Modern Guidewire Design and Commercialization

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Abstract

Guidewires are the most fundamental component of interventional procedures, yet are challenging to design and manufacture due to the risks associated with their direct interaction with the vasculature. Current coronary and peripheral guidewires consist of a variety of designs for broad use in percutaneous transluminal coronary angioplasty (PTCA), percutaneous transluminal angioplasty (PTA), and percutaneous coronary intervention (PCI) applications. Some newly designed products also address chronic total occlusion (CTO), structural heart disease, and diseases of the neurovasculature.

The design and manufacturing of guidewires for broad use in clinical settings have improved over the last few decades, with advanced knowledge of optimal materials, user experience, and design tools. In this article, we highlight key advances in guidewire design and the impact on clinical performance, including lesion access and crossing, trackability, tactile feel, and tip forces. Streamlining computational design, testing, and manufacturing is critical for efficient and cost-effective commercialization of new products in this relatively mature and competitive market.

Lastly, engineering and clinical evaluation results are presented for the novel supporting guidewire Inno-Pathwire (Suzhou Innomed Co., Ltd.) to demonstrate its safety and efficacy.

Introduction

In 1982, the article "A New Catheter System for Coronary Angioplasty" by Simpson et al.[1] first introduced a new type of device that we know today as the guidewire. The benefit of guidewires in coronary angioplasty procedures led to their widespread use in a variety of procedures today.[2,3] Modern guidewires are available through various manufacturers[4] and contain features with special characteristics to address a variety of clinical challenges.[5,6]

Guidewire manufacturing requires skilled knowledge of materials, processes, and quality control, with expertise in joining fine wires of different metal compositions and proper coatings. Nonetheless, differences in guidewire performance generally occur at the distal end of the guidewire, where the diameter begins to taper and it encounters torturous anatomy and diseased lesions.

In this article, we focus on the latest computational and technological advancements in modern guidewire design and manufacturing with an emphasis on performance of the distal end of the guidewire. We assess pushability, torqueability, and tip force computations to provide a comparison of theoretical use with clinical examples of these technologies.

Guidewire Types

The basic guidewire design includes a metal core wire which tapers at the distal end, or joins with a softer metal wire with a tapered tip to reduce distal stiffness and prevent vessel damage. Because of its high elastic modulus, a metal core is typical for all guidewires and is generally made with stainless steel (elastic modulus of 210 GPa) and Nitinol (a nickel and titanium binary alloy with elastic modulus range of 40-80 GPa and high strain recovery) due to high biocompatibility and availability.

While the use of appropriate guidewires is critical in interventional surgery, it is noteworthy that Toth, et al. (2016)[7] pointed out that that little attention has been paid to the structures and technical features of guidewires.

Guidewire design has competing requirements: they must be stiff and durable for pushability, while also being gentle and soft to avoid tissue damage. Therefore, guidewire designs must be tailored to the specific application, disease condition, and be amenable to variations in patient vessel anatomy. Examples of guidewire designs include diagnostic guidewires and complex guidewires that support other devices, such as a balloon or stent, to cross the lesion or occlusion. This article will focus on Supporting and CTO guidewires, with an emphasis on the distal ends of these two types of guidewires.

Diagnostic Guidewires

Diagnostic guidewires are used to guide a catheter into the sinus of the left ventricle or the entrance of coronary arteries to inject contrast. These guidewires typically have a diameter of 0.035 inches (typically larger than supporting or CTO guidewires), are made of a Nitinol core with a polymeric jacket and pre-shaped tips, and often contain a hydrophilic coating to minimize friction.

Special Use Guidewires

Special use guidewires include hard guidewires of 0.035-inch diameter with hydrophobic coatings for Thoracic Endovascular Aneurysm Repair (TEVAR) or TAVI (Transcatheter Aortic Valve Implantation), Fractional Flow Reserve (FFR) guidewires, and other non-circulation use guidewires.

Supporting and CTO Guidewires

Compared to diagnostic guidewires, supporting guidewires are generally finer, having a diameter of 0.014 inch or smaller. It is the first device to encounter a blocked coronary artery and is used as a rail for balloon catheters or stents to follow and reach the target location for treatment.

