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REVIEW
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# Narrative review of latest research progress about robotic percutaneous coronary intervention

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**ABSTRACT** Robotic percutaneous coronary intervention (R-PCI) is a novel technology in which operators can manipulate guidewires and catheter devices in interventional cardiology. This approach provides great benefits to interventional cardiologists in terms of reducing both radiation exposure and orthopedic injuries. Several large, high-quality cohort studies have confirmed the short-term safety and high technical success rate of R-PCI. However, randomized long-term data are still needed before adopting them as part of standard coronary interventions. Furthermore, tele-stenting for complex coronary lesions has significant potential for R-PCI. We need to overcome the present relevant challenges for its application such as inherent delays, bedside care for unstable patients from R-PCIs to manual PCIs (M-PCIs), incompatibility for a thrombus aspiration catheter and heavily calcified lesions. There is a great future in laboratory workflow teams, 3D-printed anatomical models and multiple joint collaborative control algorithms. This narrative review summarizes the latest developments in R-PCI, with a focus on developments in robotic technology, and discusses the current and future potential use of R-PCI in clinical practice globally.

Percutaneous coronary intervention (PCI) is routinely performed for the treatment of patients with coronary artery diseases.[1] However, there is considerable radiation harm for interventionalists who work in a standing position and view fluoroscopic images from across the procedure table.[2] Radiation-induced damage includes deoxyribonucleic acid damage,[3] thus resulting in cancer.[4] Moreover, orthopedic complications from the long-term use of heavy lead protective garments are also common.[5]

Recently, robotic PCI (R-PCI) has become a novel technique that aims to solve these problems by significantly reducing radiation exposure,[6] and improving ergonomics. Additionally, the advantages of R-PCI include accurate stent placement,[7] detailed visual feedback,[2] millimeter precision,[2] and potential for use in tele-stenting procedures.[8] The feasibility and safety of R-PCIs have been proven in many large medical centers, with high rates of procedural and clinical success.[9–11] Even for complex coronary lesions, the abovementioned advantages still exist for interventional cardiologists.[10]

In this narrative review, we summarize the latest research progress on R-PCIs, focusing on technology developments, the current R-PCI system, future potential use, strengths and limitations (Figure 1).

## TECHNOLOGY DEVELOPMENTS OF R-PCI

The Niobe magnetic navigation robot system developed Stereoaxis in 2002, which was based on the earliest study on vascular intervention robots.[12] The first-in-human experience was conducted by a remote navigation system in 2006.[13] Since then, R-PCIs have been validated. CorPath200 (Corindus Vascular Robotics, USA) received Food and Drug Administration approval in 2012.[9] The CorPath GRX (Corindus Vascular Robotics, USA), a second-generation device, received Food and Drug Administration approval in 2016.[14] In 2020, a new R-PCI system named R-One (Robocath, France) was permitted in Europe and has progressed successfully since its first use.[15] In China, the first R-PCI was developed in 2022 by Beijing WeMed Medical Equipment Co., Ltd., and named the ETcath200 robot-assisted system.[16] Another R-PCI named ALLVAS (Oppen, Shanghai, China) was reported at Changhai Hospital, Naval Medical University.[17] In 2023, a minimally invasive vascular interventional robot system called WSER-CD01 was reported to explore the possibility of robot-assisted vascular intervention, particularly for vascular wall protection.[18] Figure 2 shows a more concrete process.

