OPEN ACCESS
ISSN: 3106-4264

Review Article

DOI: 10.55735/bhda6w26

HJBHS

The Healer Journal of Biomedical and Health Sciences

Journal homepage: www.healerjournal.com

Contemporary Perspectives on Coronary Artery Bypass Grafting: Integrating Precision Medicine, Minimally Invasive Techniques, and Long-Term Outcomes

Naosheen Ashiq[1], Farhan Mukhtar[1*], Shahzaib Hassan[1], Iram Hassan[1], Asia Altaf[1]

[1]University College of Nursing, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

Submitted: 23-07-2025
Revised: 24-08-2025
Accepted: 22-10-2025
Published: 01-12-2025

CORRESPONDING AUTHOR

Farhan Mukhtar
University College of Nursing, The Islamia University of Bahawalpur, Bahawalpur, Punjab, Pakistan
farhan.mukhtar@iub.edu.pk

ABSTRACT

Coronary artery bypass grafting is the gold standard for surgical revascularization of complex coronary artery disease. Three decades have passed since CABG was developed, and with it, there have been developments in choices of conduit, cardiopulmonary technology, and perioperative management that have significantly enhanced survival and quality of life. However, advanced technology and precision medicine are now transforming the CABG model from mass-produced surgical practice to more individualized, data-driven care. Post-genomic biomarker risk profiling, artificial intelligence-driven risk prediction, and machine learning-powered imaging have made patient-specific risk stratification and conduit optimization possible. This has been followed by minimally invasive direct CABG, robotically assisted CABG, and hybrid revascularization methods, expanding the therapeutic armamentarium with less injury and quicker rehabilitation, but with preserved long-term graft patency. They have performed equally or better in carefully chosen populations but have been encumbered by their wider application by procedure complexity, cost, and the unavailability of large-scale randomized trials with precision-guided methods. There is increasing evidence that the incorporation of multi-arterial grafting, AI-driven perioperative planning, and personalized pharmacogenomic therapy will continue to improve graft survival and long-term cardiovascular outcomes. However, there are significant knowledge gaps in how best to incorporate precision technologies, patient selection for minimally invasive operations, and the ethics of AI-driven decision-making. Coronary artery disease multivessel and complex revascularization by CABG are more or less the same, signifying long-term survival and durability. Sixty years since its beginning, **Conclusion:** CABG is still developing as a biological science of genomics, engineering, data science, and surgical innovation. In the modern era, the development of the specialty also marks the demise and death of one-size-fits-all medicine for a precision-based, patient-specific specialty, in which every aspect, from conduit selection to postoperative care, is tailored to the patient's biological and clinical profile.

Keywords: Artificial intelligence, Coronary artery bypass grafting, Genomics and pharmacogenomics, Hybrid coronary revascularization, Minimally invasive surgery, Robotic-assisted CABG

How to cite the article: Ashiq N, Mukhtar F, Hassan S, Hassan I, Altaf A. Contemporary Perspectives on Coronary Artery Bypass Grafting: Integrating Precision Medicine, Minimally Invasive Techniques, and Long-Term Outcomes. The Healer Journal of Biomedical and Health Sciences. 2025; 1(2): 28-40.

INTRODUCTION

Since its early successful application in the 1960s, coronary artery bypass grafting (CABG) has remained the gold-standard procedure for the treatment of large and multivessel coronary artery disease (CAD). Favaloro et al. set the stage for modern-day myocardial revascularization with their landmark work, demonstrating that surgical placement of conduits would reestablish myocardial perfusion and prolong survival in patients with obstructive CAD.[1] With the continued evolution of the choice of conduits, cardiopulmonary bypass, and perioperative management, over the next few decades, CABG was a well-standardized and robust procedure with a 10-year survival of more than 80% in good-segmented candidates. Even with widespread adoption of PCI and drug-eluting stents, CABG remains superior in patients with left main, triple-vessel, and diabetic CAD.[2]

Meta-analyses and long-term registries have consistently demonstrated that CABG provides better revascularization, a lower rate of repeat intervention, and better protection against late myocardial infarction. Traditional CABG is, however, invasive in nature and entails sternotomy and cardiopulmonary bypass, both of which are postoperative causes of morbidity and recovery prolongation.[3] These limitations, combined with multimorbid and aging patients, have favored a paradigm shift toward minimally invasive and more tailored surgical revascularization techniques. Precision and innovation, combined with the shifting panorama, are remodulating CABG frontiers.[4]

Genomic evolution, biomarker science, and artificial intelligence now enable personal risk stratification and personal conduit choice, and technological innovation with robotic and minimally invasive techniques delivers equal graft patency at lower surgical trauma. Hybrid revascularization, capitalizing on the long-term durability of surgery-based grafts and the efficacy of PCI, is an emerging discipline in patient-specific coronary therapy.[5] Collectively, these advancements equate to the transformation of CABG from a standard procedure to a precision-based, technology-facilitated operation. This review aims to provide an overview of advanced CABG developments in paradigms of precision medicine and minimally invasive surgery.[6] Specifically, we are discussing recent developments in patient stratification, robotic and hybrid techniques, artificial intelligence, directed outcome prediction, and long-term graft function. Based on integration of surgical, genomic, and computational evidence, this review aims to define the state of the art as it stands today, to recognize existing gaps in evidence, and to present future directions in attaining precision-guided coronary revascularization.

1. Precision Medicine in CABG

This section constructs a synthesis of existing evidence and implementable concepts for applying precision medicine to coronary artery bypass grafting (CABG).[7] It discusses (1) risk stratification at the patient level with genomics, biomarkers, and AI; (2) customized conduit selection; (3) pharmacogenomics and tailored postoperative care; and (4) how big data/EHR-powered predictive analytics support perioperative planning and learning health-system feedback.

