Journal of the American College of Cardiology
© 2013 by the American College of Cardiology Foundation
Published by Elsevier Inc.

Vol. 61, No. 15, 2013
ISSN 0735-1097/$36.00
http://dx.doi.org/10.1016/j.jacc.2012.12.045

Safety and Feasibility of Robotic Percutaneous Coronary Intervention

PRECISE (Percutaneous Robotically-Enhanced Coronary Intervention) Study

Giora Weisz, MD,* D. Christopher Metzger, MD,† Ronald P. Caputo, MD,‡ Juan A. Delgado, MD,§ J. Jeffrey Marshall, MD,‖ George W. Vetrovec, MD,¶ Mark Reisman, MD,# Ron Waksman, MD,** Juan F. Granada, MD,§ Victor Novack, MD, PHD,†† Jeffrey W. Moses, MD,* Joseph P. Carrozza, MD‡‡

New York and Syracuse, New York; Kingston, Tennessee; Medellin, Colombia; Gainesville, Georgia; Richmond, Virginia; Seattle, Washington; Washington, DC; Beersheba, Israel; and Boston, Massachusetts

Objectives The aim of this study was to evaluate the safety as well as the clinical and technical effectiveness of robotic-assisted percutaneous coronary intervention.

Background Robotic systems have been suggested to enhance the performance of cardiovascular procedures, as well as to provide protection from the occupational hazards that are associated with interventional practice.

Methods Patients with coronary artery disease and clinical indications for percutaneous intervention were enrolled. The coronary intervention was performed with the CorPath 200 robotic system, which consists of a remote interventional cockpit and a bedside disposable cassette that enables the operator to advance, retract, and rotate guidewires and catheters. The primary endpoints were clinical procedural success, defined as <30% residual stenosis at the completion of the robotic-assisted procedure without major adverse cardiovascular events within 30 days, and device technical success, defined as the successful manipulation of the intracoronary devices using the robotic system only.

Results A total of 164 patients were enrolled at 9 sites. Percutaneous coronary intervention was completed successfully without conversion to manual operation, and device technical success was achieved in 162 of 164 patients (98.8%). There were no device-related complications. Clinical procedural success was achieved in 160 of 164 patients (97.6%), whereas 4 (2.4%) had periprocedural non–Q-wave myocardial infarctions. No deaths, strokes, Q-wave myocardial infarctions, or revascularization occurred in the 30 days after the procedures. Radiation exposure for the primary operator was 95.2% lower than the levels found at the traditional table position.

Conclusions This pivotal multicenter study with a robotic-enhanced coronary intervention system demonstrated the safety and feasibility of the system. The robotic remote-control procedure met the expected technical and clinical performance, with significantly lower radiation exposure to the operator. (Evaluation of the Safety and Effectiveness of the CorPath 200 System in Percutaneous Coronary Interventions [PCI] [PRECISE]; NCT01275092) (J Am Coll Cardiol 2013;61:1596–600) © 2013 by the American College of Cardiology Foundation

A remote-controlled robotic system was designed to address some of the procedural challenges and occupational hazards associated with traditional percutaneous coronary intervention (PCI) in addition to enhancing the degree of precision and control for the interventional procedure. We report the first large-scale, multicenter study evaluating the safety and efficacy of a novel robotic system for PCI.

A list of the participating institutions and staff(s) appears in the Online Appendix.

From the *Center for Interventional Vascular Therapy, New York Presbyterian Hospital, Columbia University Medical Center, New York, New York; †Wellmont Holston Valley, Kingsport, Tennessee; ‡Saint Joseph's Hospital, Syracuse, New York; §Corbic Cardio Neurovascular Institute, Medellin, Colombia; ‖Northeast Georgia Heart Center, Gainesville, Georgia; ¶Virginia Commonwealth University, Richmond, Virginia; the #Swedish Heart & Vascular Institute, Seattle, Washington; **Washington Heart Center, Washington, DC; ††Clinical Research Center, Soroka University Medical Center, Beersheba, Israel; and the ‡‡Saint Elizabeth's Medical Center, Boston, Massachusetts. This study was sponsored by Corindus, Inc. Dr. Caputo is a consultant for Medtronic, Inc., Boston Scientific Corporation, and Terumo Medical Corporation. Dr. Marshall has received research support from Corindus, Inc. Dr. Vetrovec is an investigator for Corindus, Inc. Dr. Novack is a paid consultant to Corindus. Dr. Carrozza has received research support from Corindus. All other authors have reported that they have no relationships relevant to the contents of this paper to disclose.