## STRENGTHS OF R-PCI

High lesion complexity requires a longer procedure ti-

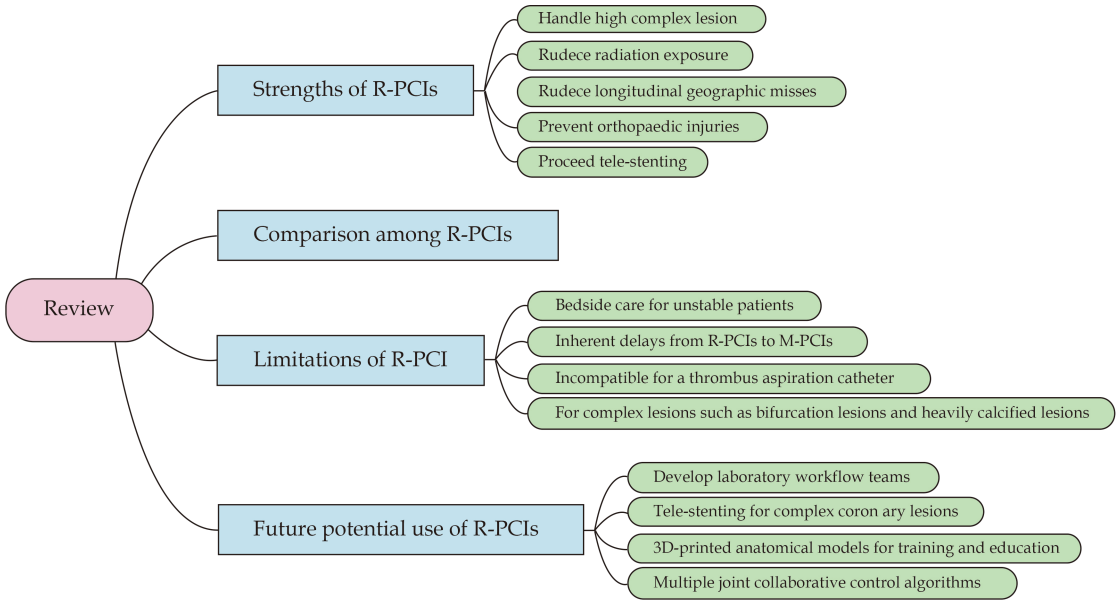


**Figure 1 The central illumination of the review.** M-PCI: manual percutaneous coronary intervention; R-PCI: robotic percutaneous coronary intervention.

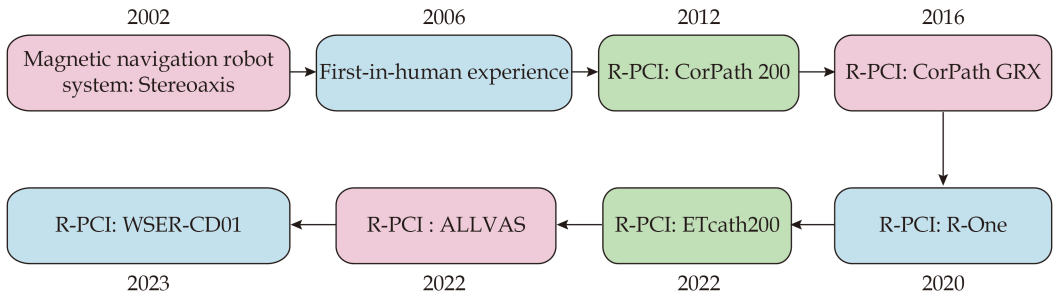


**Figure 2 The technology developments of R-PCIs.** R-PCI: robotic percutaneous coronary intervention.

me and more precise measurements. During the R-PCI procedure, the operator can sit comfortably in the robotic cockpit in front of a large screen displaying angiographic images (hemodynamic, intracoronary imaging and physiological data). With the high lesion complexity of the PCI procedure, it is more obvious that there are many benefits, such as enhanced visualization, the ability to place longer stents, and higher rates of postdilatation.[14] Additionally, current-generation R-PCI platforms can produce intracoronary wires, rapid-exchange devices, guide extension catheters, intracoronary physiology wires, and specific non-rotational-based intravascular imaging catheters. Intravascular imaging is a routine technique often used in PCI. One study reported that ($n$ = 110 patients), 94.6% of whom used intravascular ultrasound, most R-PCIs had a procedure time of 30–90 min.[19] When multiple modalities (physiological assessments) are used, R-PCIs still require considerable time. The same phenomenon also occurs for manual PCIs (M-PCIs), so the method itself may require more time. More research needs to be conducted in the future to explore the difference in time between R-PCIs and M-PCIs by overlaying multimodality evaluation methods.

The aforementioned technological developments, combined with increasing operator experience worldwide, have reduced the time of routine operations and improved the success rate of difficult operations. The 2017 CORA-PCI trial[10] further demonstrated that there was no significant difference in clinical success rates between R-PCI and M-PCI for complex coronary artery lesions.