CTO guidewires are derived from supporting guidewires, sometimes even serving as supporting guidewires, and are equally as challenging to design. The remainder of this article will focus on the design and construction of the distal tip of supporting and CTO guidewires.

Given that the distal tip is a long, fine wire, it is inevitable that this portion of a supporting guidewire will be deformed after engaging with arterial walls. The ability to recover from this deformation is vital to procedural success, as it reduces the number of guidewires used per procedure, and therefore operation time, especially in cases where a modern microcatheter is unable to assist with lesion crossing. For this reason, Nitinol is the preferred material for the distal portion of the guidewire. Nitinol is a binary alloy that exhibits approximately one quarter of the elastic modulus of stainless steel, and elastic recovery 10 times greater than other commonly used metals. This more durable distal tip allows for improved performance, avoids permanent damage to the guidewire and, most importantly, minimizes tissue damage. **Thus, use of high-plateau stress Nitinol at the distal tip results in the safest, most durable, and trackable guidewire.**

For the proximal end of the guidewire, stainless steel is preferred due to its optimal pushability and one-to-one torque. The joining of stainless steel and Nitinol wires together creates a manufacturing challenge that requires the use of a hypotube. Additionally, the furthest distal part of the Nitinol core is joined with a "shaping ribbon" made of a stainless-steel wire that can be easily flattened and deformed, providing physicians with freedom and ease of access to side branches. The unique shaping ribbon guidewire tip is illustrated in **Figure 1**.

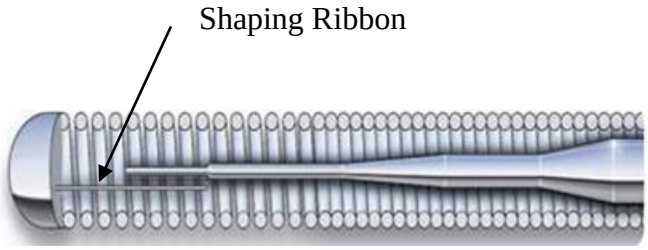

Figure 1: Shaping Ribbon Tip Structure.

In order to improve recoverability after tip deformation, reduction of the core wire diameter reduces stiffness (as measured by resistance to bending), creating a softer distal tip. The stainless-steel core wire is also “cold worked/trained” for good elasticity, and the tips of this type of guidewire are typically pre-shaped in a “core-to-tip” design (**Figure 2**).

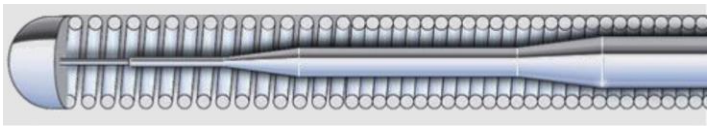

Figure 2: Core-to-Tip Structure.

For most clinical applications, the above-mentioned guidewires are sufficient. However, some complex lesions may require the use of multiple guidewires with different tip technologies by physicians with extensive clinical experience. Because of the high level of expertise required to treat complex lesions, guidewire failure is common.

To address these points of failure, guidewire manufacturers have developed complex structures for the distal end and tip, including micro-braided wires, laser-slotted tubing, polymeric jackets, and combinations of these.

Evaluation of Key Guidewire Performance Metrics

Tip Force

Guidewire tip force is the most important design attribute to prevent vessel damage; therefore, evaluation of tip force metrics are crucial for patient safety.

Using the shaping ribbon design as an example, the Nitinol core wire is typically tapered to reduce stiffness, with the end of the Nitinol core flattened such that the shaping ribbon can be easily and steadily connected to the core wire. This structure is covered by a radiopaque coil to enhance visibility, with a rounded cap at the tip as shown in **Figure 1**. The distal end contains a hydrophilic coating to reduce friction, enabling the entire wire to easily follow the tip across the lesion. The shaping ribbon, Nitinol core, springs, and coating all impact tip force.

To evaluate tip force, a simple experimental platform similar to **Figure 3** can be used. A more sophisticated fixture can also be used by connecting the guidewire to a universal mechanical testing system.

