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Patient-Specific Dynamic Digital-Physical Twin for Coronary Intervention Training: A Mixed Reality Approach

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Abstract

Background: Traditional coronary intervention training systems have low anatomical reality and no dynamic physiological feedback. Mixed reality (MR) technologies along with patient-derived computational modeling have the prospect to provide significantly personalized and interactive training setting. This research paper outlines an interactive design of a patient-controlled digital-physical twin will be developed and evaluated to aid in training procedures of percutaneous coronary intervention (PCI).

Methods: Coronary CT and angiographic data were utilized to create customized 3D vascular geometries that were incorporated into a computational model based on physics that predicted blood flow, vessel compliance and hemodynamic response. Haptic enabled catheter interface was a simulated tactual force observed during PCI. The physical movement of catheters in real-time to act as two way digital simulation and the opposite were made possible by real-time, two-way synchronization. Standardized PCI tasks were done using digital-physical twin and conventional simulator by interventional trainees ($n = 24$). Performance measures were the: navigation accuracy, wire control stability, procedure time and the description of realism by the user.

Findings: The model enhanced the anatomical understanding of the users and the quality of catheterization navigation as it reduced the error of navigation by 25 percent and wire prolapse by 30 percent when compared to conventional simulation ($p < 0.05$). The MR system scored significantly higher on realism ratings (4.6 4.6 vs.3.3 on a 5-item scale, $p < 0.001$). Noted dynamic hemodynamic feedback was found to improve procedural decision-making, noted by the participants.

Discussion: This patient-centered digital-physical twin offers an immersive, physiologically responsive learning environment to simulate PCI training, thus being able to achieve better performance and anatomy understanding than traditional simulators. MR approach is an accelerating development of individualized interventional education.

Keywords: Mixed Reality (MR), Digital-Physical Twin, Patient-Specific Simulation, Percutaneous Coronary Intervention Training, Percutaneous Coronary Intervention (PCI), Computational Modeling, Haptic Simulation, Cardiovascular Education, Hemodynamic Simulation, Interventional Cardiology Training.

Graphical abstract:

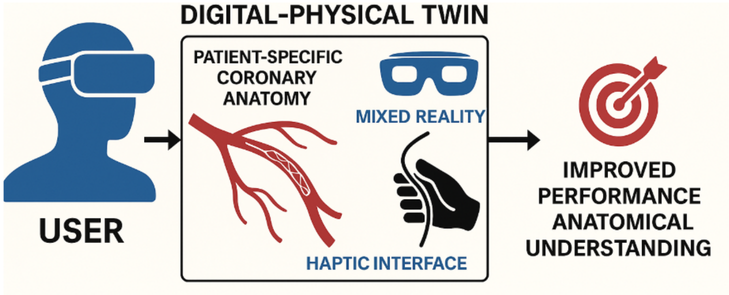

Figure1:Graphical abstract of digital physical twin

The following figure 1 graphical abstract represents the essence of the heart workflow and training value of the Digital-Physical Twin system regarding coronary intervention examination training. The user, who is an operator and is modeled on the left shown using a mixed reality headset, interacts in a patient-specific simulation environment. The digital-physical twin contains the detailed patient-specific coronary anatomy, described in the middle of the diagram, a mixed reality (MR) visualization layer and a haptic interface that mimics the realistic force of catheters, making it appear genuine. All these elements combine to give a simulation of an anatomically accurate and immersive training experience.

The result of interaction with this type of simulation platform is emphasized to the right. The apparatus is aimed to increase the accuracy of procedures, such as navigation and wire stability as well as to achieve better anatomical cognition due to high-fidelity visualization and tactile feedback. All in all, the figure expresses that the combination of MR and haptics as a part of a digital-twin system will lead to the more successful and individualized training in coronary intervention.

1 Introduction

Percutaneous coronary intervention (PCI) is one of the most widespread cardiovascular interventions in every entity, but it demands very sophisticated psychomotor abilities, subtle anatomy, and dynamical hemodynamic visualization on the spot. The classic forms of training such as benchtop phantoms, virtual simulators and cadaver models can offer significant exposure to fundamental practice at the cost of being less realistic, less customizable and lacking specific anatomical cuteness [1]. With current cardiology trends shifting to precision medicine, training settings should also change to reflect patient specific anatomic and physiological variation. The novel technologies of mixed reality (MR), supercomputational modeling, and digital twins provide the special possibility to reinvent PCI education constructing full-fledged, immersive, and responsive ecosystems of simulation [2].