Interventional cardiologists have high radiation exposure, with an estimated maximum annual dose of up to 5.0 μSv in percutaneous transluminal coronary angioplasty.[20] A concerning study revealed that there is a growing possibility of a relationship between the incidence of left-sided brain tumours and the incidence of these tumours among interventional cardiologists.[21] Additionally, it also increased, with one study reporting that it occurred. Fifty percent of interventional cardiologists experienced posterior subcapsular changes when the percentage of age-matched contr-

ols was less than 10%. This meant that the risk of cataracts increased with long-term radiation exposure.[22] Notably, radiation exposure through the radial approach was 51% greater than that through the femoral approach in a study including 297 PCI patients.[23] The mean fluoroscopic time between the two approaches was similar. Therefore, the reason may be the closer proximity to the fluoroscopic-source.

We reviewed a total of 21 reports on actual clinical trials (Table 1) of the R-PCI platform, starting with the first R-

**Table 1 Studies reporting system, design and exclusion criteria for robotic PCI.**

| Author | Robotic PCI system | Study design | Inclusion criteria | Exclusion criteria |
|---|---|---|---|---|
| Beyar, *et al.*[13] (2006) | Remote navigation system | First-in-human experience | NR | NR |
| Granada, *et al.*[44] (2011) | CorPath 200 | Single-arm, open-label, prospective investigation | Angiographic documentation of obstructive coronary artery disease<br>Evidence of myocardial ischemia | Planned coronary artery bypass graft surgery or PCI within 30 days of target procedure<br>Congestive heart failure or left ventricular ejection fraction of < 30%<br>Recent (< 72 h) myocardial infarction<br>Recent stroke (< 30 days) or bleeding diathesis<br>Prior stent within 5 mm of the target lesion, ostial or bifurcation lesion, total occlusion, and severe tortuosity or calcification |
| Weisz, *et al.*[9] (2013) | CorPath 200 | Prospective, single-arm, multicenter, open-label, nonrandomized study | A *de novo* stenosis of at least 50% by visual estimate<br>Maximal length of 24 mm<br>Reference diameter of 2.5–4.0 mm<br>Could be completely covered by a single stent | Planned PCI or coronary artery bypass graft surgery<br>Required treatment of more than 1 coronary artery<br>Previous stent implantation within 5.0 mm of the target lesion<br>Planned treatment with directional or rotational atherectomy, intraluminal thrombus, severe tortuosity or calcification of the lesion or proximal to it, total occlusion, ostial location, involvement of a bifurcation<br>Unprotected left main coronary artery |
| Smilowitz, *et al.*[45] (2014) | CorPath 200 | Single-center study | The *de novo* obstructive coronary artery disease with a stenosis of ≥ 50% on angiography<br>Evidence of myocardial ischemia on noninvasive stress testing<br>Indications for single-vessel PCI<br>Single or multiple coronary artery stenoses (with 10 mm or less between diseased segments) if they were ≤ 24.0 mm in length | Left ventricular ejection fraction < 30%<br>Acute myocardial infarction<br>Recent PCI within 72 h prior to the study procedure<br>A major recent complication from PCI within 30 day<br>Planned PCI or coronary artery bypass graft within 30 days |
| Mahmud, *et al.*[10] (2017) | CorPath 200 | Postmarket, prospective, single-arm, multicenter registry | Mild to moderate calcification<br>Chronic total occlusion<br>Bifurcation disease<br>Severe tortuosity<br>Unprotected left main coronary artery stenosis<br>Multivessel disease<br>Left ventricular dysfunction | ST-segment elevation myocardial infarction |
| Madder, *et al.*[8] (2017) | CorPath 200 | Single-center prospective observational study | Inclusion if subsequent invasive angiography demonstrated a severe stenosis requiring PCI and the target lesion was deemed suitable for treatment using a robotic approach | Hemodynamic instability<br>Emergent need for PCI, including emergent primary PCI for ST-segment elevation myocardial infarction<br>Cardiogenic shock<br>Severe multivessel coronary artery disease<br>Target lesion located in a coronary artery bypass graft<br>Ejection fraction < 35% |
| Smitson, *et al.*[6] (2018) | CorPath GRX | Single-arm, open-label, single-center investigation of a novel | Obstructive coronary artery disease (> 70% stenosis by visual estimate) and clinical indication for PCI | ST-elevation myocardial infarction<br>Lesions not treatable due to known limitations of the robotic platform |
| Harrison, *et al.*[34] (2018) | CorPath 200 | Postmarket, prospective, single-arm, multicenter registry study | ≥ 18 yrs of age | NR |