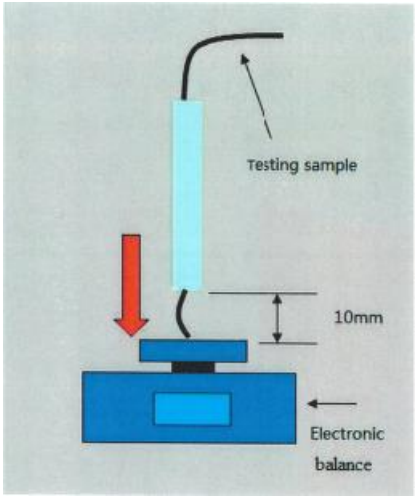

Figure 3. Tip force experimental evaluation method.

Figure 4 demonstrates the relationship between tip force (F) and critical pressure (P) when the material of the slender rod is Nitinol.

$$F = UP = \frac{U\Pi^2 EI}{(\mu L)^2}$$

When the slender rod is made of Nitinol, $U \approx 2.1$. The U coefficient will change if the material of the slender rod changes.

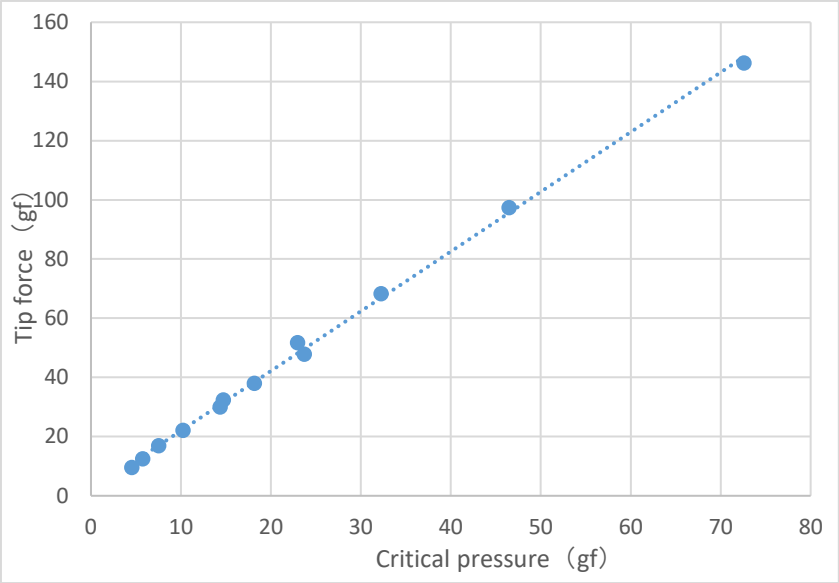

Figure 4. The ratio of critical pressure to tip force.

Support

To measure a wire's stiffness (support), a force is applied to deflect a segment of 15 mm wire by 2 mm when this portion of the wire is braced as shown in **Figure 5**. The support of a guidewire can be evaluated along its entire length, with the distal end having the least stiffness (support) and providing support that increases through the guidewire length to the proximal end.

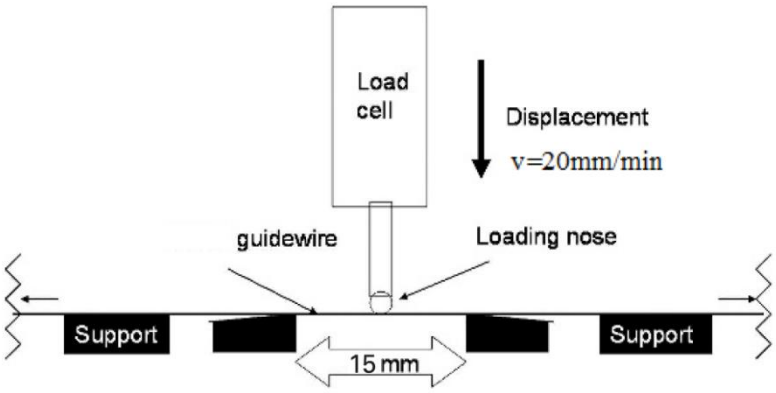

Figure 5. Method for measuring wire stiffness.