1.1 Patient-Specific Risk Stratification

Modern risk stratification for CABG moves beyond demographic/clinical scoring (STS, EuroSCORE II) to address molecular biomarkers (troponin phenotypes, high-sensitivity CRP, circulating miRNAs), and genetic risk inherited by polygenic risk scores (PRS). CAD-PRS can identify individuals with lifetime genetic risk who may have differential benefit from aggressive revascularization or specific conduit strategies.[8] Several cohort studies and reviews (2022-2025) show incremental predictive value when PRS or biomarker panels are added to clinical risk models for major adverse cardiovascular events, but direct validation of PRS per se for post-CABG outcome is scarce and remains exploratory.[9]

Artificial intelligence (AI)/machine learning (ML) models that were trained from high-dimensional preoperative data (laboratory, imaging features, and unstructured electronic health record text) proved better than historical scores in short-term mortality and major complication rates in registry and multicenter analyses. For example, recent ML models were better discriminative than EuroSCORE II/STS in external validation sets for 30-day mortality.[10] Integration of molecular and genetic data can maximize risk-benefit calculation (e.g., younger individuals with elevated PRS may benefit preferentially from multi-arterial methods), but challenges remain: population transportability of PRS, calibration between ethnic groups, limited prospective validation specific to CABG, and regulatory/ethical concerns for applying genetic data to clinical practice. Preoperative decision streams require prospective trials that incorporate genomic testing.[11]

1.2 Personalized Conduit Selection

The increasing evidence base of randomized and observational data supports greater long-term patency and clinical success with arterial conduits (LIMA ± radial artery, bilateral ITA, or other arterial grafts) over saphenous vein grafts (SVG) in some patients. Large propensity-matched series and meta-analyses (with 10-year follow-ups) demonstrate reduced composite cardiovascular events and improved survival with radial artery (RA) and multi-arterial grafting (MAG) techniques, whereas outcomes from randomized trials (e.g., ART) have been variable for bilateral ITA, highlighting patient-selection considerations.[7] Clinical predictors (age, diabetes, target vessel diameter/quality, competitive native flow) remain important determinants of arterial vs venous graft function.

Incubating data suggest that intimal hyperplasia and SVG failure can be host factor-dependent (inflammation biomarkers, metabolic milieu) and possibly variant-dependent, but robust genomic predictors of patency are absent at this time. Inflammatory signatures underpinning SVG stenosis are found by newer mechanistic and registry studies, opening the potential for biomarker-guided conduit choice in the future. PMC +1 Clinical translation.[12] Anatomical imaging (lesion physiology/target vessel size) would be added to patient life expectancy/comorbidity and biomarker/genetic risk to choose MAG instead of LITA+SVG or hybrid revascularisation. Benefit needs to be determined and trade-offs assessed using pragmatic randomised trials stratified on the risk axes.[13]

1.3 Pharmacogenomics and Postoperative Care

Clopidogrel metabolism and differential antiplatelet effect have been affected by CYP2C19 genotype; genotype-directed P2Y12 inhibitor selection has resulted in enhanced PCI outcomes and is being evaluated in cardiac surgery populations.[14] Early implementations of CYP2C19 clinical decision support within EHRs have been possible and have reported reductions in potential drug-gene interactions. Genotype-directed antiplatelet selection, personalized statin potency (possibly guided by genetic predictors of LDL-response to statin therapy), and biomarker-directed anti-inflammatory therapy to prevent graft occlusion constitute precision postoperative management.

Evidence supporting personalized anti-inflammatory or lipid strategies per se to enhance CABG graft patency is encouraging but in its infancy; interventional trials that integrate pharmacogenomic decision support into discharge protocols are ongoing or forthcoming.[15] Perioperative genotyping on a routine basis requires fast turnaround time, decision support, cost data, and education for clinicians. Ethical issues of genetic data storage and consent must be addressed in trial protocols and implementation plans.[16]

1.4 Big Data and Predictive Analytics

Multicenter registries, large administrative databases, and integrated electronic health records (EHRs) enable the development of ensemble ML models (XGBoost, random forests, neural networks) that incorporate intraoperative telemetry, imaging, laboratory, and free-text notes to predict perioperative mortality, stroke, acute kidney injury, and long-term outcomes.[17] New large-scale trials (n>200,000) and institutional ML deployments have shown improved discrimination and clinical utility compared to traditional risk models. Examples are ML models enhancing mortality prediction after CABG+AVR and AI systems for 30-day mortality performing better than EuroSCORE II in single-institution validation; ML output has been used by some institutions in "heart-team" meetings to inform conduit strategy and hybrid planning. There are early suggestions of potential reduction in complication rates with ML-alerts linked with care pathways, but robust randomized implementation trials do not exist.[18]

Big-data approaches enable a learning health system for CABG, optimally fine-tuning risk models and identifying subgroups benefiting from targeted interventions on an ongoing basis. Explainability of the model, bias in the dataset, prospective validation requirements, and data stewardship, however, remain core challenges. Transparency in external validation, clinical utility (decision impact studies), and the infrastructure to accommodate on-time integration of genomic and imaging data with EHR-based models are top priorities.[19,20]

2. Advances in Minimally Invasive and Robotic CABG

This section incorporates new evidence (2020-2025) and provides a critical, hypothesis-driven overview of minimally invasive direct CABG (MIDCAB), entirely endoscopic/robotic CABG (TECAB/robotic-assisted CABG), and hybrid coronary revascularization (HCR).

