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INTERVENTIONAL CARDIOLOGY - THE LATEST DEVELOPMENTS AND THE FUTURE

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ABSTRACT

Introduction: Cardiovascular disease (CVD) remains one of the leading causes of morbidity and mortality worldwide, accounting for a significant proportion of deaths globally. Percutaneous coronary intervention significantly improves the treatment of obstructive coronary artery disease, reducing mortality and restenosis.
This article discusses key innovations in percutaneous coronary interventions (robotics, smart implantable materials, intravascular imaging, the use of machine learning, and transcatheter electrosurgical methods) to identify their advantages, challenges, and future directions.
Materials and methods: A five-year literature review analysed scientific articles on innovations in percutaneous coronary interventions, including smart materials (alloys, shape memory polymers), intravascular ultrasound, optical coherence tomography, interventional robotics, transcatheter electrosurgery, as well as the use of machine learning in diagnostics and coronary artery bifurcation stenting.
Results: Smart materials (alloys, polymers) support advanced implants. Intravascular imaging increases the precision of percutaneous coronary interventions, reducing restenosis, stent thrombosis, the number of serious cardiac events and reinterventions. Interventional robotics ensures precise stent positioning, reducing the risk of operator injury and radiation exposure. Transcatheter surgery allows for precise correction of structural defects. Machine learning optimises clinical decisions and imaging analysis, although its full application is limited by regulatory and legal issues.
Conclusions: Key advances in percutaneous coronary interventions — modern implantable materials, integrated imaging, robotics, and artificial intelligence — ensure precise, safe procedures with fewer complications.

KEYWORDS

Interventional Cardiology, Percutaneous Coronary Intervention, Nitinol, Smart Materials, Intravascular Imaging, Stents

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Introduction

We searched for articles in the PubMed database using keywords such as "interventional cardiology", "Percutaneous coronary intervention", "Nitinol", "Smart materials", "Intravascular imaging", "Stents". The articles found were published between 2019 and 2024.

Interventional cardiology has developed rapidly in recent decades, but cardiovascular disease (CVD) remains the leading cause of death worldwide, accounting for 17.9 million deaths in 2019. The main treatment for CVD in most cases is medication, but invasive procedures improve treatment outcomes in many patients.(1)

Interventional cardiology is an important medical specialty that encompasses the diagnosis and minimally invasive treatment of heart disease. The main procedures performed by interventional cardiologists include: haemodynamics (assessment and treatment of congenital and acquired heart and blood vessel defects), electrophysiology (implantation of cardioverter-defibrillators and pacemakers, as well as diagnosis and treatment of arrhythmias and procedures such as: angiography of peripheral arteries and veins, coronarography, cardiac catheterisation, pacemaker implantation, ablation, percutaneous coronary intervention (PCI). (2) (3) (4)

Percutaneous coronary intervention (PCI) is a revascularisation procedure that helps to unblock narrowed arteries. This method is preferred for most patients with coronary artery disease (CAD), and thanks to advances in stent technology and technology, interventional cardiologists are now able to treat more complex cases, such as chronic total occlusions (CTOs) or complex branch lesions (CBLs). There is growing evidence of the effectiveness of PCI, but further research is needed on methods of anaesthetising patients during procedures (9) (12) (4).

Aim of the study.

The aim of this review is to discuss and evaluate the effectiveness of the latest advances in interventional cardiology and to indicate the direction of development of the entire field.

Research questions.

How can interventions in interventional cardiology be optimised?

What are the latest advances in CBL stenting and CTO treatment?

What are the limitations and advantages of intravascular imaging (IVI)?

How do smart materials, the use of robotics and transcatheter electrosurgery improve interventional cardiology?

What are the main differences between mechanical thrombectomy and PCI?

What role do machine learning and the use of artificial intelligence play in interventional cardiology?

Research hypotheses.

The use of modern technologies in interventional cardiology increases patient safety and improves their health. The interaction of modern imaging methods and precise surgical techniques leads to the optimisation of procedures. The introduction of robotics and machine learning will enable diagnostic and therapeutic advances in interventional cardiology.

Research materials and methods

A literature review was conducted, analysing available data from the sources submitted. Key areas covered by the review included percutaneous coronary interventions (PCI), intravascular imaging (IVI), advanced materials in cardiovascular implants, transcatheter valve interventions (TAVI), transcatheter electrosurgery, robotics and artificial intelligence in interventional cardiology.