Torque Response

To evaluate one-to-one torque, a guidewire is forced through multiple paths of known curvature while the proximal end is rotated. The rotation of the tip is then measured. Ideally, the input rotation at the proximal end should be identical with the output rotation at the tip. Deviation from this baseline indicates possible loss of one-to-one torqueability in a clinical setting.

Example

The Suzhou Innomed Medical Device Co. has designed and manufactured a family of supporting guidewires (Inno-Pathwires) of 0.014 inches and 0.018 inches with both shaping ribbon and core-to-tip structures. The 0.014-inch shaping ribbon guidewires are constructed with a unique high-strength stainless steel flat shaping ribbon at the distal tip with ease of navigability through tortuous anatomy. In addition, the 0.014-inch Inno-Pathwire uses high-plateau Nitinol at the distal end to enhance prolapse resistance and durability. This guidewire is designed to have excellent flexibility, trackability, and torqueability while maneuvering through severely angulated and/or extremely tortuous vessels. Multiple levels of support are available for a variety of clinical applications (**Figure 6**). The EXS provides the highest level of support, the MDS provides balanced support, and the STS provides the most flexibility during clinical use.

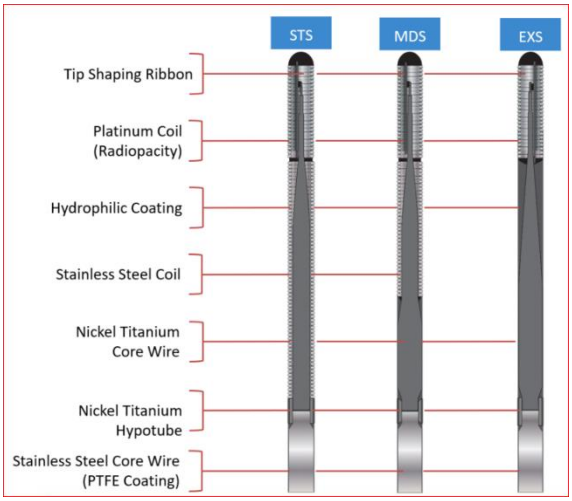

Figure 6. Innomed Coronary Guidewire Inno-Pathwire Design Structures.
STS=light support; MDS=moderate support; EXS=extra support.

In vitro Evaluation Results

Tip forces

Inno-Pathwires are available in a wide range of tip forces ranging from the safest low tip force of less than 0.010 grams to the highest with close to 20 grams for CTO lesions.

Support

Figure 7 shows a comparison of the bending support for the MDS Inno-Pathwire and the Abbott BMW wire, which has a similar shaping ribbon tip design. Support forces were measured for approximately 40 cm of the guidewire length, starting from the distal tip.

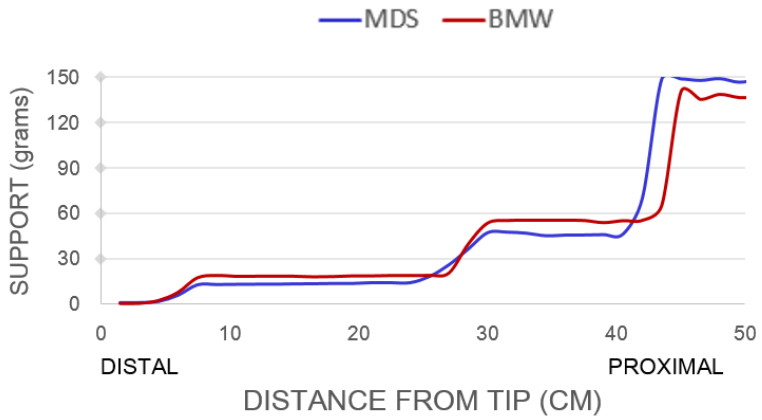

Figure 7. Comparison of Bending Support between Inno-Pathwire (MDS) and Abbott (BMW) Guidewires.

Torque

Figure 8 compares the one-to-one torque of a typical Inno-Pathwire with a commercially available guidewire of similar structure (Abbott BMW).