2.1 Evolution of Techniques

Minimally invasive coronary artery bypass surgery now ranges from left anterior mini-thoracotomy MIDCAB (largely LIMA → LAD) to robotically supported MIDCAB and totally endoscopic CABG (TECAB) that enable multi-vessel arterial grafting without median sternotomy.[21] Hybrid coronary revascularization (HCR) integrates surgical LIMA grafting (often by way of a minimally invasive approach) with percutaneous coronary intervention (PCI) to non-LAD territories, to obtain the durability of LIMA and the versatility of PCI. Recent systematic reviews indicate that robot-assisted techniques have acceptable perioperative safety and mid-to-long-term graft patency with satisfactory results in experienced centers.[22]

Aggregate data from meta-analyses and comparative series suggest that, in well-selected patients, minimally invasive and robot-assisted approaches can yield similar short-term mortality and MACCE as conventional on-pump CABG, with reductions in blood loss, wound infection, and hospital stay, and improved functional recovery, but randomized evidence remains limited and cohort heterogeneity (case selection, operator experience, adjunctive PCI volume) prevents direct inference.[23] Large registry trials and novel multi-center meta-analysis prove non-inferior mid-term survival and patency but identify selection bias toward lower-risk patients for minimally invasive programmers.[24] The current evidence base supports minimally invasive/robotic methods as adjuncts rather than wholesale replacements for traditional CABG. To determine superiority (or genuine equipoise), pragmatic randomized trials must be conducted that (a) prospectively define anatomic/physiologic inclusion criteria, (b) stratify by program/operating-surgeon experience, and (c) include long-term graft-patency and patient-reported outcomes as co-primary endpoints.

2.2 Technological Enablers

The 3-D high-fidelity endoscopic vision and robotic motion enabled intrathoracic LIMA harvest with accuracy, hand-sewn or robotic creation of anastomoses in confined spaces. These consoles reduce tremor and accelerate scaled motion, facilitating technical reproducibility for fine anastomoses in skilled surgeons.[25] Recent publications illustrate improved operative accuracy and the feasibility of multi-arterial robotic grafting in the referral centers. Anastomotic devices and distal connectors are created to reduce ischemic and operative time and normalize the distal anastomosis to accommodate minimally invasive procedures. Meta-analytic syntheses indicate connector patency of at least non-inferiority compared with hand-sewn anastomoses during early and mid-term follow-up, though device performance is inconsistent and arterial applications remain technically challenging. Connector technology may be especially justified in TECAB workflows to reduce operative time and promote greater use.[26]

The combination of preoperative CT/angiography with intraoperative imaging (near-infrared fluorescence, intraoperative angiography) and emerging AR overlays can improve target selection and conduit placement. Early single-centre experience shows improved graft alignment and fewer technical revision rates, but hard outcome data and cost–benefit analysis are not available.[27] Comparative studies of connector types, normalized measures of anastomotic quality (flow, geometry), and multicenter device registries; as important are efforts to integrate imaging, robotics, and adjunctive devices into reproducible standardized pipelines transferrable to training.

2.3 Clinical Outcomes and Limitations

Systematic reviews (2023-2024) show that robotic/MIDCAB methods share short-term stroke and mortality with traditional CABG in well-selected cohorts, with advantages in wound complications and length of stay; mid-term graft patency is encouraging in specialist units, but large-scale, long-term patency data are lacking outside high-volume programs. HCR series and meta-analyses are similar mid-term MACCE and revascularization rates for conventional CABG in well-selected patients, but once more have heterogeneity and selection bias modifying conclusions. The learning curve of robotic CABG is variable and steep; performance improves substantially with experience to favor centralization and formal proctorship schemes.

Recent scoping reviews quantify large improvements in safety and efficiency as centers ascend the learning curve.[28]

Prohibitive capital expenditure, ongoing maintenance, and capacity for staff training limit dissemination to high-resource centers; cost-benefit analysis between minimally invasive/robotic vs. traditional CABG (accounting for recovery and length of stay) is not performed.[1] Anatomic morphologies (extensive disease, small target vessels, heavy calcification) cannot be addressed with minimally invasive methods in every instance; decision-support algorithms integrating coronary anatomy, comorbidity, and frailty must be constructed.[28] Few well-powered randomized controlled trials for long-term clinical outcomes; restricted generalizability from single-centre series; device heterogeneity (connectors) renders meta-analysis difficult.

Minimally invasive and robotic CABG is a clinically important development in surgical revascularization, with patient-centric gains in recovery and wound morbidity at the expense of preserving graft durability in well-selected populations. But to transform practice at scale, the field must generate high-quality comparative effectiveness trials, standardized training/certification pathways, and interoperable technical standards (for devices and imaging), all ideally nested in registries that monitor long-term patency, functional recovery, and health-economic outcomes.[29]

3. Integrating Precision Medicine and Minimally Invasive CABG

This section synthesizes recent evidence (2020-2025) and offers a hypothesis-driven description of how hybrid strategies, AI, and cutting-edge imaging can be integrated into precision CABG pathways. It critically assesses planning and diagnostic tools, gives clinical data for hybrid treatment, and delineates real-world barriers (training, economic, and ethical) that must be addressed before safe, equitable deployment (Figure 1).[21]

3.1 Preoperative planning with AI and imaging

Both anatomic and physiologic definition of coronary lesions is provided by coronary computed tomography angiography (CCTA) with the addition of CT-based computational fractional flow reserve (FFR-CT) in a non-invasive way, and have been demonstrated to change revascularization plans in a substantial percentage of patients when used for planning PCI. Software that blends CCTA/FFR-CT with three-dimensional cardiac models can provide a virtual simulation of graft routing and post-revascularization flow, potentially to direct conduit choice and anastomotic targets. [30]. However, the direct benefit of FFR-CT–guided planning on CABG is not yet established: registry experience shows incremental value of lesion-level invasive physiologic measurements (FFR/iFR) for surgical decision-making to be modest, and experimental planner tools have demonstrated potential for virtual stenting and post-PCI physiology prediction. Integration of FFR-CT into surgical planning processes is an emerging but promising approach.[31]

ML algorithms that combine imaging (CCTA metrics, features of plaque), clinical variables (comorbidities, frailty, life expectancy), and biomarkers can be trained to recommend conduit strategies (e.g., single LIMA + SVG vs. multi-arterial grafting) by estimating freedom from MACCE, graft patency, and net benefit over time. Early experience and model derivation have demonstrated improved discrimination for postoperative risk and economics when ML enhancements are added to back-calculated historical risk scores; pilot implementation has also provided patient-specific conduit suggestions within multidisciplinary planning.[32] These algorithms must be externally validated properly, subjected to prospective decision-impact analysis, and uncertainty reported openly before they can be trustworthy for surgeons to use.