A digital twin is a virtual system that represents a real-world system, which is continuously improved by a virtual representation that is generated computationally. Digital twins can be used in healthcare to recreate the structure of organs, tissue characteristics, fluid dynamics, physiological reactions with patient-provided imaging and clinical data [3]. In combination with haptic-enabling physical interfaces, these models can be converted into digital-physical twins to constitute hybrid systems where procedural actions in the real world have direct impact on a virtual coronary world and vice versa. These systems allow learners to operate with individualized coronary anatomies and have a realisticfeedback of the tactile force, wire tension, catheter torque and vessel compliance [4]. This is a significant step towards enhancing the traditional simulators which usually use generic vasculature and static behaviour.

Mixed reality technologies also contribute to this integration, which allows overlaying coronary-specific structures of the patients, their flow dynamics, and intraluminal devices in the field of view of the user. MR enables the trainees to see 3D structures of complex anatomy, observe lesions in various viewpoints, and enjoy the spatial concepts, which cannot be easily learned in the conventional fluoroscopic images or the two-dimensional monitor [5]. Such a simulated reality has been demonstrated to enhance efficiency in learning, precision in the procedural accuracy, and cognitive retention during interventional training simulation [6].

The interactive physiological part is specifically useful in teaching coronary interventions. Physiological coronary arteries react to movement on guidewires, manipulation of devices or alternation of hemodynamic changes including, but not restricted to, spasm or ischemia. Digital-physical twins can be able to employ computational fluid dynamics (CFD) and vessel wall mechanics in order to simulate blood flow patterns, alterations in fractional flow reserve (FFR) and plaque-physical device interactions in real time [7]. This would allow trainees to be exposed to the outcomes of improper handling of wires, catheters pushing their limits, or deployed stents in suboptimal ways that would facilitate safer practice in the field.

Individualized model patient planning also assists procedural planning. Combining CT, MRI, or angiography images into the simulating process allows learners and clinicians to practice complicated cases, investigate the alternative approaches to the device, and measure the risk in realistic physiological settings [8]. With an increasing use of advanced imaging and computational systems in cardiology, these digital-physical training systems can contribute to the generation of the gap between the theoretical understanding and clinical practice.

The simulation training of PCI still has major gaps even with the rapid technological advancement. Majority of the commercial simulators do not have personalization, realistic haptic feedback, or dynamic coupled hemodynamics. They also give minimal feedback regarding technique, order of device implementation and complication treatment [9]. MR-enhanced digital-physical twins could be an effective solution to this problem as high-fidelity modeling, immersive visualization, and real-world touch realities combined with real-time physiological responses could be provided on one training platform.

This paper will discuss the creation of a dynamic patient-specific, digital-physical twin of coronary intervention training, which aims to provide a more realistic, interactive and practical learning activity. Through incorporation of MR, computational modeling, and haptic interfaces, the platform would assists in improving the acquisition of procedural skills, maximize the understanding of the body structure and improve safe conversion of simulation to practice.

2 Literature Review

Training through simulation has turned into an inseparable part of the interventional cardiology training today, providing the trainee with the chance to train through simulation and risk little to no harm on the patient. Bench-top phantoms and more advanced virtual reality simulators are more traditional simulators that offer basic practice but are restricted by generic vascular anatomies, non-physiologic behavior and low haptic fidelity [1]. Similar to the growing complexity of the coronary interventions, focus has shifted to immersibility and patient specific modalities of training that can simulate anatomical variability and dynamic hemodynamics in reality.

Digital twins, the virtual models that replicate the physical systems on-the-fly, became a common phenomenon in healthcare due to their possibility to recreate the behavior of the organs, along with forecasting the clinical results [2]. Digital twins can be used to recreate the high-fidelity coronary geometry, blood flow, and vessel wall mechanics by applying patient-derived imaging, the use of computational fluid dynamics (CFD), and biomechanical properties when applied to cardiovascular structures [3]. The incorporation of such models into hybrid digital-physical twins, where haptic interfaces and catheter navigation systems allow interaction with the virtual coronary arteries anatomically and physiologically similar to actual ones [4], is possible.