Continued

| Author | Robotic PCI system | Study design | Inclusion criteria | Exclusion criteria |
|---|---|---|---|---|
| Hirai, *et al.*[46] (2019) | CorPath GRX | Retrospective study at two CTO referral centers | > 18 yrs of age<br>Had symptoms suggestive of ischemic heart disease, with TIMI grade 0 flow<br>More than 3 months<br>Only patients undergoing PCI of a single CTO with successful manual crossing of the CTO | Underwent CTO PCI of more than two lesions at the same setting<br>Unsuccessful cases with or without subintimal plaque modification |
| Patel, *et al.*[47] (2019) | CorPath GRX | Single-center, open-label, one-arm study | Presence of a *de novo*, previously untreated, native coronary artery stenosis (> 80% occlusion by visual estimate)<br>Lesionlength ≤ 20 mmbyvisualestimate<br>Vessel diameter between 2.5 mm and 4.0 mm | Left ventricular ejection fraction < 40%, acute coronary syndrome in the past 48 h<br>Prior stent placement within 5 mm proximal or distal to the target vessel lesion<br>A lesion requiring planned treatment with atherectomy, or any device except for balloon dilatation prior to stent placement<br>Evidence of intraluminal thrombus or moderate to severe tortuosity (> 90°) proximal to the target lesion<br>Total vessel occlusion, severe target vessel calcification proximal to target lesion<br>Lesion located in a native vessel distal to an anastomosis with a saphenous vein graft or a left/right internal mammary artery bypass that must be approached through the bypass graft<br>Presence of > 50% diameter stenosis in the left main coronary artery |
| Dou, *et al.*[48] (2019) | CorPath GRX | Single-center study | NR | NR |
| Patel, *et al.*[11] (2020) | CorPath GRX | Single-center study | NR | NR |
| Walters, *et al.*[49] (2020) | CorPath GRX | Single-center study | NR | NR |
| Sooknanan, *et al.*[50] (2021) | CorPath GRX | Single-center study | NR | NR |
| Koeda, *et al.*[19] (2022) | CorPath GRX | Single-center study | Stable effort angina pectoris<br>Silent myocardial ischemia<br>Unstable angina pectoris<br>≥ 90% stenotic lesion and stenotic lesion possibly causing chest symptoms | Acute myocardial infarction<br>Culprit lesion in left main trunk<br>Culprit lesion in coronary bypass graft<br>With transcatheter aortic valve replacement<br>Using debulking device<br>Using mechanical circulatory support<br>Without intravascular imaging |
| Zhai, *et al.*[16] (2022) | ETcath200 | Single-arm, single-center, open-label, prospective trial | Age ≥ 18 yrs, no gender restrictions<br>Patients with coronary heart disease and clinical indications for PCI<br>The *de novo* lesions<br>Reference vessel diameter of 2.5–4.0 mm, target lesion length ≤ 40 mm<br>Target lesions that could be completely covered by the stent<br>The degree of stenosis in the target lesion > 50% | Acute myocardial infarction experienced within one week<br>Stroke occurrence within six months, or a history of major gastrointestinal bleeding in the past six months, or determination by the investigator that the patient had a bleeding disorder<br>The target vessel having received a previous stent treatment, and the target lesion located within 5 mm of the proximal end of the treated lesion<br>Severe calcification at the proximal end of the target lesion or within the lesion<br>Thrombosis in the target vessel lumen<br>Unprotected left main coronary artery disease<br>Allergy to any component of the drug or research device necessary for surgery, such as aspirin, clopidogrel, heparin, contrast agent, ticagrelor, bivalirudin, and paclitaxel<br>Pregnant or breastfeeding women<br>Having participated in clinical trials of other drugs or medical devices during the same period |
| Li, *et al.*[17] (2023) | ALLVAS | One patient | NR | NR |

