>
<th>Endothelialization</th>
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<tbody>
<tr>
<td>Traditional DES</td>
<td>+</td>
<td>+++</td>
<td>+</td>
<td>-</td>
<td>++</td>
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<tr>
<td>Cypher</td>
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<td>Taxus</td>
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<tr>
<td>New DES</td>
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<td>+++</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>+</td>
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<tr>
<td>Endeavour</td>
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<td>Xience</td>
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<td>Self-expanding</td>
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<td>VShield (nitinol)</td>
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<td>X-tent</td>
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<tr>
<td>Bioabsorbable polymer</td>
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<td>++</td>
<td>++</td>
<td>+++</td>
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<tr>
<td>Biolimus erodible</td>
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<tr>
<td>Fully bioabsorbable BVS</td>
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</tr>
<tr>
<td>IDEAL BIONETIC</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+++</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

-: Poor; +: Acceptable; ++: Good; +++: Excellent.
Acute clinical outcome

- **Tortuous lesions**: conformable and flexible stents
- **Ostial lesions**: stents with strong radial support and good radiological visibility
- **Bifurcational lesions**: 
  - **Chronic total occlusions**: good lesion coverage and favorable radial support
- **Small vessels**: stents with good flexibility, very thin strut structure, and good stent trackability
Stent cell size: an important parameter when stenting bifurcation lesions

<table>
<thead>
<tr>
<th>Stent Type</th>
<th>Cell Circumference</th>
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</thead>
<tbody>
<tr>
<td>Endeavor (Medtronic)</td>
<td>19.8 mm</td>
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<tr>
<td>PRO-Kinetic (Biotronik)</td>
<td>10.8 mm</td>
</tr>
<tr>
<td>Promus (Boston Scientific)</td>
<td>12.6 mm</td>
</tr>
<tr>
<td>Taxus Liberté (Boston Scientific)</td>
<td>12.6 mm</td>
</tr>
</tbody>
</table>
The size of the ostium depends on the bifurcation angle and the side and main branch diameters.
The ostium circumference of a 3mm parent vessel
Stent cell requirements for different stenting strategies

Provisional bifurcation stenting:
Stent cell size > side branch ostium

Crush stenting:
Stent cell size > side branch ostium

Culotte stenting:
Stent cell size > cross section of the main branch

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Long-term clinical outcome

- Stent configuration
- Strut thickness
- Stent coating (Gold, Tantalum coating, phosphorylcholine, carbon coating, and silicone carbide)
- Drug-elution
Percentage stenosis due to neointimal formation with different Multi-Link family stents

Ann Ist Super Sanità 2007 | Vol. 43, No. 1: 89-100
Stent Design and Strut Thickness (ISAR-STEREO-2 trial)

ACS RX Multi-Link stent (Guidant) vs. BX Velocity (Cordis)

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Conclusions

Developing a better systematic understanding of mechanical properties of Stent and delivery system

1. help the selection of optimal instrumentation

2. markedly improve the technical operator’s performance, particularly in challenging cases
Thank you for your listening!