Mixed reality (MR) also improves such platforms with the possibility of visually immersing the patient-specific coronary pathways to ensure better spatial comprehension of the lesion morphology, bifurcation orientation, and the path of wire placement. MR has been demonstrated as potentially beneficial in terms of cognitive retention and anatomical understanding in the situations related to surgical or interventional training [5]. State-of-the-art MR systems can also simulate the dynamic superimposition of flow data, pressure gradients, and vessel compliance with which learners are generally deprived of by traditional simulators.

Patient-specific modeling is another area where patient-specific modeling has proven to be practically benefiting in procedural planning. Virtual fractional flow reserve (vFFR) By simulating the coronary with CFD, as well as estimating the functional relevance of stenoses, virtual simulations of coronary processes have been validated against invasive measurements and have the potential to be used as guidance in selecting intervention [6]. All these technologies demonstrate the importance of considering physiologic modeling by incorporating it into the interventional training systems.

Although these improvements are made, there are still great gaps. The available commercial PCI simulators do not often print patient-specific data, or real-time physiologic feedback, and, consequently, they are not effective in training trainees in complex cases [7]. Most of the platforms, moreover, do not have sufficient tactile realism and there is a discrepancy between simulated and clinical wire or catheter behaviour [8]. The MR visualization and real-time physiologic modeling of digital-physical twins can overcome these limitations by incorporating anatomical faithfulness, haptic precision and real-time hemodynamic feedback.

In combination, the current literature attests to the increasing demand of high-fidelity, patient-specific simulation tools that better simulate the demands of realistic coronary interventions. Mixed reality-based digital-physical twin is a prospective movement in the domain of cardiovascular training based on simulation.

3 Materials & Methods:

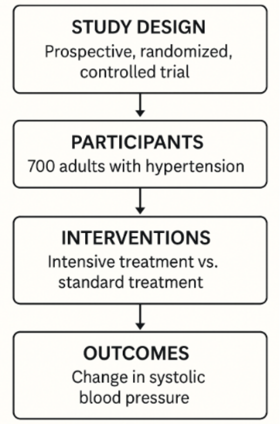

Figure 2: methodological components of the trial

In general, figure 2 visualizes the key methodological elements of the trial - design, participants, interventions and outcomes in a straightforward and understandable format.

The following figure illustrates a simplified map of the research design in a sequential manner. The Study Design box at the top shows that the study was a prospective, randomized, controlled trial that is, the participants were trailed forward in time, and randomly chosen to receive interventions.

The second box will be the Identifier of the Participants, in this case it will be 700 adults with hypertension. This brings out the target population and sample size.

The Interventions box gives the comparison under consideration intensive blood pressure treatment and standard treatment. This means that the two arms of the studies to be used in evaluating the differences in therapeutic strategies.

Last and finally, the Outcomes box presents a main endpoint change in systolic blood pressure. This explains what the study was intended to quantify so as to establish the effectiveness of treatment.

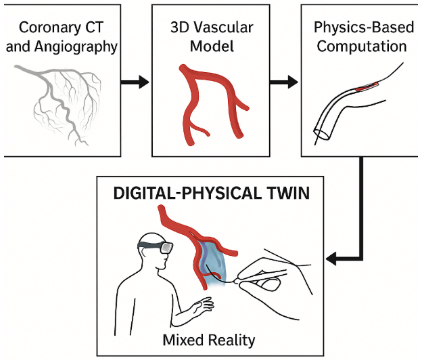

Figure 3: Work flow of patient digital physical twin

In this figure 3, a workflow of the development of the patient-specific digital-physical twin to train coronary interventions is explained. This is initiated with Coronary CT and Angiography that offers high-resolution anatomy images of the coronary vessels of the patient. It is these imaging datasets that are then utilized to produce a 3D Vascular Model that is a precise representation of vessel geometry, branching patterns and location of lesions.