Results

1. Key advances in interventional cardiology.

Coronary bifurcation stenting (CBL) accounts for approximately 20% of all PCI procedures in coronary bifurcations. The standard approach is a provisional strategy for the side branch (SB), although the final decision on the specific stenting strategy depends on factors such as the size and function of the side branch and the likelihood of occlusion

Randomised controlled trials (RCTs) and meta-analyses have been conducted to evaluate the efficacy of different stenting techniques.

A 2020 study by Kumsars et al. Smart et al. involving 450 patients found no statistically significant difference in the incidence of cardiac complications (between patients treated with a single temporary stent in the side branch and patients treated with a two-stent strategy) in terms of major adverse cardiac events (MACE) and the incidence of stent thrombosis in the case of drug-eluting stents (DES). The two-stent strategy is generally associated with a higher risk of myocardial infarction and long-term stent thrombosis. (10).

The use of the DK Crush technique in patients has been shown to result in lower rates of MACE, TVR and stent thrombosis compared to other techniques, especially in patients with complex lesions and lesions in the main coronary artery.

The Crush and Culotte techniques were compared in terms of clinical outcomes. The Culotte technique may offer better results in reducing stent restenosis. Advanced balloon angioplasty techniques, such as the "Balloon Sent Kissing Technique" (BSKT), provide significantly better patient outcomes compared to the standard Jailed-wire Technique (JWT) in terms of side branch occlusion, target lesion revascularisation (TLR), and MACE. However, the modified BSKT technique (m-BSKT), which includes an additional optimisation step, requires further study to evaluate its usefulness.(10)

1.1 Intravascular imaging (IVI)

PCI optimisation includes intravascular imaging (IVI), intravascular ultrasound (IVUS) and optical coherence tomography (OCT).

Numerous meta-analyses have shown a reduction in the incidence of MACE after IVUS-guided PCI compared to angiography-guided PCI.

IVUS and OCT have been shown to detect calcifications to a greater extent than angiography, thus enabling the prediction of incomplete stent expansion (the main factor contributing to stent thrombosis and restenosis). IVI is mainly used to assess the severity of lesions and as an aid in selecting the length and diameter of the stent; it also supports the process of optimising stent expansion.

The ULTIMATE study (Intravascular Ultrasound Guided Drug Eluting Stents Implantation in 'All-Comers' Coronary Lesions) showed that with IVUS-guided PCI, vascular failures such as cardiac death, myocardial infarction or vascular reintervention occur less frequently than with angiography-guided PCI. (22)

The effectiveness of OCT, in turn, is no less than that of IVUS in areas such as minimum stent area after PCI and rare procedure-related MACE. OCT is particularly useful for imaging stent strings and detecting their misalignment. (22)

With significantly better image resolution than angiography, IVI helps to make more accurate measurements of the vessel lumen and more accurate imaging of the plaque shape. IVI detects calcifications twice as often, which is crucial for intervention planning.

IVI is most effective for complex lesions, such as lesions (LMCA) in the main coronary artery, chronic total occlusion (CTO) or lesions of significant length. IVI helps to assess the degree of calcification, which is important in the removal of atherosclerotic plaque.

Despite numerous evidence of the beneficial effects of IVI, the frequency of use of this procedure is still insufficient due to high costs and length of procedures, as well as an insufficient number of trained operators.

Studies have shown that performing PCI with IVUS or OCT leads to better stent expansion (larger stent sizes, minimal stent areas), as well as a reduction in the number of geographical errors and more effective treatment of edge dissections, which directly reduces the incidence of MACE (especially adverse cardiac events).

Incomplete stent expansion is often a precursor to stent thrombosis or restenosis, so the use of IVI helps to avoid these complications.

Diagnostic techniques for assessing calcification based on OCT and IVUS help predict incomplete stent expansion and decide on the need for plaque modification. Studies: ULTIMATE, OCTOBER and RENOVATE-COMPLEX PCI studies have shown that performing PCI using IVI significantly reduces the incidence of adverse events such as acute stent mismatch – although its occurrence is quite common and usually resolves, it is not associated with the occurrence of other adverse events. (23)

1.2 Robotics in PCI (R-PCI)

The use of robotics in percutaneous coronary interventions is a very promising procedure, enabling the operator to perform procedures remotely. As a result, the operator is not exposed to ionising radiation, and R-PCI also improves the ergonomics of procedures. The PRECISE study demonstrated the high level of efficacy and safety of R-PCI, with as many as 98.8% of procedures not requiring manual performance.