Continued

| Author | Robotic PCI system | Study design | Inclusion criteria | Exclusion criteria |
|---|---|---|---|---|
| Durand, *et al.*[2] (2023) | R-One | Prospective, multicenter, single-arm clinical study | Age ≥ 18 yrs<br>Candidate for percutaneous coronary intervention<br>Presence of a *de novo* coronary artery stenosis of ≥ 50% and < 100% in a native coronary artery indicated and suitable for stent placement<br>Reference vessel diameter of 2.5–4.0 mm<br>Target lesion length allows for treatment with a single stent up to 38 mm<br>Up to 2 target vessels, each with a single target lesion requiring a single stent per lesion and treatable within a single procedure<br>Written informed consent as approved by the applicable Ethics Committee<br>Willing to comply with all study requirements including 30 days of follow-up | Target lesion with Thrombolysis in Myocardial Infarction flow < 3<br>Treatment of in-stent restenosis or prior stent in the target vessel proximal to the target lesion<br>> 1 target lesion per vessel requiring treatment at the time of procedure<br>Severe vessel tortuosity<br>Severe vessel calcification<br>ST-segment elevation myocardial infarction, cardiopulmonary resuscitation, or cardiogenic shock ≤ 48 h of the procedure<br>Significant issue detected prior to intervention, such as presence of visible thrombus<br>Need for any procedure other than balloon angioplasty or stenting (e.g., atherectomy, laser)<br>Patients under judicial protection, tutorship, or curatorship (for France only)<br>Participating in another clinical study evaluating a drug or medical device (except registries) for which the primary endpoint was not yet evaluated<br>Pregnant, breastfeeding, or intention to become pregnant prior to completion of all follow-up procedures |
| Jonas, *et al.*[51] (2023) | CorPath GRX | Prospective, single-center study | NR | NR |
| Bay, *et al.*[52] (2024) | CorPath GRX | Contemporary, single-center, prospective cohort study | Age > 18 yrs<br>Ability to give written informed consent<br>Adequate knowledge of the German language | Cardiogenic shock<br>Hemodynamic instability due to other causes, including arrhythmias |

CTO: chronic total occlusion; PCI: percutaneous coronary intervention; NR: not reported.

PCI system in 2006. Both clinical and technical success rates were maintained at a very high level (> 90%) (Table 2). Compared to the M-PCI group, the R-PCI group showed significantly reduced total radiation exposure and maintained procedural times. Meta-analyses reported that both contrast volume (mean difference: -15.27, 95% CI: -22.37–-8.18, $P < 0.0001$) and fluoroscopy time (mean difference: -1.26, 95% CI: -2.37–-0.16, $P = 0.03$) were significantly lower in the R-PCI group.[24] Our experience suggests that the performance of R-PCIs can be assessed in a short time frame. Early experienced interventionalists became significantly faster at completing R-PCIs after performing three procedures without compromising patient safety.[25] As interventionalists gain experience performing R-PCIs over time, the number of procedures and fluoroscopies is expected to decrease. Therefore, we cannot exclude the possibility that a learning curve effect might partly explain the slightly increased total procedure time of this technique compared to that of M-PCI.[26]

Another potential advantage of R-PCI may be a reduced incidence of lesion-stent mismatch, called geographic miss. Compared with that of M-PCIs ($n = 1557$ patients), the rate of longitudinal geographic misses decreased by 72% for R-PCIs ($n = 164$ patients).[27] Previous studies reported that geographic misses were related to poor clinical outcomes, including increased rates of restenosis and revascularization problems.[28,29] A retrospective study demonstrated that there was a threefold increase in 1-year myocardial infarction rates ($n = 1557$ patients) with angiographic evidence of geographic misses.[30] When suffering from instances of geographic misses, stent implantations might fail to cover the entire portion. Thus, thrombosis or restenosis may develop at the proximal or distal edge of the stent.[31] Moreover, 8.3% of patients could save extra stents. This was because visual measurements overestimate lesion length compared with robotic measurements.[32]

Orthopaedic injuries are caused by wearing lead aprons for a long time. Although the weight of lead aprons has decreased with the development of technology, there has been no significant improvement in the incidence of orthopedic injuries.[5] By using the R-PCI platform, doctors can operate in a comfortable way based on ergonomics, which will improve muscle and orthopedic strain.