To be clinically useful, imaging AI pipelines must (1) standardize image acquisition and segmentation; (2) provide clinically understandable results (e.g., expected 5- and 10-year patency for alternative conduit strategies); (3) integrate seamlessly with heart-team workflows; and (4) be prospectively validated in representative populations of the ethnic and anatomical diversity of typical CABG populations.[33] Hybrid coronary revascularization (HCR), typically LIMA→LAD by surgery with PCI to non-LAD targets, is designed to integrate the long-term patency of LIMA grafts with the minimally invasive benefits of PCI. Survival cohorts and randomized pilots have reported comparable survival and faster recovery rates with HCR versus conventional CABG in specific patients, but higher rates of repeat revascularization or mid-term MACCE in certain meta-analyses.[34]

Long-term registry experience (10 years) describes equal survival but higher needs for future interventions in HCR cohorts, emphasizing the importance of strict patient selection and prolonged follow-up. Evidence supports HCR as an option for judiciously selected patients when implemented as part of a heart-team coordinated program.[34,35] Optimal HCR candidates present a disease pattern well-suited for an excellent LIMA→LAD graft and PCI-treated non-LAD lesions (anatomically advantageously located for durable stenting). Paradigms for heart-team decision making—structured multidisciplinary conferences involving cardiac surgeons, interventional cardiologists, imagers, and anesthesiologists—are central to weighing competing risks (rePET revascularization vs surgical risks), timing (staged vs synchronous procedures), and antiplatelet therapy.[35]

Formalized pathways and shared decision aids improve appropriateness and patient understanding of trade-offs. The questions are: which anatomical/physiologic phenotypes benefit net from HCR, how to sequence procedures optimally, and whether, prospectively, who will be most benefited can be predicted using FFR-CT/AI. Large pragmatic randomized trials and registry studies with standardized endpoints are required.[35]

3.2 Real-world implementation barriers

These technologies (FFR-CT, robot platforms, and AI systems) require capital investment, specialist skills, and regular maintenance. Reduced length of stay and faster recovery can compensate for some of the costs, but extensive cost-effectiveness analyses that include long-term endpoints (repeat revascularization, graft failure) are limited.[33] Local volume, payment models, and good economic modeling should inform health-system choices for optimal CABG pathways. Robotic and minimally invasive CABG have substantial learning curves that have a material effect on outcome; therefore, proctorship, formal training, simulation, and regionalization of complex cases are needed to deliver reproducible safety. Implementation studies show improved metrics with formal training courses and volume consolidation. Clinician training is also needed for AI-based decision support integration to interpret model output and step in where the algorithm and clinical experience differ in edge cases.[36]

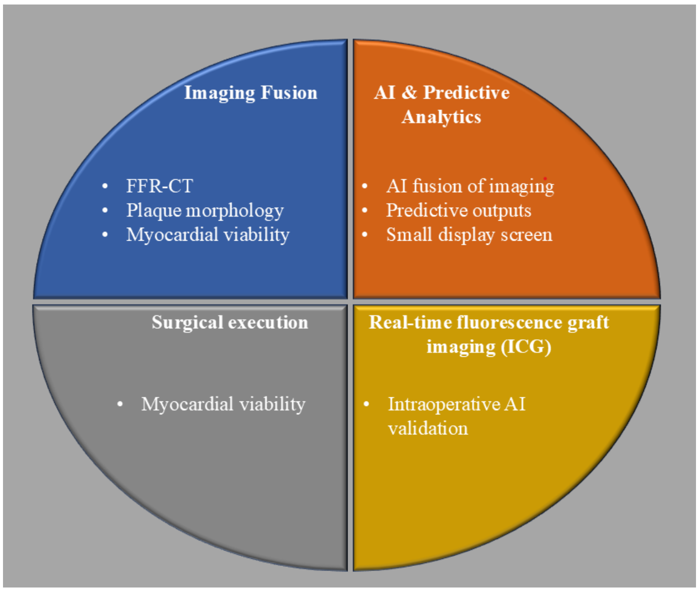
AI-related technology issues involve explainability, bias (especially where models are trained using non-representative datasets), decision accountability, and patient confidentiality when genetic and imaging information are combined. Ethical advice recommends transparency in model performance, prospective external validation, clinician oversight (utilizing AI as a decision support rather than a replacement), and informed consent policies when genetic or predictive findings inform surgical planning. Regulatory pathways and medico-legal certainty still change and must track clinical use.[33]

4. Long-term outcomes in the precision and minimally invasive Era

Long-term durability of CABG continues to define its superiority over percutaneous revascularization for complex CAD. But as surgery advances into the precision medicine and minimally invasive era, long-term outcomes need to be reassessed on a multilayered platform ranging from survival, graft patency, and patient-reported recovery to equity across sex, ethnic, and genetic subpopulations. [37]. Modern registry information and randomized trial extensions now enable a more nuanced understanding of the impact of conduit type, surgical approach, and biologic variability on outcomes after the first decade postoperatively.

Long-term follow-up of seminal trials such as SYNTAXES (2020), ART (2023), and PREVENT IV (2024) confirms that CABG is linked with long-term survival and reduced MACCE rates compared with PCI in patients with multivessel or left main disease. The SYNTAX 10–12-year results gave ongoing survival benefit to CABG, particularly in those with high anatomical complexity, and emphasize the long-term benefit of surgical revascularization.[38] Recent reviews highlight that graft type remains the strongest predictor of long-term patency. The MAG with left internal mammary artery (LIMA) and radial artery (RA) has shown superior 10–15-year patency and survival compared with saphenous vein grafts (SVG). The 10-year outcome of the ART trial indicated no difference in mortality from bilateral vs single internal thoracic artery grafting, but registry-based meta-analyses that include MAG strategies

Figure1: Future map for precision and minimally invasive CABG



show a definite survival benefit and decrease in repeat revascularization.