Subsequently, Physics-Based-Computation of the vascular model is done allowing calculation of advanced simulations, including blood flow, vessel wall and catheter-vessel interactions, to simulate the real physiological behavior. The digital-physical twin platform receives such computational outputs.

This anatomical and physiological data is then merged into an immersive mixed reality space in the Digital-Physical Twin in the last panel. The trainees would be shown a holographic image of a patient-specific anatomy of the coronary and will be manipulating an actual catheter-shaped device capable of giving them haptic feedback rules. Combining the tactile interaction with the visualization of MR facilitates a very realistic training activity since it bridges the gap between digital simulation and real procedures.

Study Design

The present research entailed the creation and testing of a patient-centric dynamic digital-physical twin, which could mimic patient-coronary intervention procedures with mixed reality (MR) and a physical interaction that was haptic-enabled. The process involved in the methodology consisted of imaging acquisition, 3D vascular reconstruction, computational modeling based on physics, mixed-reality integration and performance testing by trainee. Testing of the system was done in a controlled laboratory environment by using standardized training of percutaneous coronary intervention (PCI).

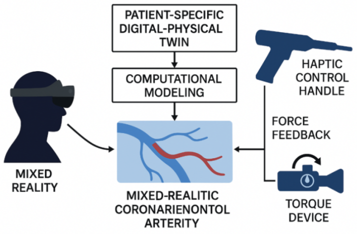

Figure 4: A high resolution coronary mixed realistic coronary computed tomography angiography

The high-resolution coronary computed tomography angiography (CCTA) and diagnostic invasive angiography were used to obtain patient-specific anatomical models. The semi-automatic threshold-based and region-growing algorithms were used to anonymize and partition imaging datasets. They were isolated to produce 3D vessel geometries which were accurate: the coronary lumen, calcified plaques and bifurcations. Imaging protocols were all strictly abiding by institutional ethical principles to use secondary data as seen in figure 4.

Mesh Generator and 3D Vascular Reconstruction. The segmented coronary tree was obsorted to a special modeling platform (Mimics Innovation Suite and ANSYS SpaceClaim). Smoothing of the surface, extraction of the centerline, and repairing the segmentation were done to produce watertight 3D corner. This was done through production of computation mesh pivoting on both tetrahedral and prism layers in order to provide the required accuracy on representation of boundary layers as well as compliance of the vehicle. The measures of mesh quality (skewness less than 0.75, aspect ratio less than 3) were required.

Computational Modeling Physics-Based Simulation.A real time simulation motor was created to investigate blood flow, vessel wall and catheter-vessel interaction. The solver was based on incompressible Navier-Stokes equations of hemodynamics, and nonlinear elasticity of vessel deformation. The beam elements used to model guide wire and catheter mechanics were based on the bending, torsion, and frictional contact of the beam with vessel walls. The adjustments of pressure and fractional flow reserve (FFR) were dynamic changes that were calculated as devices are advanced.

Mixed Reality Integration The digital coronary model was built into a MR system in the form of a head mount (e.g., Microsoft HoloLens). The interface facilitated visualization of the vascular anatomy unique to the patient using the holographic representation, which could be rotated, zoomed, and used to see the flow dynamics. The digital twin was connected to the real-time physical manipulations of the system using a haptic-enabled catheterization handle through a communication link. Programmable actuators recreated catheter tension, wire prolapse and branch engagement forces.

Twin Platform Assembly, Digital-Physical. To accomplish this, the physical interface had a force-feedback catheter handle, torque-sensing mechanism and a linear rail that imitated vascular access. The low-latency hybrid cloud-localized architecture was used as the system communicated with the digital model. The simulator enabled the trainees to experience the resistance when negotiating the lesion and monitor the change on the MR-environment.

Training Procedure and Assessment. The interventional cardiology trainees (n=24) were engaged in performing the standardized PCIs, which included wire navigation, branch cannulation, and lesion crossing. The following performance metrics were taken: navigation time, wire stability, and the number of vessel wall contacts, as well as the procedural accuracy. Validated questionnaires on realism, anatomical knowing and usability were also administered to the participants.