**Table 2 Studies reporting actual clinical data for R-PCI.**

| Author | Number of patients | Lesion complexity* | Clinical success | Technical success | Total radiation exposure | Times |
|---|---|---|---|---|---|---|
| Beyar, *et al.*[13] (2006) | 18 | NR | 100% | 83% | NR | Remote navigation system: 9.1 ± 3.5 min<br>Total fluoroscopy time: 8.8 ± 4.8 min |
| Granada, *et al.*[44] (2011) | 8 | 0 | 100% | 97.9% | Interventional cockpit: 1.81 ± 1.93 μGy<br>Procedure table: 61.57 ± 54.95 μGy | Robotic system procedure time: 26.5 ± 8.0 min |
| Weisz, *et al.*[9] (2013) | 164 | 31.7% | 100% | 98.8% | Interventional cockpit: 0.98 μGy<br>Procedure table: 20.6 μGy | Robotic system procedure time: 24.4 ± 14.1 min |
| Smilowitz, *et al.*[45] (2014) | 40 | NR | 100% | 95% | Robotic group: 1389 ± 599 mGy<br>Manual group: 1665 ± 102 mGy | R-PCI: 10.1 ± 4.7 min<br>M-PCI: 12.3 ± 7.6 min |
| Mahmud, *et al.*[10] (2017) | 108 | 78.3% | 99.1% | 91.7% | Robotic group: 12,518 ± 15,970 cGy·cm$^2$<br>Manual group: 14,048 ± 18,437 cGy·cm$^2$ | Robotic group: 44:30 ± 26:04 min<br>Manual group: 36:34 ± 23:03 min |
| Madder, *et al.*[8] (2017) | 20 | 50% | 95.0% | 86.4% | Robotic group: 1263 ± 751 mGy<br>Manual group: 1826 ± 637 mGy | Robotic group: 15.5 ± 7.6 min<br>Manual group: 18.5 ± 7.7 min |
| Smitson, *et al.*[6] (2018) | 40 | 77.8% | 90.0% | 97.5% | NR | NR |
| Harrison, *et al.*[34] (2018) | 108 | 78.3% | 99.1% | 91.7% | Complete R-PCI: 10,440 ± 13,726 cGy·cm$^2$<br>Manual assistance: 21,667 ± 21,576 cGy·cm$^2$ | R-PCI fluoroscopy time: 31.6 ± 11.7 min<br>Manual assistance fluoroscopy time: 15.2 ± 7.2 min |
| Hirai, *et al.*[46] (2019) | 49 | 80.0% | 98.0% | 98.0% | Robotic group: 1522 ± 1129 mGy<br>Manual group: 2466 ± 1204 mGy | Robotic group: 89.6 ± 27.1 min<br>Manual group: 93.4 ± 30.5 min |
| Patel, *et al.*[47] (2019) | 5 | NR | 100% | 100% | R-PCI: 989–1713 mGy | R-PCI procedure: 23.6 (19–29) min |
| Dou, *et al.*[48] (2019) | 100 | 63.6% | 100% | 100% | Early cases: 1932 ± 978 mGy·cm$^2$<br>Late cases: 1007 ± 70 mGy·cm$^2$ | Early cases: 48.3 ± 32.9 min<br>Late cases: 25.5 ± 13.0 min |
| Patel, *et al.*[11] (2020) | 310 | NR | NR | NR | R-PCI: 833 (521–1378) mGy<br>T-PCI: 1235 (793–1873) mGy | R-PCI: 36 (26–49) min<br>T-PCI: 31 (21–42) min |
| Walters, *et al.*[49] (2020) | 10 | NR | 90% | 60% | NR | Total time: 55.1 ± 28.7 min<br>Fluoroscopy time: 29.9 ± 14.5 min |
| Sooknanan, *et al.*[50] (2021) | 13 | NR | 100% | 100% | R-PCI: 741.75 mGy | R-PCI: 71.1 min |
| Koeda, *et al.*[19] (2022) | 102 | 60% | 100% | NR | 81.8% had an entrance skin dose of < 1.00 Gy | Most R-PCIs: 30–90 min<br>10% R-PCIs: < 30 min or > 90 min |
| Zhai, *et al.*[16] (2022) | 11 | NR | 100% | 100% | R-PCI: 1674 (1056–4360) mGy | R-PCI: 53 (39–67) min |
| Li, *et al.*[17] (2023) | 1 | NR | 100% | 100% | R-PCI: 2202.32 mGy | NR |
| Durand, *et al.*[2] (2023) | 62 | 25% | 100% | 95.2% | R-PCI: 7.2 ± 8.7 μSv<br>T-PCI: 57.1 ± 61.2 μSv | R-PCI: 17.4 ± 78.02 min<br>T-PCI: 22.23 ± 10.99 min |
| Jonas, *et al.*[51] (2023) | 21 | 72% | 100% | 81% | R-PCI: 5118 (4350–8886) cGy·cm$^2$ | R-PCI: 47 (18–76) min |
| Bay, *et al.*[52] (2024) | 70 | 88.2% | 100% | 74.1% | R-PCI: 2309.0 (1631.0–4230.0) cGy·cm$^2$<br>T-PCI: 2135.5 (1230.8–3733.8) cGy·cm$^2$ | R-PCI: 20.4 (13.8–27.2) min<br>T-PCI: 14.4 (10.4–24.3) min |