New precision strategies, using patient genomics, markers of inflammation, and artificial intelligence-based risk prediction, will likely soon allow personalized conduit selection and additional prolongation of graft life.[22] In robotic and minimally invasive CABG, mid- to long-term results are more and more favorable. 5–10-year survival and graft patency in high-volume center series are similar to those for traditional sternotomy CABG if technical skill and patient selection are optimized.[39] However, high-quality multicenter randomized long-term evidence is still scarce, and standardization of follow-up imaging (e.g., CTA or FFR-CT–based graft assessment) is necessary to adequately assess the durability of these new techniques.

Joining survival, quality of life (QoL), and functional recovery are today's primary endpoints in evaluating CABG outcomes under the era of precision and minimally invasive technology. In prospective trials with proven tools such as the Seattle Angina Questionnaire (SAQ) and EQ-5D, physical limitation, angina frequency, and global health status have all demonstrated striking improvements at six months after CABG, with sustained gains for a decade.[21] Minimally invasive CABG (MIDCAB, robotic, or hybrid revascularization) has brought tangible improvement in the early recovery markers, like less postoperative pain, faster ambulation, and faster return to normal activities or work. A 2023 meta-analysis of over 6,000 patients found that minimally invasive CABG saved 3–5 days of hospital stay and provided faster return to work by approximately two weeks, without adversely impacting long-term quality-of-life outcomes.[40]

Psychological well-being is increasingly recognized as a prognostic indicator for postsurgical recovery. Less anxious, less depressed, and less postoperative fatigue patients undergo sternotomy CABG. Addition of precision perioperative therapy, including biomarker-stratified control of inflammation and personalized rehabilitation protocols, further maximizes recovery pathways. Combined, these findings portend that the success of CABG in the future will be as much determined by functional outcome and patient satisfaction as by graft durability.[41] Despite tremendous progress, excessive disparities in outcomes of CABG continue across sex, ethnicity, and genetic stratification. Women have traditionally had increased perioperative mortality and poorer long-term graft patency owing to smaller coronary vessel size and lower rates of arterial conduit use, exacerbated by delayed referral for surgery. Nevertheless, recent precision medicine initiatives aim at sex-directed conduit strategy, preferential RA usage, and pharmacologic optimization leading to narrowing gaps in outcomes across contemporary cohorts.[40]

Ethnic disparities also influence CABG results. Multinational registry findings reveal that Black and South Asian individuals have increased long-term mortality and graft failure, often due to a higher burden of comorbidities (e.g., diabetes mellitus, renal failure) and disparate access to multi-arterial revascularization. Preoperative risk stratification with precision based on socioeconomic, genetic, and inflammatory risk factors can prevent isolated disparities.[37] At the molecular level, polymorphisms in the gene that depend on endothelial repair, inflammatory, and coagulant responses have been identified in recent genomic research that can all affect the healing and patency of grafts.[37] For instance, polymorphisms within the NOS3, IL6, and VEGF pathways have been demonstrated to influence long-term graft function. Including such genetic information in the preoperative planning phase, combined with AI risk estimation and population-calibrated calibration, could mark the beginning of the era of truly fair, genotype-guided CABG.[38]

Long-term outcomes are a 3D interaction between patient, surgeon, and technology applicable to the era of minimally invasive and precision. Multi-arterial grafting and minimally invasive strategies, combined with genomics-informed decision-making, will optimize survival and quality of life.[42] Achievement of this actual vision is dependent upon long-term follow-up information being standardized, inclusive study designs, and systematic application of sex- and ethnicity-sensitive algorithms. Thus, the next decade of CABG research should shift away from procedural success to outcomes of revascularization that are personalized, equitable, and sustainable.[21]

5. Challenges, Controversies, and Future Directions

There has been a paradigm-level change in cardiac surgery with the conversion of the cardiac surgery of CABG into a precision-guided, technology-oriented field. Along with the rapid progress, great scientific, ethical, and practical implications are cropping up in areas such as robotics, AI, and molecular profiling. The future advancements ought to be premised on the coexistence of a technology-driven, clinical evidence-based, regulatory, and translational research merging molecular science and operative technique.

5.1 Balancing Innovation and Evidence

The application of robotic and minimally invasive CABG is one of the growing manifestations of the clash between technology and evidence-based practices. Observational experience and preliminary reports have demonstrated rehabilitation profiles equal, if not superior, to conventional CABG with larger multicenter randomized trials. Long-term evidence is rare. Hence, the controversy on whether this should be adopted widely and outside specialized centers.[43] For example, robotically assisted CABG requires huge capital costs, structural training, and, above all, a multidisciplinary approach.

Registry reports from high-volume centers indeed reveal excellent perioperative outcomes; probably, such results may not be generalized to the community hospital. The core is that there really isn't a high-level evidence base for measuring new surgical technology according to outcomes other than short-term mortality rate, quality of life, long-term graft patency, and cost-effectiveness. Pragmatic multi-center trials, learning-curve-corrected analysis, and real-world registries should supplement early feasibility studies. Even beyond this, continual assessment is of the human factors of surgeon ergonomics, fatigue, and cognitive workload that affect safety and the sustainability of robotic surgery programs.