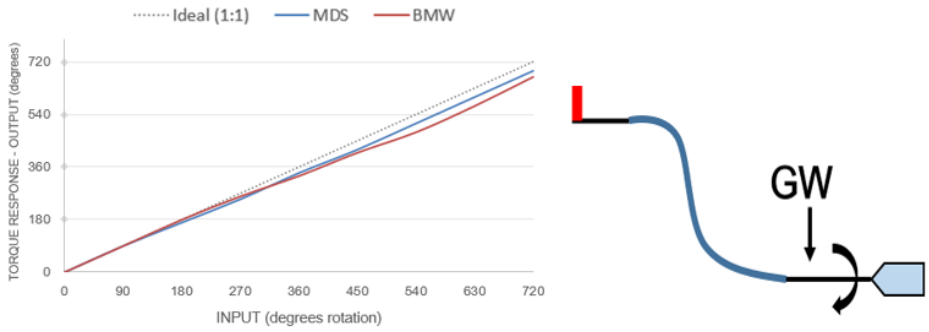

Figure 8. Comparison of One-to-One Torque Response between Inno-Pathwire (MDS) and Abbott (BMW).
GW=guidewire

Clinical Performance

To demonstrate the clinical benefits of Inno-Pathwire, two clinical cases are presented below.

Case 1: PCI using Inno-Pathwire in left main (LM) coronary artery bifurcation lesions

A 77-year-old female patient presented with acute coronary syndrome (ACS). 6F TIG angiography showed approximately 90% stenosis of the LM end, 99% ostial stenosis of the left ascending artery

(LAD) with thrombolysis in myocardial infarction (TIMI) flow grade 1, and 95% ostial stenosis of the left circumflex artery (LCX) with TIMI flow grade 3 (**Figure 9 A-B**). In addition, right coronary artery (RCA) 1-2 segment stenosis was about 75% with TIMI flow grade 3 and supplied blood to LAD through the septal branch collateral circulation so that LAD was retrogradely perfused to segment 7 (**Figure 9 C**).

The patient underwent PCI using Inno-Pathwire in LM coronary artery bifurcation lesions. After placing a 6F EBU 3.5 guide, the Inno-Pathwire MDS was carefully navigated to pass through the stenosis and arrived at the distal end of the LAD. Narrow lesions were immediately expanded with balloons of different sizes (**Figure 9 D-E**), resulting in residual stenosis of approximately 25% in the LM end and LAD 7 segment. There was obvious dissection in the LAD 7 segment, but blood flow recovered to TIMI grade 3 (**Figure 9 F**). A stent was implanted in the LAD 7 segment. Another Inno-Pathwire MDS was sent into the distal end of LCX, and the ostial stenosis was expanded with a balloon. Inverse-mini crush technology was adopted to treat the true bifurcation lesions in the LM end (**Figure 9 G**) and angiography showed that the stents fully expanded with TIMI flow grade 3 (**Figure 9 H**). The Inno-Pathwire MDS was carefully manipulated to successfully pass through the three-layer stent mesh to the distal end of the LAD (**Figure 9 I-J**). The three-layer stent mesh was then further expanded with a balloon (**Figure 11 K**). The key Final Kissing (**Figure 9 L**) and Proximal Optimization Techniques (POT) steps (**Figure 9 M**) were then completed, resulting in a successful procedure (**Figure 9 N-O**).