*Refers to it was defined by the American Heart Association (AHA) for type B2/C lesions. M-PCI: manual percutaneous coronary intervention; NR: not reported; R-PCI: robotic percutaneous coronary intervention; T-PCI: traditional percutaneous coronary intervention.

Moreover, if there are difficult surgeries that subordinate hospitals cannot accomplish, superior hospitals can provide convenient guidance through the internet. Some studies have shown that R-PCI remote stent placement is technically feasible ($n$ = 20 patients with all manipulations, including guidewires and stents).[8] In fact, it was proven that models of tele-stenting could be achieved over transcontinental distances.[33]

## COMPARISON AMONG CURRENT R-PCI SYSTEMS

The CorPath 200 consists of a robotic arm (at the patient's bedside) and a robotic cockpit (either inside or outside the laboratory). The robotic arm contains all intracoronary guidewires and devices. Then, operators use a joystick to control the robotic cockpit. The separate location of the robotic arm and robotic cockpit meant that interventional operators could manipulate intracoronary guidewires and devices without being in the radiation field.[14] However, the ability to manipulate the guide catheter and simultaneously advance two stents is limited.[34]

The CorPath GRX platform consists of a bedside unit (a single sterile cassette, articulating arm and robotic drive) and an interventional cockpit. The bedside unit is installed on the procedure table. Specifically, there is a communication cable that translates operator commands to manipulate each device independently. This device is mounted on the robotic drive, which is tethered to the control cockpit. The single-use cassette, which manipulates guiding catheters and angioplasty devices using motorized rollers that provide axial and rotational force, is manually loaded with commercially available 0.014-inch guidewires.[7,35] However, a previous review reported that there was no significant difference in the rates of technical success between the two CorPath devices (mean difference: 2.1%, $P = 0.71$).[24]

Compared with other R-PCI systems, the R-One system has a simpler intracoronary device to improve the learning curve for operators.[2]

The ETcath200 system consists of control and executive units. Interventionists can remotely control the movement of the guiding catheter, guidewire, balloon, or stent in the control room using three joysticks on the control unit. They could also achieve axial movement (forward/backwards) and rotational movement of the guidewire and simultaneously push and rotate the guidewire. Balloon or stent catheter advancement and retraction were controlled precisely, and the robot recorded the distance travelled by the device to accurately measure the length of the target lesion. Importantly, the device was compatible with common components of interventional procedures, including guidewires, rapid exchange balloon dilatation catheters, and stent delivery systems.[16]

The ALLVAS can accomplish complex actions in multivessel coronary lesions, such as insertion, withdrawal and rotation of the guidewire, balloon and stent.[17] Compared with the robots currently available for clinical use, the main difference is that the novel robotic system accomplished multiple collaborative manipulations with twelve degrees of freedom though four robotic manipulators.[36]

The WSER-CD01 system uses novel safety indicators such as speed, error of the secondary actuator and the maximum safety delay to confirm the safety of blood vessels. In addition, multijoint collaboration reduces the communication system jitter to 1 μs based on EtherNet Control Automation Technology (EtherCAT).[18]

## LIMITATIONS OF R-PCI

Unstable patients, such as those with ST-segment elevation myocardial infarction and severely impaired left ventricular function, may experience rapid decompensation. Therefore, bedside care may also be needed.

Additionally, there are inherent delays in switching from R-PCIs to M-PCIs. In some emergency situations, these delays can lead to severe consequences for patients. Although there is no evidence that more complications will occur in R-PCIs than in M-PCIs, abrupt vessel closure and perforation still require manual assistance for emergent procedures.[7] This is also a major problem in the implementation of tele-stenting, where interventional cardiologists may not necessarily be available on site.