The most important advantages of R-PCI include: protection of the operator from ionising radiation, less orthopaedic trauma for interventional cardiologists, and greater precision of procedures in aspects such as lesion length measurement and stent selection, which saves stents and increases the accuracy of their implantation. (4,6,7)

The use of robotically assisted percutaneous coronary intervention (R-PCI) is a rapidly developing branch of PCI, with a similar level of safety and effectiveness as manual (M-PCI). The CorPath 200 and CorPath GRX systems demonstrate high technical and clinical efficacy. The most important advantage of R-PCI is the reduction of the operator's exposure to radiation during the procedure. In addition, the ability to control the catheter via a console significantly increases the precision of movements and potentially reduces the number of geographical errors when inserting the stent. The disadvantage of R-PCI is that it can only be used in uncomplicated cases; previous systems were not effective in cases of chronic total occlusion (CTO) or in cases of changes in bifurcations and in the main left coronary artery. However, newer versions offer hope: CorPath GRX, which are being tested in more complex interventions, including STEMI (4).

PRECISE is the first large, multicentre study evaluating R-PCI. The study confirmed a 98.8% technical success rate for this method, but at the beginning of the implementation of the R-PCI system, its application was limited in the treatment of lesions such as chronic total occlusions (CTOs), lesions in arterial branches, lesions requiring a double-stent strategy, lesions with significant shortening or calcification, or lesions in the left main coronary artery.

Despite these limitations, in the future, R-PCI will be integrated with intravascular imaging systems (IVUS, OCT) and artificial intelligence, and it will also be possible to perform procedures remotely.

1.3. Smart materials and stents.

Shape Memory Alloys (SMAs) and Shape Memory Polymers (SMPs)

Nitinol is a shape memory alloy widely used in the manufacture of self-expanding stents. When inserted into the catheter, the Nitinol stent is compressed, but once placed in the vessel where it can expand, the stent returns to its original shape, although it cannot expand completely because its diameter is larger than the artery in which it is to operate. As a result, the stent does not move and remains exactly where it was expanded. Stress changes caused by heart contractions and those caused by musculoskeletal movements also affect the fatigue life of medical implants. Studies have shown that Nitinol performs best under higher stresses and constant pressure and deformation, thanks to the formation of stable martensite during deformation with high fatigue life.

Shape memory polymers (SMPs) can recover their shape over a wide range of temperatures, allowing them to be tailored to recover their shape at body temperature, which is a clear advantage when used in medicine. However, such a wide range of shape recovery temperatures can also be a disadvantage, causing premature recovery of the original shape or slow recovery of the original shape.

Sterilisation of temperature-responsive SMPs is only possible using chemicals (ethyl oxide), as the high temperature range precludes thermal sterilisation in an autoclave (because their temperature programming could be erased).

1.4 Comparison of Self-Expanding Stents and Balloon-Expandable Stents.

Self-expanding stents have an advantage over traditional balloon-expandable stents in that their diameter increases gradually over several days to weeks after implantation, which significantly reduces the risk of restenosis occurring in 30-40% of patients after balloon-expandable stent implantation. Another advantage of self-expanding stents is the reduced risk of calcification ring rupture (in areas with severe calcification), compared to the increased risk of rupture with balloon-expandable stents, where the external force exerted on the ring is applied suddenly and has greater potential, unlike stents made of shape memory materials.

1.4.1 Transcatheter valves

Transcatheter valve replacement (TAVR) was introduced relatively recently and allows for the minimally invasive implantation of heart valves without the need for sternotomy or cardiopulmonary bypass, using endovascular catheters.

Catheter-delivered valves can be made from both Shape Memory Alloys (SMAs) and Shape Memory Polymers (SMPs).

Thanks to the shape memory effect of SMA, the valve can adapt to the shape of the vessel, calcifications or other asymmetries in the ring, and allows for better stabilisation of the valve in the vessel, but it also carries the risk of valve deformation, which can result in valve leakage and valve leaflet movement disorders.