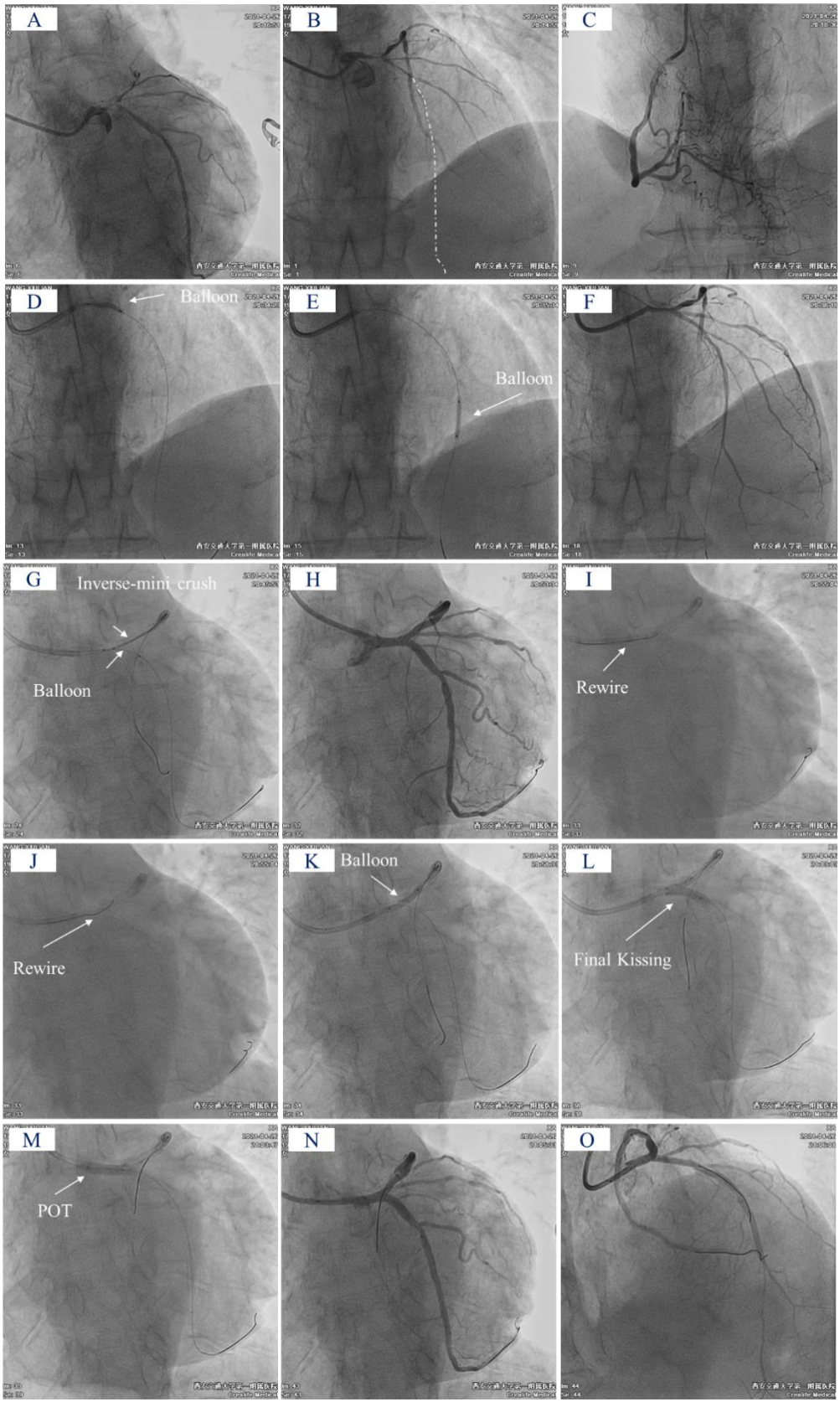
A
B
C
D
Balloon
E
Balloon
F
G
Inverse-mini crush
Balloon
H
I
Rewire
J
Rewire
K
Balloon
L
Final Kissing
M
POT
N
O

Figure 9. Case 1 Angiographic Imaging.

A) Initial angiographic assessment of LM, LAD, and LCX with 6F TIG angiography. **B)** White dotted line shows no forward blood supply to LAD. **C)** RCA supplied blood to LAD through septal branch collateral circulation. **D)** Inno-Pathwire MDS passed through stenosis in LAD and lesion expanded with balloon. **E)** Inno-Pathwire MDS passed through stenosis in another region of LAD and lesion expanded with balloon. **F)** Dissection in LAD 7 segment. **G)** Ostial stenosis of LCX expanded with balloon; Inverse-mini crush technology treated bifurcation lesions of LM end. **H)** Stents fully expanded with TIMI flow grade 3. **I, J)** Inno-Pathwire MDS passed through stent mesh to distal end of LAD using Rewire technology. **K)** Stent mesh expanded with balloon. **L)** Final Kissing. **M)** Proximal Optimization Technique (POT). **N, O)** Procedure completed. LAD=left ascending artery, LCX=left circumflex artery, LM=left main, MDS=moderate support, RCA=right coronary artery.