5.2 Integrating Multi-Omics Data into Surgical Planning

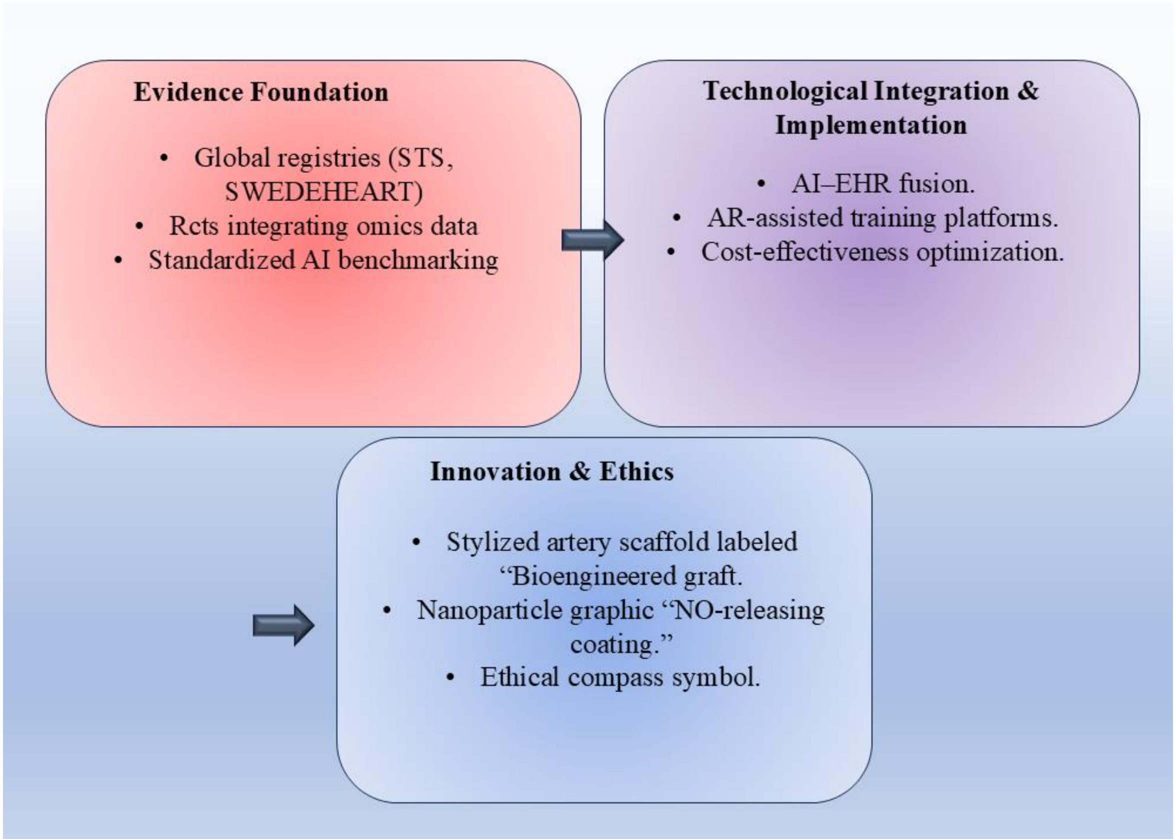
The convergence of genomics, proteomics, metabolomics, and transcriptomics offers a novel way to tailor CABG at the molecular level. The integration of multi-omics information into the process of making surgical decisions may facilitate personalized risk stratification, conduit selection, and postoperative therapy optimization. Genomic differences in endothelial repair pathways (e.g., NOS3, VEGFA), for instance, may confer graft patency, while metabolomic profiles of oxidative stress may be utilized to identify patients at higher perioperative risk of myocardial damage.[44,45] Pilot trials conducted using systems biology approaches in recent times have demonstrated that combining transcriptomic and proteomic data can identify molecular pathways of impaired graft healing or premature occlusion. These results would be utilized for the creation of intraoperative pharmacologic adjuncts or postoperative anti-inflammatory therapy. However, at present, clinical usage is being hindered by the complexity of data convergence, costly analytics, as well as a dearth of standardized bioinformatics pipelines.[45]

Over the next decade, AI-supported multi-omics integration will be of central importance. Large-scale genomic and proteomic data sets may be used to train machine learning models that identify latent molecular phenotypes previously unapparent, which can predict surgical outcomes. However, these algorithms need to be validated on heterogeneous populations and healthcare systems to prevent bias and optimize reproducibility.

5.3 Ethical and Regulatory Aspects of AI-Supported Surgical Decision-Making

As AI systems become increasingly embedded in preoperative risk prediction, intraoperative imaging, and postoperative management, ethical and regulatory governance will define the boundaries of acceptable implementation. AI's capacity to analyze multimodal data—imaging, genomics, and clinical parameters- brings up concerns of transparency, accountability, and informed consent. Whereas an algorithm suggests a conduit configuration or surgical plan that is

Figure 2: AI, imaging, and predictive modeling in CABG planning



opposite to the surgeon's judgment, the question arises as to who will be liable and take clinical responsibility (Figure 02).[46]

Regulatory frameworks so far have lagged in keeping pace with technology. The U.S. FDA and European regulators have begun developing adaptive routes to clearance for AI-based medical devices, but these remain focused on diagnostic rather than on surgical decision-making systems. Ethical regulation must facilitate algorithmic fairness, particularly since most training sets underrepresent women, ethnic minorities, and low-resource populations, further vulnerable groups already subject to worse CABG outcomes. In addition, the use of genomic and proteomic data in AI models necessitates tough data privacy measures under regimes such as GDPR and HIPAA. Future regulation will need to allow algorithmic explainability, control by clinicians, and patient self-determination, bringing in AI as decision support, rather than decision replacement.

5.4 Bioengineered and Nanomaterial-Enhanced Grafts

Of all the most thrilling CABG horizons, perhaps the most exciting is that of bioengineered vascular grafts and nanomaterial-enhanced conduits. Traditional autologous grafts, such as saphenous vein and radial artery, are constrained by availability, injury at the time of harvesting, and long-term failure rates. New tissue engineering technologies have led to the creation of decellularized scaffolds populated with autologous endothelial or stem cells that aim to mimic native vessel biomechanics and reduce thrombosis. Early-stage human testing of bioengineered grafts, including Humacyte's human acellular vessels, has reported promising patency and biocompatibility results in peripheral uses, with cardiac applications being actively explored.[47]

At the nanolevel, polymer coatings and drug delivery systems based on nanoparticles are being investigated to inhibit neointimal hyperplasia and enhance reendothelialization. Experimental grafts with nitric oxide–releasing polymers or graphene oxide nanocomposites have been found to exhibit enhanced endothelial cell adhesion and reduced platelet aggregation in preclinical models. In the world of translation, it remains difficult from confirming long-term safety, cost, and approval among the cardiovascular community. As such, one can view this substance, once the clinical stages advance, as redefining the graft model of longevity, somewhere between biological pliability and synthetic resilience.[47]

The future of CABG is a high-tech combination of biological intelligence and advanced technology. Being feasible, it should be realized by innovation, funded by judicious deliberations, moral priority, and fair distribution. In a way, integration of multi-omics data and surgical planning with AI can provide personalization of revascularization, and the use of bioengineered conduits can potentially conquer the biological disadvantages of current grafts. But adjustment to these advances can only be made in terms of solid clinical data, open regulation, and unshakeable commitment to research equity.