The use of SMP in valve construction allows for the utilisation of its ability to biodegrade the valve stent. it is even possible to design the stent so that it biodegrades in predetermined locations (induced by hydrolysis), which could ensure widening of the outflow tract as children grow; thanks to this solution, it would be possible to avoid subsequent valve replacement procedures as the patient grows.

1.4.2 Transcatheter electrosurgery

Trans-epithelial electrosurgery (TES) is a procedure that uses radiofrequency (RF) energy to vascularise, cut and incise tissue intravascularly, despite the flow of blood. It is a new type of structural procedure in which a conductive guide wire is used to make precise incisions in the tissue. The shaft of the guide wire is electrically insulated, allowing the concentrated charge at the tip of the wire to vaporise tissue using lower power settings. The wire should be extended to an appropriate length beyond the insulated catheter to increase the effectiveness of tissue vaporisation and minimise current dispersion.

TES procedures can be used in treatments such as pulmonary valve stenosis perforation, recanalisation of occluded vessels (e.g. subclavian vein, SVC, CTO of coronary arteries), transseptal punctures, catheter access for large catheters, intentional incision of the mitral valve leaflet to prevent left ventricular obstruction. (12)

The choice of guidewire is crucial: the preferred guidewires for electrosurgery are those designed for chronic total occlusions (CTOs) with an uncoated hydrophobic tip and high tip resistance (guidewires with low tip resistance may bend and cut tissue in an uncontrolled manner). The guidewire must reach a threshold voltage to pierce the tissue; guidewires with low puncture power and high tip load perform best here. To ensure maximum cutting precision, the "Flying V" technique is used to optimise charge density. Anticoagulant therapy is recommended prior to electrification to minimise the risk of clot formation.

TES is a safe and effective method that allows for the vaporisation of specific tissue with minimal damage to surrounding tissue. It can be used for transseptal puncture, transcranial procedures, aortic valve laceration prior to TAVR, as well as for recanalisation of chronic venous occlusions.

1.5 Computed tomography angiography

Computed tomography angiography of the coronary arteries (CCTA), which was previously used exclusively for diagnosis, has now become a tool to aid planning and navigation in coronary interventions, especially in complex lesions. The advantage of CCTA is the ability to accurately measure the dimensions of the observed lesions, as well as to visualise the course of the coronary arteries without distortion caused by image overlap, which has been a common problem in invasive angiography to date. (10,13,14)

CCTA has made it possible to accurately measure bifurcation lesions and assess the spatial distribution of atherosclerotic plaques in relation to the bifurcation of vessels, which allows for complete plaque coverage and minimises the risk of revascularisation. "Identification of patients with lesions in the left main coronary artery (LMCA) prior to invasive procedures" may facilitate decisions regarding the method of revascularisation and the potential need for haemodynamic support. (10)

This method is more sensitive in recognising and describing the shape of calcifications than angiography (which is an invasive method). In addition, CCTA allows for precise measurement and assessment of bifurcation dimensions and spatial distribution of atherosclerotic plaque, as well as prediction of fluoroscopic angles during imaging of lesions, all of which help to streamline the procedure, minimise the operator's exposure to radiation and contrast, and improve clinical outcomes.

1.6 Machine learning (ML) and artificial intelligence (AI)

ML and AI in interventional cardiology offer significant benefits, although their implementation also requires addressing emerging challenges, and their role in interventional cardiology is growing.

Various types of ML algorithms such as unsupervised learning (K-means clustering for ECG analysis, principal component analysis – PCA for dimensionality reduction and prediction), deep neural network models and deep generative models (GANs, VAEs), PCA was used to measure the severity of metabolic syndrome, making it possible to more effectively predict the likelihood of cardiovascular events in ethnically diverse cohorts.

Both technologies can be used to support the diagnosis of cardiovascular diseases based on imaging tests in an objective manner, free from observer-dependent variability, and to predict the outcomes of procedures.

Potential areas where ML and AI can be applied in interventional cardiology include:

1) Diagnostics: diagnosis of coronary artery disease, assessment of fractional flow reserve (FFR) based on CCTA.

2) Risk prediction: MACE, mortality after myocardial infarction, likelihood of rehospitalisation due to heart failure or stent restenosis.

3) Imaging: vessel segmentation in X-ray angiography, noise reduction in computed tomography.