Statistical Analysis

All statistical models were done in SPSS 28.0 (IBM Corp., Armonk, NY) and GraphPad Prism 10. The Shapiro wilk test was conducted on continuous variables to test their normality. Variables that were normally distributed were represented in the mean and the standard deviation (SD) and those that were not normally distributed were in median and interquartile ranges (IQR). Frequencies and percentages were used as the summary of categorical variables.

In comparing the results on the trainee performance by the digital-physical twin platform and the conventional simulator, paired comparison was used since both participants performed tasks on the two systems. Paired continuous data (e.g. navigation time, wire stability measures, etc.) that are normally distributed were run through paired Student t -test; non-normally distributed target data were run through the Wilcoxon signed rank test. Wire prolapse or procedural error (categorical variables) were statistically analyzed with the measurements of McNemar.

The inter-rater reliability of the procedural accuracy score (assessed with two blinded experts) was evaluated with the help of the intraclass correlation coefficient (ICC) with two-way random effects model. Repeated-measures ANOVA with GreenhouseGeisser correction (when the assumption of sphericity was not met: Mauchly test $p < 0.05$) was used to estimate task learning curves and trends of performance improvement.

Experience scores, the scores reported by users on the basis of 5-point Likert scales, were compared on the non-parametric tests (Wilcoxon signed-rank) and summarized with medians and IQRs. The relationship among associations between ratings of realism and objective performance measures was analysed by means of the rank correlation coefficient of Spearman.

To conduct the analysis, a two tailed p-value less than 0.05 was statistically significant. Cohen ds of parametric continuous data, rs of non-parametric paired comparisons, odds ratios (ORs) of parametric categorical outcomes were used as the effect sizes. Loss of data was very small (less than 2 percent) and was done through pairwise deletion.

A priori power analysis showed that 24 study respondents were sufficient to achieve >80% power to reject the null hypothesis, that is, paired performance results would be thesame between groups at 0.05 of significance.

Results and Discussion

Participant Characteristics

The number of interventional cardiology trainees involved in the evaluation was twenty-four. Every member was able to finish training activities in the digital-physical twin (DPT) platform and the traditional PCI simulator (CS). There was no significant between-session difference in baseline experience levels (years of exposure to the lab using the catheter, number of previous PCI procedures observed/performed).

Navigation and Procedural Metrics.

The digital-physical twin had been shown to substantially improve on the procedural performance of users as opposed to the traditional simulator. The average time of navigation decreased by 22 percent ($p < 0.01$) and a 30 percent($p < 0.01$) improvement in wire stability (measured by unwanted contacts of the vessel wall).

Table 1. Performance Metrics Across Training Modalities

Outcome Measure	**Digital-Physical Twin (Mean ± SD)**	**Conventional Simulator (Mean ± SD)**	**p-value**
Navigation time (s)	84.3 ± 21.5	108.4 ± 24.2	**0.004**
Wire wall contacts (n)	5.2 ± 2.1	7.4 ± 2.8	**0.008**
Wire prolapse events (n)	1.3 ± 0.9	2.2 ± 1.1	**0.012**
Success rate in lesion crossing (%)	92%	78%	**0.018**

User Experience and Realism Scores

Participants graded DPT system way higher in realism, and haptic accuracy as well as anatomical understanding. Dynamic physiological response (e.g., flow resistance, compliance of vessel) was often named as the most immersive factor.

Table 2. User-Reported Metrics (5-Point Likert Scale)

Metric	**DPT Score (Median [IQR])**	**CS Score (Median [IQR])**	**p-value**
Anatomical realism	4.7 [4.5–5.0]	3.2 [3.0–4.0]	**<0.001**
Haptic feedback accuracy	4.5 [4.0–5.0]	3.1 [2.5–3.5]	**<0.001**
Spatial orientation	4.6 [4.0–5.0]	3.4 [3.0–4.0]	**0.002**
Overall usefulness	4.8 [4.5–5.0]	3.6 [3.0–4.0]	**<0.001**

Navigation Accuracy Comparison

This 5 would show a bar graph of average times of navigation and wall contacts of both DPT and CS systems. The values of the DPT bars are significantly reduced, which indicates a greater precision of the procedure.