In the end, as of today CABG will mean improved survival, but in the distant, distant future it will really mean a global paradigm shift, where the diagnosis actually resulting in that CABG operation would be with molecular insight, the operation would be done with precision engineering, and the success would be defined by patient-oriented outcomes like durability, recovery, and quality of life.

CONCLUSION

Coronary artery disease multivessel and complex revascularization by CABG are more or less the same, signifying long-term survival and durability. Sixty years since its beginning, CABG is still developing as a biological science of genomics, engineering, data science, and surgical innovation. In the modern era, the development of the specialty also marks the demise and death of one-size-fits-all medicine for a precision-based, patient-specific specialty, in which every aspect, from conduit selection to postoperative care, is tailored to the patient's biological and clinical profile.

Precision medicine is revolutionizing CABG risk stratification, graft choice, and perioperative management with genomic and proteomic markers, AI-generated predictive models, and articulated real-time data analysis. Minimally invasive and robotic techniques offer the interventional orchestra ample room while offering comparable graft durability but less morbidity, faster recuperation, and better quality of life. Intersecting technological innovation with biologic individualization, therefore, is the future of coronary surgery.

Though these adventures start in the esoteric domain, their landing in day-to-day life will be with stringent validation, ethical review, and conditioning for equal access. Multicenter mega-trials, standardized outcome registries, and cross-disciplinary collaboration among surgeons, data scientists, and molecular biologists will be the pathway to precision and minimally invasive CABG to provide proven, long-lasting benefits. In short, the future of CABG will not be decided by replacement; it will be; instead, it will be redefined: a combination of surgical skill, molecular insight, and computer sophistication that extends both the life and quality of life of the patient with coronary artery disease.

DECLARATIONS

Competing interests: None
Funding: No funding source involved.
Authors' contributions: All authors had read and approved the final manuscript.
Acknowledgments: We express our sincere gratitude to the University College of Nursing, the Islamia University of Bahawalpur, for providing a conducive academic environment and the necessary resources for this research.

REFERENCES

1. Pačarić S, Turk T, Erić I, et al. Assessment of the quality of life in patients before and after coronary artery bypass grafting (CABG): a prospective study. International journal of environmental research and public health 2020; 17(4): 1417. https://doi.org/10.3390/ijerph17041417
2. Caliskan E, De Souza DR, Boening A, et al. Saphenous vein grafts in contemporary coronary artery bypass graft surgery. Nature Reviews Cardiology 2020; 17(3): 155–69. https://doi.org/10.1038/s41569-019-0249-3
3. Shawon MSR, Odutola M, Falster MO, Jorm LR. Patient and hospital factors associated with 30-day readmissions after coronary artery bypass graft (CABG) surgery: a systematic review and meta-analysis. Journal of Cardiothoracic Surgery 2021; 16(1): 172. https://doi.org/10.1186/s13019-021-01556-1
4. Noor Hanita Z, Khatijah L, Kamaruzzaman S, Karuthan C, Raja Mokhtar R. A pilot study on development and feasibility of the 'MyEducation: CABG application patients undergoing coronary artery bypass graft (CABG) surgery. BMC nursing 2022; 21(1): 40. https://doi.org/10.1186/s12912-022-00814-4
5. Leivaditis V, Maniatopoulos A, Mulita F, et al. Between Air and Artery: A History of Cardiopulmonary Bypass and the Rise of Modern Cardiac Surgery. Journal of Cardiovascular Development and Disease 2025; 12(9): 365. https://doi.org/10.3390/jcdd12090365