Moreover, the use of thrombus aspiration catheter, which is the first option for patients with a high thrombus burden,[37] is currently incompatible with R-PCIs. If there is no reflow in patients, it is necessary for interventionalists to change to M-PCI to deliver a microcatheter distally (administer intracoronary drugs such as adenosine or nitrates to the microvascular bed).[38]

The different results of various studies may affect the technical and clinical success rates of R-PCI procedures. These factors could be attributed to the incidence of adverse events, lesion complexity, and the experience of interventional cardiologists. Lesion complexity is divided into A, B1, B2, and C based on the American Heart Association. However, the meta-analysis revealed that there was no relationship between the percentage of B2 or C lesions and the technical success rate.[24] One reason for this may be that more experienced interventional cardiologists were chosen for handling severe lesions. Therefore, this approach reduced the occurrence rate of manual conversion.

For complex lesions with certain characteristics, such as bifurcation lesions, robotic drive had limited ability to advance 2 balloons or stents simultaneously when operato-

rs performed provisional bifurcation stenting or final kissing balloon angioplasty. It is necessary to solve these problems to update the technology of over-the-wire device delivery, which could enable atherectomy and antegrade wire upgrading for chronic total occlusions. This approach can avoid manual assistance and manual conversion during the R-PCI procedure.

However, heavily calcified lesions still require the use of rotational or orbital atherectomy devices. Due to the incompatibility between these devices and R-PCIs, they cannot be performed without manual assistance. Moreover, R-PCI still faces challenges, including a lack of force feedback systems, poor wire compatibility, potentially extended operation time, and high costs.

## FUTURE POTENTIAL USE OF R-PCI

R-PCI has an ever-growing evidence base to support its use and has been successfully utilized in the treatment of highly complex coronary lesion. However, patients with ST-segment elevation myocardial infarction were excluded from R-PCI trials. Therefore, this evidence gap must be investigated if R-PCIs are to be increasingly incorporated into cardiac catheterization laboratories.

Tele-stenting is an application of R-PCI with significant potential to impact future practice. This may open the possibility for remote interventional treatment of coronary heart disease in rural areas without access to an interventional cardiologist or a local hospital specializing in emergency cardiovascular care.

Not only do we need to expand the benefits of R-PCI, but we also need to expand the methods used for this procedure. Learning R-PCIs should start with learning equipment, techniques, and catheter laboratory workflows. Therefore, new training and educational methods are needed to assist operators, and a wider number of catheter laboratory workflow teams should acquire the necessary skills for R-PCIs.

Compared with digital or electronic simulators, 3D-printed anatomical models are more suitable for practice because 3D models are more realistic and closer to the *in vivo* feel.[39] 3D models require fewer resource and have fewer ethical concerns than preclinical animal models. The main advantage is the ability to perform the same procedure repeatedly within the same model, which can accelerate an operator's learning progression.[40] Based on coronary artery computed tomography scans, coronary artery illusions that closely replicate coronary artery size and trajectory can be developed to support different robotic wiring techniques. Complex wiring scenarios, such as rethreading through stent pillars or navigating through highly curved blood vessels, can also be simulated.[14] Models can also be invented with different anatomical structures of the aortic sinus and coronary artery orifice, allowing operators to use guide catheters of different sizes and shapes for multiple repeated insertions in each model.[41] The use of silicon or 3D-printed anatomical models for simulation training is increasingly being used for training and education in interventional cardiology.[42,43]

For R-PCI safety indicators, theoretical modelling of the deformation problem of arterial blood vessel walls under force, solving boundary values, ensuring the safety of blood vessels even under extreme conditions where the guidewire end face directly contacts the arterial wall, providing a basis for the determination of safety indicators for vascular intervention surgical robots, and minimizing potential damage to the vascular wall during R-PCI operation, we studied and designed multiple joint collaborative control algorithms and remote control algorithms for vascular intervention surgery robots to achieve remote surgery functionality.

## CONCLUSIONS

R-PCI is a novel technology in interventional cardiology. This approach provides great benefits to interventional cardiologists in terms of reducing both radiation exposure and orthopedic injuries. Several large, high-quality cohort studies have confirmed the short-term safety and high technical success rate of R-PCI. However, randomized long-term data are still needed before adopting them as part of standard coronary interventions. Furthermore, tele-stenting has significant potential for R-PCI. We need to overcome the present relevant challenges for its application.

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