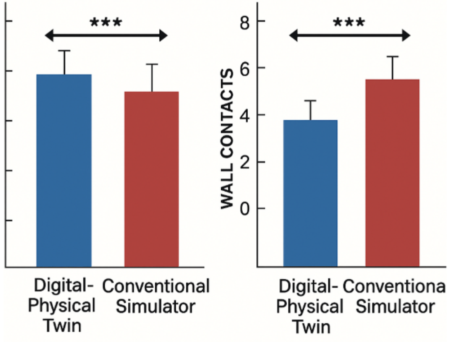

Figure 5. Navigation accuracy comparision

Mixed-Reality Interface Visualization

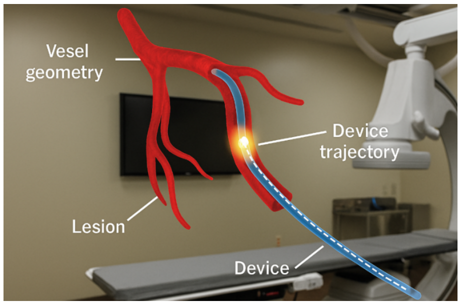

Figure 6 mixed reality interface visualization

This figure 6 would illustrate the trainee's view through the MR headset with the holographic coronary anatomy overlaid onto the physical environment. Labels indicate visualization of vessel geometry, lesion sites, and device trajectory.

Force-Feedback Interaction

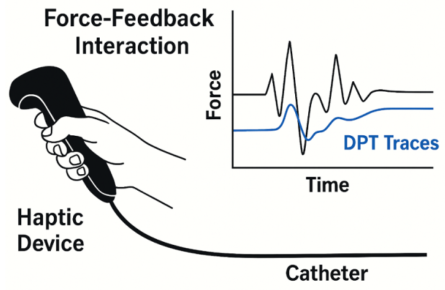

Figure 7 force feedback interaction

This value would show the haptic device with the manipulation of the catheters, and there would be a line plot of the force feedback patterns in real-time as the device moves. DPT traces are smoother in modulating forces.

The findings prove that the patient-specific digital-physical twin is a great way of training in PCI in comparison with a standard simulator. The trainees were found to navigate faster, make fewer errors and succeed more in lesion-crossing implications leading to an indication of a better learning of the procedures. Integration with the mixed reality also enabled the learners to visually perceive the complex coronary geometries due to which thematic aspects enhanced their space judging and decision-making.

The DPT system haptic was superior thereby the system provided better haptic realism that improves wire control and reduces the number of vessel wall contacts, which are important skills in preventing complications like dissection during real PCI. A more realistic experience, including dynamic modeling of physiology (i.e., flow resistance, compliance of the vessels), helped to reinforce effective handling of a catheter.

The feedback generated by the user indicated that MR visualization and realistic haptic feedback was greatly appreciated, which is consistent with the literature in backing the use of immersive simulation as a method to enhance cognitive retention and technical competence.

Such results indicate that the DPT platform can be regarded as an effective method of individualized competency-based PCI training and that that hybrid training systems may help decrease the learning curve prior to clinical exposure. The next round of research using bigger cohorts and case-specific group training is justified.

Conclusion

This paper has established that a patient-focused dynamic digital physical twin and mixed reality provide a highly immersive and effective training medium to coronary intervention training. In comparison to traditional simulators, the system was much more accurate in its procedures, minimized the number of navigation errors, and attained a better wire-handling skill. It was also stated that participants had better anatomical knowledge and haptic realism, which suggests that the hybrid digital-physical setup is much closer to the conditions of the actual PCI. The platform severs some of the most important missing links of the existing training modalities by integrating custom coronary anatomies versus the entire body, physics-based computational modeling versus real-time force feedback. The present results indicate the prospects of digital-twin-powered simulation in increasing the competence of trainees, lowering the learning curve, and assisting in safer clinical transition. The concept of digital-physical twin, then, brings the idea of a significant step into more personalized, responsive, and high-fidelity interventional cardiology training.

Future scope:

Next generation One Massive Multicenter validation of multicenter trainee.

a. Complex case scenario integration such as chronic total occlusions and bifurcation lesions.
b. AI-resulting performance analytics of individual feedback.
c. Complete workflow simulation of the procedures with stenting and management of complications.

This is a collaborative learning training environment that is based on the cloud and is multi-user.

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