Case 2: PCI using Inno-Pathwire in RCA CTO with retrograde wire approach

A 46-year-old female patient presented with angina. 6F angiography demonstrated CTO at the beginning of the RCA 2 segment and partial forward blood supply to the middle of the RCA 2 segment through bridging collateral circulation (**Figure 10 A**). The posterior branch of the left ventricle (PL) and posterior descending branch (PD) (**Figure 10 B**) were retrogradely perfused by tortuous septal collateral circulation (**Figure 10 C**).

The patient underwent PCI using the Inno-Pathwire MDS with a retrograde wire approach. This approach was adopted to open the RCA CTO because of its long occlusion distance and poor vascular condition. After placing a 7F EBU 3.5 guide, angiography was performed to determine the appropriate septal collateral circulation (**Figure 10 D**). Inno-Pathwire MDS was carefully navigated through the tortuous septal collateral circulation to enter the PD and PL in turn under the support of the 1.7F APT microcatheter (**Figure 10 E-G**). After pushing the microcatheter along the Inno-Pathwire MDS (**Figure 10 H**) into the PD and confirming tip injection (**Figure 10 I**), the Inno-Pathwire MDS was replaced with a UB 3 via the microcatheter, and the UB 3 was manipulated through the occluded vessel segment under the guidance of multi-position angiography and entered the forward 6F JR 4.0 (**Figure 10 J-K**). The UB 3 was anchored with a balloon to forcefully push the 1.7F APT microcatheter into 6F JR 4.0. Rendezvous technology was used to manipulate the Inno-Pathwire MDS to successfully complete the externalization procedure (**Figure 10 L-M**). Subsequently, stents were implanted after dilating the occluded blood vessel with predilated balloons of different sizes along the Inno-Pathwire MDS (**Figure 10 N-O**). The operation was completed successfully.