Challenges associated with the implementation of ML and AI in interventional cardiology include data quality, standardisation and control of the algorithms used, as well as ethical and legal issues. (6)

The use of ML can help overcome observer-dependent differences in the interpretation of coronary angiography results. Generative algorithms can help augment data and increase privacy protection by creating synthetic data samples.

ML can be used for: diagnosing coronary artery disease, calculating computed tomography indices, predicting the likelihood of cardiovascular events, and predicting the possibility of stent restenosis.

The results of previous studies on robotically assisted PCI (R-PCI) did not show the possibility of treating complex lesions such as CTO or bifurcation lesions (requiring two stents). However, the use of machine learning may in the future allow for the effective treatment of patients even with such complex lesions.

The challenges associated with implementing ML in interventional cardiology relate to legal regulations for medical software using AI and ML, and finding universal and repeatable ways of presenting the results of predictive models.

In summary, the use of ML in interventional cardiology can significantly improve diagnostic accuracy and prognosis, provided that legal regulations are adapted and uniform methods for interpreting results are developed.

1.7 The main areas that can ensure high-quality care in interventional cardiology are coordinated care and the creation of centres of excellence. Centres of excellence (CoE) would facilitate the management of patients with complex aetiologies, support interaction between physicians, and facilitate patient management.

The study was conducted in Dubai, but the conclusions may be applicable worldwide, as the staff and patients analysed came from all over the world. The article also noted a higher risk of mortality and the use of higher doses of radiation when PCI procedures for ST-elevation myocardial infarction (STEMI) were performed outside standard working hours. [1]

1.8 Comparison of primary percutaneous coronary intervention (PPCI) and mechanical thrombectomy (MT) and assessment of interventional cardiologists' ability to perform MT procedures.

Due to the growing number of patients, there is a need for an increase in the number of neurointerventionalists. Interventional cardiologists performing PPCI could perform MT procedures after appropriate training.

PPCI procedures used in acute myocardial infarction (STEMI) and MT in acute ischaemic stroke with large vessel occlusion (LVO AIS), although at first glance they may seem similar (these are standard revascularisation procedures aimed at rapid restoration of blood flow, and the fastest possible intervention time is very important for the success of both procedures), they differ in key aspects that interventional cardiologists need to be aware of in order to perform MT procedures.

1) The need for rapid action stems from the sensitivity of brain tissue to ischaemia. According to a 2015 study, good results (approximately 90% brain tissue regeneration) are only possible within 2 hours of the onset of the first symptoms.

2) Anatomical differences and the need to preserve all small branches of cerebral vessels. Unlike coronary vessels, the loss of even small branches of cerebral vessels can lead to severe disability, so it is necessary to preserve all vessels during cerebral interventions.

3) Different tests are used to decide whether intervention is necessary: ECG for STEMI and CT angiography for LVO AIS. Cardiologists should also familiarise themselves with the NIHSS scale used to assess the severity of a patient's stroke.

4) There are key differences in the use of anticoagulants between AIS and STEMI.

5) Training is essential for interventional cardiologists wishing to start working in the field of MT in the following areas: cerebral vascular anatomy, clinical symptoms of stroke, operation of specialised equipment and the ability to work as part of a multidisciplinary team.

1.9 The use of nanomaterials in treatment and regeneration.

Given that cardiovascular diseases are the leading cause of mortality and morbidity worldwide, innovative solutions are being sought in the field of cardiology, many of which are based on the use of nanotechnology, i.e. particles measuring 1-100 nm. Nanoparticles (NPs) have unique mechanical, electrical and magnetic properties.

The use of nanoparticles (NPs) in cardiology can be effective in four main areas: precise drug delivery, diagnostics, imaging, and tissue engineering and regeneration.

1.9.1 Precise drug delivery

Nanogels and nanopatches are modern methods of treating heart muscle damage after a heart attack. Nanogels (e.g. hyaluronic acid-based hydrogels) can release drugs in a controlled manner in a specific ischaemic area of the heart muscle, and can also capture drugs in a given location.

Nanopatches, in turn, can thicken the walls of the heart muscle by supporting the long-term survival of implanted stem cells.

1.9.2 Diagnostics

The use of nanotechnology significantly increases both the sensitivity and specificity of diagnostic methods. Thanks to the use of nanomaterials, it is possible to detect biomarkers and improve the quality of imaging tests.