Manuscript received August 2, 2012; revised manuscript received November 20, 2012, accepted December 19, 2012.

Figure 1 The CorPath 200 Robotic System in the Catheterization Laboratory

On the right, the operator sits in the shielded interventional cockpit, performing the interventional procedure by remotely controlling the robotic cassette **(red arrow)** that is connected to the guiding catheter. The intracoronary devices (guidewire, balloon, and stent catheters) are loaded into the sterile cassette.

Methods

This was a prospective, single-arm, multicenter, open-label, nonrandomized study. The study protocol was approved by the institutional review boards or local ethics committees of the participating facilities, and all patients provided written informed consent.

The objectives of this study were to evaluate the safety, clinical, and technical performance of the robotic system in the delivery and manipulation of coronary guidewires, balloons, and stents for PCI.

Patients. Patients with angiographic documentation of obstructive coronary artery disease and evidence of myocardial ischemia were enrolled in the study. Major inclusion criteria included a de novo stenosis of at least 50% by visual estimate, with maximal length of 24 mm and reference diameter of 2.5 to 4.0 mm, that could be completely covered by a single stent. Major clinical exclusion criteria included planned PCI or coronary artery bypass graft surgery, required treatment of more than 1 coronary artery, previous stent implantation within 5.0 mm of the target lesion, 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, or unprotected left main coronary artery.

Post-procedural creatine kinase and its myocardial band isoenzyme were routinely measured at 8 and 16 to 24 h, and all patients were followed for clinical events throughout their hospital stays and for 30 days afterward.

Robotic system. All patients underwent PCI with the robotic CorPath 200 System (Corindus Vascular Robotics, Natick, Massachusetts). The system was designed for coronary PCI and consists of 2 major components: the interventional cockpit and a bedside unit (Fig. 1). The interventional cockpit is a radiation-shielded, mobile workstation that was positioned in the corner of the catheterization laboratory. The interventional cardiologist sits at the cockpit and remotely performs the PCI using the console joysticks or touch-screen buttons. Commands from the control console are delivered as electrical signals along a communication cable that runs from the control console to the robotic drive, on which a sterile cassette is placed. The cassette, which is loaded with the interventional devices and connected to the guiding catheters, imposes axial and rotational forces on the intracoronary devices. The robotic-assisted system is compatible with all commercially available 0.014-inch guidewires, rapid-exchange coronary angioplasty balloons, and stent delivery systems. Fluoroscopic, electrocardiographic, and hemodynamic images are "slaved" to the duplicate monitors inside the cockpit, enabling visualization from a closer distance. All operators had training on the system that included either animal laboratory experience or using a high-fidelity simulator before enrolling patients in the study.

Abbreviation and Acronym

PCI = percutaneous coronary intervention

After completion of diagnostic angiography, the guiding catheter was positioned at the ostium of the coronary artery and connected to the disposable cassette on the robotic drive. The guidewire was loaded into the cassette before starting the robotic-enhanced PCI. Anticoagulation was administrated according to local site protocols. Pre-dilation was mandated by protocol, and post-dilation was done per operator discretion. All intracoronary devices were to be manipulated exclusively by the robotic system, with bailout to manual conversion when needed.

Study endpoints. The 2 primary endpoints were clinical procedural success and device technical success.

Clinical procedural success was defined as <30% residual stenosis at the completion of the procedure of robotically-treated lesions as determined by a quantitative coronary angiographic core laboratory, in the absence of major adverse cardiovascular events, either within 48 h of the procedure or before hospital discharge, whichever occurred first. Major adverse cardiovascular events were defined as cardiac death, Q-wave or non–Q-wave myocardial infarction, or clinically driven target vessel revascularization. Non–Q-wave myocardial infarction was defined as elevated creatine kinase myocardial band isoenzyme >3 times the upper limit of normal in the absence of new pathological Q waves. All events were adjudicated by an independent clinical events committee.

Device technical success was defined as the successful intracoronary advancement and retraction of the PCI devices (guidewire, angioplasty balloon, and stent) by the robotic system, without conversion to manual operation.

The radiation exposure to the operator at the interventional cockpit and at the procedure table were monitored using Educational Direct Dosimeters (EDD-30, Unfors, Billdal, Sweden).