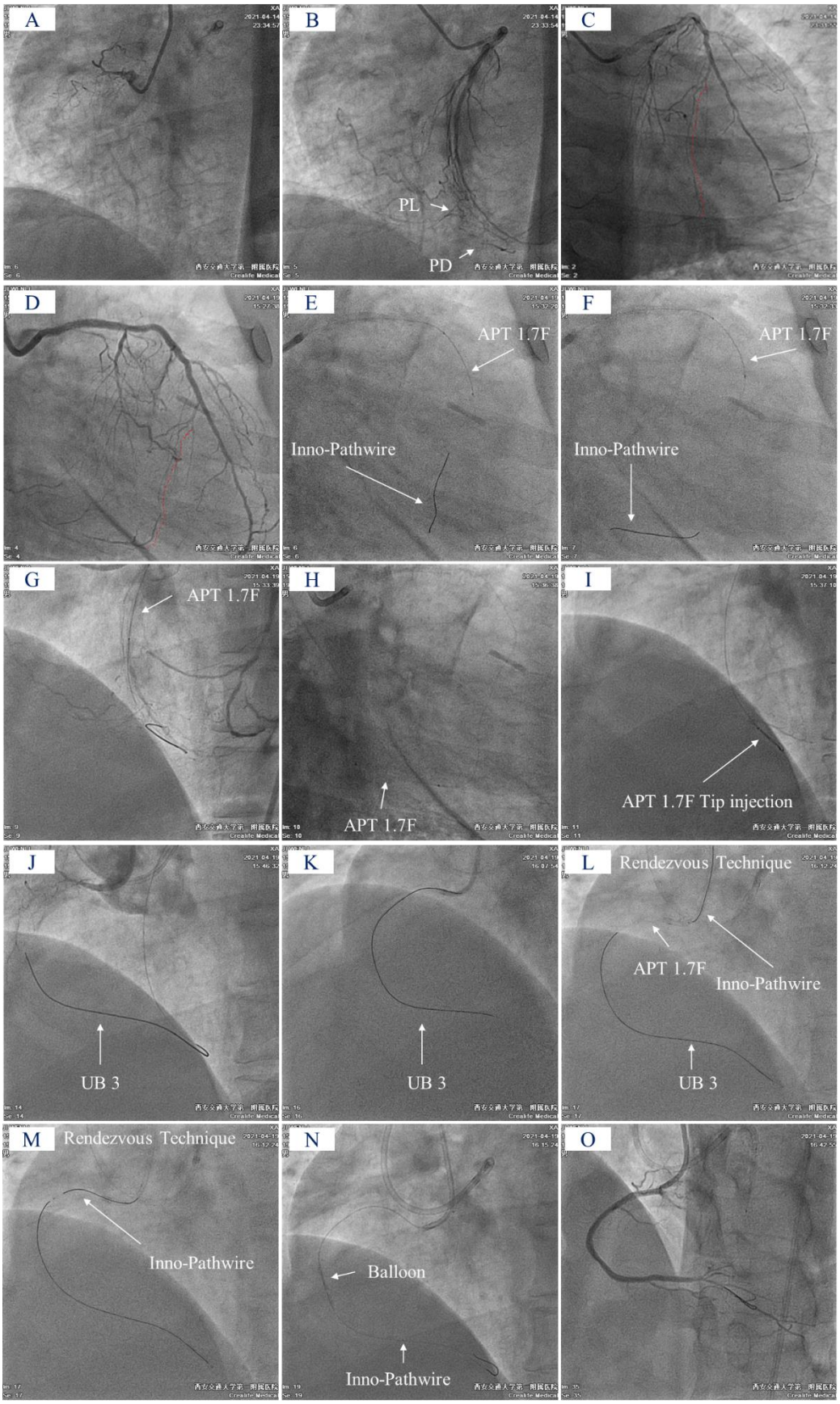
A
B
PL
PD
C
D
E
APT 1.7F
Inno-Pathwire
F
APT 1.7F
Inno-Pathwire
G
APT 1.7F
H
APT 1.7F
I
APT 1.7F Tip injection
J
UB 3
K
UB 3
L
Rendezvous Technique
APT 1.7F
Inno-Pathwire
UB 3
M
Rendezvous Technique
Inno-Pathwire
N
Balloon
Inno-Pathwire
O

Figure 10. Case 2 Angiographic Imaging.

A) Initial assessment of RCA with 6F TIG angiography. **B)** Posterior branch of left ventricle (PL) and posterior descending branch (PD). **C)** Red-dotted line shows retrograde perfusion by septal collateral circulation. **D)** Red-dotted line shows retrograde pathway used during procedure. **E-G)** Inno-Pathwire MDS navigated through septal collateral circulation to enter the PD and PL under support of 1.7F APT microcatheter. **H)** 1.7F APT microcatheter pushed along Inno-Pathwire MDS. **I)** Tip injection confirmed in PD. **J, K)** Inno-Pathwire MDS replaced with UB 3; UB 3 manipulated through occluded vessel and entered forward 6F JR 4.0. **L, M)** UB 3 anchored with balloon to push 1.7F APT microcatheter into 6F JR 4.0; Rendezvous technology manipulates Inno-Pathwire MDS. **N)** Stents implanted after balloon dilation along Inno-Pathwire MDS. **O)** Procedure completed. MDS=moderate support, RCA=right coronary artery.

Conclusion

We utilized the Inno-Pathwire family of supporting and CTO guidewires as an example of the design, engineering evaluation, and clinical performance of a successful guidewire. Inno-Pathwire guidewires include a high-strength stainless steel shaping ribbon at the very distal tip with optimal tip force for ease of maneuverability through tortuous anatomy and a high-plateau Nitinol at the mid-to-distal end to enhance prolapse resistance and durability. Excellent flexibility, trackability, and torqueability were demonstrated in bench tests, and two illustrative clinical cases demonstrate procedural success in patients with LM bifurcation lesions or CTO. We anticipate that these guidewires will continue to help clinicians treat patients with a variety of vascular conditions more effectively.

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