An example of the application of nanotechnology in diagnostics are cardiac immunological tests (CIA), based on antigen-antibody reactions, which enable rapid and relatively inexpensive measurement of clinical indicators (biomarkers). Measurements include troponin I*,* myoglobin and C-reactive protein. Research is ongoing on the detection of miRNA molecules, whose increase or decrease in concentration may indicate disease states, e.g. (miRNA-208 is present in over 90% of patients with acute myocardial infarction (AMI) but is not detected in healthy patients; AMI is also associated with an increase in miR-133 and miR-499 concentrations, while a decrease in miR-103 concentration has been observed in patients with heart failure.

1.9.3 Imaging.

Another area of application for nanomaterials in cardiology is the use of exosomal vesicles as biomarkers. The ability of extracellular vesicles released by cells to transport proteins and nucleic acids may facilitate the diagnosis of heart failure and heart attacks. In diagnostic imaging methods, including Magnetic Resonance Imaging (MRI), computed tomography (CT), positron emission tomography (PET), and photoacoustic tomography (PAT), exosomes absorbing nanoparticles act as contrast agents, improving the visibility of individual structures of the heart and blood vessels.

1.9.4 Tissue engineering (treatment and regeneration)

The use of nanoparticles allows targeting atherosclerotic plaques or specific activated fibroblasts, thus minimizing the side effects of therapy.

Biomimetic nanoparticles coated with cell membranes, e.g., red blood cells, can effectively avoid the immune system response and thus remain in the bloodstream for a longer time, combining therapeutic function and imaging support.

Nanofibers have a structure similar to the extracellular matrix (ECM), which aids in tissue regeneration. According to research, cardiac patches made of PLGA nanofibers help cardiomyocyte growth and support the calcium cycle. Scaffolds that support angiogenesis and myocardial cell maturation are created using polycaprolactone and sericin silk nanofibers.

The use of nanotechnology in cardiology has great potential, but in order for it to be fully implemented, problems such as toxicity increasing proportionally to size, problems with long-term use, and maintaining batch repeatability with difficulties in scaling pharmaceutical production. It is also necessary to ensure safety and efficacy and simplify the production processes of nanoparticles.

Artificial intelligence can be helpful in the implementation of nanotechnology, as it enables the analysis of large amounts of data (Big Data) and allows for the creation of personalized treatment plans that take into account individual patient data (age, ethnicity, comorbidities). Cooperation between scientific institutions and the pharmaceutical industry will also be essential.

Discussion

The continuous improvement and development of techniques and technologies in the field of interventional cardiology testify to the dynamic development of this field.

Temporary stenting of side branches remains the standard treatment for LBC, but for large lesions in side branches, more advanced and complex procedures such as BST or DES are becoming increasingly promising.

Intravascular imaging methods (IVUS and OCT) serve to improve the results of PCI treatment, especially in advanced and complex cases, despite barriers to their widespread use.

The use of robotics in interventional cardiology has increased operator safety and procedural precision, and smart materials and stents (including bioresorbable stents) can adapt to the growing needs of patients, which is particularly important in paediatric patients.

Transcatheter electrosurgery allows for high-precision incisions and tissue vaporisation within blood vessels.

The use of CCTA for planning and performing procedures and the growing role of ML/AI in diagnostics and predicting treatment outcomes are the future of data-driven and precision-based coronary interventions.

In the future, it is possible that interventional cardiologists will be involved in performing mechanical thrombectomy procedures, as both types of procedures have many aspects in common. but it is essential to train interventional cardiologists in: cerebral vascular anatomy, the use of specialised equipment, the clinical symptoms of stroke, and the skills required to work as part of a multidisciplinary stroke team.

Conclusions

Interventional cardiology is a rapidly developing field in which the use of modern technologies and techniques can improve patient outcomes (1-4). Optimising interventional cardiology services requires a holistic approach, including the use of the latest medical technologies, research, staff training, and interdisciplinary collaboration. (5-8) Further research, especially randomised controlled trials, is a prerequisite for the full implementation of innovations in everyday clinical practice (10-12), and expanding the competence of interventional cardiologists in performing procedures such as (13-15) mechanical thrombectomy is possible after completing specialised training (16-20)(21).

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