JACC Vol. 61, No. 15, 2013
April 16, 2013:1596–600

Statistical analysis. The necessary sample size for testing the endpoint of clinical procedural success was calculated on the basis of the Fisher exact test using assumptions of an expected rate of clinical procedural success of 91.6% and type I error (α) of 0.05 (1-sided). A sample size of 163 would provide 90% power to reject the null hypothesis, signifying that the CorPath 200 System met the performance goal for clinical procedural success. For device technical success, a lower limit of the 1-sided 95% confidence interval of 90.0% and statistical power of 90%, the true rate of device technical success would need to be higher than 94.5% to reject the null hypothesis, assuming 163 patients. Both primary endpoints had to be met for the study to be declared successful.

Data were analyzed on an intention-to-treat basis. Standard summary statistics were calculated for all patient and study outcome variables. Continuous variables were summarized using estimated means, standard deviations, minimums, maximums, medians, and interquartile ranges. Categorical data were summarized using frequencies, percentages, and 95% confidence intervals.

The powered secondary effectiveness endpoint of a reduction in operator radiation exposure (the median ratio of operator dose to table dose) was evaluated using an ordinal test for paired samples (the Wilcoxon signed rank test). The alternative hypothesis formulated for the study to be successful was to achieve a minimum of 50% reduction in the operator's radiation exposure compared with the radiation exposure measured at the procedure table during the procedure.

Results

A total of 164 patients from 9 sites met the inclusion and exclusion criteria and underwent PCI using the robotic system. Baseline clinical characteristics and quantitative coronary angiographic findings are detailed in Tables 1 and 2.

Table 1 Patients Demographics and Baseline Characteristics (n = 164)

Age (yrs)	64.1 ± 10.0
Men	74.4%
Hypertension	141 (86%)
Diabetes mellitus	58 (35.4%)
Hyperlipidemia	145 (88.4%)
Prior myocardial infraction	83 (50.6%)
Prior PCI	129 (78.7%)
Prior CABG	10 (6.1%)
Prior stroke or TIA	14 (8.5%)
Peripheral vascular disease	29 (17.7%)
Left ventricular ejection fraction (%)	54.9 ± 8.9
Indication for PCI	
Stable angina	47 (28.7%)
Unstable angina	94 (57.3%)

Values are mean ± SD or n (%).
CABG = coronary artery bypass grafting; PCI = percutaneous coronary intervention; TIA = transient ischemic attack.

Table 2 Quantitative Angiographic Analysis

Variable	Pre-Procedure	Post-Procedure
LAD	55 (33.5%)	
Main LAD	53 (32.3%)	
Diagonal	2 (1.2%)	
LCX	47 (28.7%)	
Main LCX	35 (21.3%)	
Ramus intermedius	8 (4.9%)	
Obtuse marginal	4 (2.4%)	
RCA	62 (37.8%)	
Main RCA	60 (36.6%)	
Posterior descending	2 (1.2%)	
ACC/AHA class		
A	47 (28.7%)	
B1	65 (39.6%)	
B2	31 (18.9%)	
C	21 (12.8%)	
Lesion length (mm)	12.2 ± 4.8	
Reference vessel diameter (mm)	2.66 ± 0.45	2.73 ± 0.46
MLD (mm)	0.95 ± 0.33	2.59 ± 0.43
Diameter stenosis (%)	64.10 ± 10.9	4.90 ± 7.85

Values are n (%) or mean ± SD.
ACC = American College of Cardiology; AHA = American Heart Association; LAD = left anterior descending coronary artery; LCX = left circumflex coronary artery; MLD = minimal luminal diameter; RCA = right coronary artery.

All PCI procedures were performed via femoral arterial access, with 6-F guiding catheters in 119 (72.6%) and 7-F guiding catheters in 45 (27.4%). All devices (guide catheters, guidewires, balloons, and stents) were commercially approved and selected by the operator, similarly to manual PCI. A mean of 1.1 ± 0.34 stents were deployed per patient. In 12 patients, more than 1 stent was used to treat stent-edge dissection or plaque shift. post-dilation was performed in 33 patients (20.1%). In 162 procedures (98.8%), the entire procedure was performed with the robotic system, with successful advancing and retrieving of all intracoronary devices. In all patients, advancements of the guidewire proceeded uneventfully, without any dissection or perforation and no injury related to the guiding catheter. In all patients (except for 1 in whom it was unintentionally omitted), the pre-dilation balloon was successfully delivered to the lesion, inflated, and successfully retrieved by the robotic system back into the guiding catheter. In 2 procedures (1.2%), the operators converted to manual operation because of severe resistance to delivery of the stent. In both cases, the procedure was also difficult to perform manually and was completed successfully only after upgrading to a more supportive guiding catheter and the use of advanced interventional techniques, including buddy wires and the use of a GuideLiner (Vascular Solutions, Inc., Minneapolis, Minnesota). The conversion to manual operation was immediate and not associated with myocardial ischemia, hemodynamic compromise, or any other complications. In both cases, there were no periprocedural complications or myocardial enzyme elevations.

Table 3 In-Hospital and 30-Day Follow-Up Outcomes (n = 164)

In-hospital	
Death	0 (0.0)
MI (all)	4 (2.4)
Q-wave	0 (0.0)
Non–Q-wave	4 (2.4)
TLR	0 (0.0)
MACEs	4 (2.4)
Out-of-hospital to 30 days	
Death	0 (0.0)
MI (all)	0 (0.0)
Q-wave	0 (0.0)
Non–Q-wave	0 (0.0)
TLR	0 (0.0)
MACEs	0 (0.0)
All events to 30-day follow-up	
Death	0 (0.0)
MI (all)	4 (2.4)
Q-wave	0 (0.0)
Non–Q-wave	4 (2.4)
TLR	0 (0.0)
MACEs	4 (2.4)
Stent thrombosis, 0–30 days	0 (0.0)

Values are n (%). All events were adjudicated by the clinical events committee.
MACE = major adverse cardiovascular event(s); MI = myocardial infarction; TLR = target lesion revascularization.

All procedures ended with residual stenosis of <30% and Thrombolysis In Myocardial Infarction flow grade 3. There were no clinical adverse events related to the use of the robotic system. The mean robotic system procedure time was 24.4 ± 14.1 min with a mean fluoroscopy time of 11.1 ± 6.2 min. The mean patient cumulative dose was 1.5 ± 0.8 Gy. The mean contrast media volume used was 144.2 ± 70.4 ml.

Clinical outcomes are detailed in Table 3. The primary endpoint of clinical procedural success was achieved in 97.6% of patients (160 of 164), with the 1-sided exact 95% confidence interval yielding a lower bound of calculated performance goal at 94.5%, significantly higher than the protocol-specified performance goal of 84% ($p < 0.001$). In 4 patients (2.4%), there were modest post-procedural elevations in myocardial biomarkers corresponding to the definition of non–Q-wave myocardial infarction. Device technical success was achieved in 162 of 164 patients (98.8%), with the 1-sided exact 95% confidence interval yielding a lower bound of calculated performance goal at 96.2%, significantly higher than the protocol-specified performance goal of 90% ($p < 0.001$). Thus, both primary endpoints were successfully met at a high level of significance.

The powered secondary effectiveness endpoint of a minimum 50% reduction in operator radiation exposure was successfully met. The median radiation exposure to the operators at the interventional cockpit was 95.2% lower than at the procedure table (0.98 vs. 20.6 μGy, $p < 0.0001$).

Discussion

The prospective multicenter PRECISE (Percutaneous Robotically-Enhanced Coronary Intervention) study demonstrated the safety and feasibility of remote-controlled PCI using the CorPath 200 robotic system. In 164 patients treated by 23 operators, there were no system-related complications and no major clinical events. Only 4 patients (2.4%) had periprocedural myocardial biomarker elevations, without clinical consequences. The primary endpoint of clinical procedural success was achieved in 97.6%, and device technical success was achieved in 98.8%. In only 2 patients was conversion to traditional manual operation required.

This is the first large multicenter study of a remote-controlled robotic system. Animal studies have shown that the robotic system tested in this study is safe and effective in the manipulation of interventional devices into normal porcine coronary arteries. Histological evaluation of the coronary arteries showed similar injury scores and vascular healing patterns when the robotic system was compared with manually treated vessels (1,2). An early experimental robotic system proved to be safe and feasible (3). The first human experience in 8 PCI cases with the currently studied CorPath 200 system demonstrated 97.8% technical success rate by completing 47 of 48 procedural segments, without major adverse cardiovascular events (4).

Remote-controlled robotic systems are expected to reduce occupational hazards to interventional cardiologists. As the current practice of interventional cardiology evolves into more complex procedures, interventional cardiologists and professional societies have called for improved catheterization laboratory safety by reducing radiation exposure to both patients and operators and making the catheterization laboratory more ergonomically friendly through technological innovations (5–7). Interventional cardiologists develop posterior lens opacities and cataracts at younger ages and at higher rates than other professionals (6,8,9). A recent observational report raised concern for a possible association of career-long exposure to radiation in interventional cardiologists with the development of left-sided brain tumors (10).

In the present study, we measured the radiation exposure to the operator seated in the shielded interventional cockpit and compared it with radiation exposure at the procedure table. We found a significant decrease in operator radiation exposure, with a median reduction of 95.2%. The mean fluoroscopy time and patient radiation exposure compare favorably with previously published results (11).

Another occupational hazard for the interventional cardiologist is orthopedic injury. Long hours donning a heavy lead apron while standing may adversely affect interventional cardiologists, resulting in reduced performance and loss of productivity (12). Although no measurement of "operator comfort" was used in this study, the benefits of the system are intuitive. Sitting at the shielded interventional

JACC Vol. 61, No. 15, 2013
April 16, 2013:1596–600

cockpit without the need for a heavy lead apron minimizes back discomfort, allowing the operator to focus on the procedure without being distracted by the physical strain.

Study limitations. Although it was a registry without a control group, all patient characteristics, angiographic features, and procedural parameters were comparable with published data, including patient exposure to radiation and the volume of contrast media used (11). Although the lesions that were treated in this study were relatively simple, they do not differ from the types of lesions usually studied in prospective PCI studies.

Conclusions

Incorporating a remote-controlled, robotic-assisted PCI system into the catheterization laboratory addresses some of the occupational hazards associated with PCI, without affecting procedural performance and patient safety.

Reprint requests and correspondence: Dr. Giora Weisz, Center for Interventional Vascular Therapy, Columbia University Medical Center, 161 Fort Washington Avenue, 6th Floor, New York, New York 10032. E-mail: gw2128@columbia.edu.

REFERENCES

1. Beyar R, Wenderow T, Lindner D, Kumar G, Shofti R. Concept, design and pre-clinical studies for remote control percutaneous coronary interventions. EuroIntervention 2005;1:340–5.
2. Kaluza G, Pankratov MM, Conditt GB, et al. Robotically-assisted 3-vessel PCI with CorPath 200 System results in reduced operator radiation exposure but equivalent procedure and x-ray time, contrast volume and histology outcome when compared to conventional manual intervention in swine. J Am Coll Cardiol 2011;57:E1952.
3. Beyar R, Gruberg L, Deleanu D, et al. Remote-control percutaneous coronary interventions: concept, validation, and first-in-humans pilot clinical trial. J Am Coll Cardiol 2006;47:296–300.
4. Granada JF, Delgado JA, Uribe MP, et al. First-in-human evaluation of a novel robotic-assisted coronary angioplasty system. J Am Coll Cardiol Intv 2011;4:460–5.
5. Hirshfeld JW Jr., Balter S, Brinker JA, et al. ACCF/AHA/HRS/SCAI clinical competence statement on physician knowledge to optimize patient safety and image quality in fluoroscopically guided invasive cardiovascular procedures. A report of the American College of Cardiology Foundation/American Heart Association/American College of Physicians Task Force on Clinical Competence and Training. J Am Coll Cardiol 2004;44:2259–82.
6. Klein LW, Miller DL, Balter S, et al. Occupational health hazards in the interventional laboratory: time for a safer environment. Catheter Cardiovasc Interv 2009;73:432–8.
7. Miller DL, Schueler BA, Balter S. New recommendations for occupational radiation protection. J Am Coll Radiol 2012;9:366–8.
8. Ciraj-Bjelac O, Rehani MM, Sim KH, Liew HB, Vano E, Kleiman NJ. Risk for radiation-induced cataract for staff in interventional cardiology: is there reason for concern? Catheter Cardiovasc Interv 2010;76:826–34.
9. Vano E, Kleiman NJ, Duran A, Rehani MM, Echeverri D, Cabrera M. Radiation cataract risk in interventional cardiology personnel. Radiat Res 2010;174:490–5.
10. Roguin A, Goldstein J, Bar O. Brain tumours among interventional cardiologists: a cause for alarm? Report of four new cases from two cities and a review of the literature. EuroIntervention 2012;7:1081–6.
11. Nikolsky E, Pucelikova T, Mehran R, et al. An evaluation of fluoroscopy time and correlation with outcomes after percutaneous coronary intervention. J Invasive Cardiol 2007;19:208–13.
12. Goldstein JA, Balter S, Cowley M, Hodgson J, Klein LW. Occupational hazards of interventional cardiologists: prevalence of orthopedic health problems in contemporary practice. Catheter Cardiovasc Interv 2004;63:407–11.

Key Words: angioplasty ■ robotic-enhanced PCI ■ stent.

APPENDIX

For a listing of the participating centers, please see the online version of this article.