6. Vallely MP, Hameed I, Gaudino M. Commentary: The evolution of coronary artery bypass surgery: Toward a better operation. The Journal of Thoracic and Cardiovascular Surgery 2021; 162(4): 1122–4.
7. Infante T, Del Viscovo L, De Rimini ML, Padula S, Caso P, Napoli C. Network medicine: a clinical approach for precision medicine and personalized therapy in coronary heart disease. Journal of Atherosclerosis and Thrombosis 2020; 27(4): 279–302. https://doi.org/10.5551/jat.52407
8. Bertsimas D, Orfanoudaki A, Weiner RB. Personalized treatment for coronary artery disease patients: a machine learning approach. Health care management science 2020; 23(4): 482–506. https://doi.org/10.1007/s10729-020-09522-4
9. Baumann AA, Mishra A, Worthley MI, Nelson AJ, Psaltis PJ. Management of multivessel coronary artery disease in patients with non-ST-elevation myocardial infarction: a complex path to precision medicine. Therapeutic advances in chronic disease 2020; 11. https://doi.org/10.1177/2040622320938527
10. Hamilton DE, Albright J, Seth M, et al. Merging machine learning and patient preference: a novel tool for risk prediction of percutaneous coronary interventions. European Heart Journal 2024; 45(8): 601–9. https://doi.org/10.1093/eurheartj/ehad836
11. Singh P, Porta A, Ranucci M, et al. Identifying and preliminary validating patient clusters in coronary artery bypass grafting: integrating autonomic function with clinical and demographic data for personalized care. European Journal of Cardiovascular Nursing 2025: zvaf059. https://doi.org/10.1093/eurjcn/zvaf059
12. Chaudhuri K, Pletzer A, Smith NP. A predictive patient-specific computational model of coronary artery bypass grafts for potential use by cardiac surgeons to guide selection of graft configurations. Frontiers in Cardiovascular Medicine 2022; 9: 953109. https://doi.org/10.3389/fcvm.2022.953109
13. Chaudhuri K, Pletzer A, Waqanivavalagi SW, Milsom P, Smith NP. Personalized surgical planning for coronary bypass graft configurations using patient-specific computational modeling to avoid flow competition in arterial grafts. Frontiers in Cardiovascular Medicine 2023; 10: 1095678. https://doi.org/10.3389/fcvm.2022.953109
14. Le NN, Frater I, Lip S, Padmanabhan S. Hypertension precision medicine: the promise and pitfalls of pharmacogenomics. Pharmacogenomics 2025: 1–24. https://doi.org/10.1080/14622416.2025.2504865
15. Yeh C-H, Chou Y-J, Tsai T-H, et al. Artificial-intelligence-assisted discovery of genetic factors for precision medicine of antiplatelet therapy in diabetic peripheral artery disease. Biomedicines 2022; 10(1): 116. https://doi.org/10.1080/14622416.2025.2504865
16. Forte JC, Yeshmagambetova G, van der Grinten ML, et al. Comparison of machine learning models including preoperative, intraoperative, and postoperative data and mortality after cardiac surgery. JAMA Network Open 2022; 5(10): e2237970–e. https://doi.org/10.1001/jamanetworkopen.2022.37970
17. Montisci A, Palmieri V, Vietri MT, et al. Big Data in cardiac surgery: real world and perspectives. Journal of cardiothoracic surgery 2022; 17(1): 277. https://doi.org/10.1186/s13019-022-02025-z
18. Stamate E, Piraianu A-I, Ciobotaru OR, et al. Revolutionizing cardiology through artificial intelligence—Big data from proactive prevention to precise diagnostics and cutting-edge treatment—A comprehensive review of the past 5 years. Diagnostics 2024; 14(11): 1103. https://doi.org/10.3390/diagnostics14111103
19. Skaria R. Machine Learning and Deep Phenotyping Towards Predictive Analytics and Therapeutic Strategy in Cardiac Surgery: The University of Arizona; 2020.
20. Johnson KW. Applications of Data Science for Precision Cardiology: Icahn School of Medicine at Mount Sinai; 2020.
21. Raja SG. New Clinical Advances in Minimally Invasive Coronary Surgery. Journal of Clinical Medicine 2025; 14(9): 3142. https://doi.org/10.3390/jcm14093142
22. Marin-Cuartas M, Sá MP, Torregrossa G, Davierwala PM. Minimally invasive coronary artery surgery: robotic and nonrobotic minimally invasive direct coronary artery bypass techniques. JTCVS techniques 2021; 10: 170. https://doi.org/10.1016/j.xjtc.2021.10.008
23. Ersoy B, Onan B. Robotic cardiac surgery: Advancements, applications, and future perspectives. Handbook of Robotic Surgery: Elsevier; 2025: 505–11. https://doi.org/10.1016/B978-0-443-13271-1.00009-1
24. Fatehi Hassanabad A, Kang J, Maitland A, Adams C, Kent WD. Review of contemporary

techniques for minimally invasive coronary revascularization. Innovations 2021; 16(3): 231–43.
25. Sivertsson BCP, Gartner AV. Implementation of a Telerehabilitation Device for Post-Coronary Artery Bypass Graft Patients in a Rehabilitation Program on The Faroe Islands: Exploring Opportunities and Barriers.
26. Pearse BL. Implementation Of Bleeding Management in Adult Cardiac Surgery Units in Australia. 2021. https://dx.doi.org/10.25904/1912/4304
27. Almoghairi AM. Barriers and Facilitators to Uptake of Cardiac Rehabilitation Following Percutaneous Coronary Intervention in Saudi Arabia: Queensland University of Technology; 2025.
28. Subih M, Elshatarat RA, Sawalha MA, et al. Exploring the Impact of Cardiac Rehabilitation Programs on Health-Related Quality of Life and physiological outcomes in patients Post Coronary artery bypass grafts: a systematic review. Reviews in cardiovascular medicine 2024; 25(4): 145. https://doi.org/10.31083/j.rcm2504145
29. Schaefer A, Conradi L, Schneeberger Y, et al. Clinical outcomes of complete versus incomplete revascularization in patients treated with coronary artery bypass grafting: insights from the TiCAB trial. European Journal of Cardio-Thoracic Surgery 2021; 59(2): 417–25. https://doi.org/10.1093/ejcts/ezaa330
30. Samant S, Panagopoulos AN, Wu W, Zhao S, Chatzizisis YS. Artificial Intelligence in Coronary Artery Interventions: Preprocedural Planning and Procedural Assistance. Journal of the Society for Cardiovascular Angiography & Interventions 2025; 4(3): 102519. https://doi.org/10.1016/j.jscai.2024.102519
31. Miller CL, Kocher M, Koweek LH, Zwischenberger BA. Use of computed tomography (CT) for preoperative planning in patients undergoing coronary artery bypass grafting (CABG). Journal of Cardiac Surgery 2022; 37(12): 4150–7. https://doi.org/10.1111/jocs.17000
32. Nedadur R, Bhatt N, Liu T, Chu MW, McCarthy PM, Kline A. The emerging and important role of artificial intelligence in cardiac surgery. Canadian Journal of Cardiology 2024; 40(10): 1865–79. https://doi.org/10.1016/j.cjca.2024.07.027
33. Raja SG. Global trends and practices in coronary artery bypass surgery. Academia Medicine 2025; 2(3). https://www.doi.org/10.20935/AcadMed7806
34. Wang X, Zhu H. Artificial intelligence in image-based cardiovascular disease analysis: A comprehensive survey and future outlook. arXiv preprint arXiv:240203394 2024. https://doi.org/10.48550/arXiv.2402.03394
35. Sulague RM, Beloy FJ, Medina JR, et al. Artificial intelligence in cardiac surgery: A systematic review. World Journal of Surgery 2024; 48(9): 2073–89. https://doi.org/10.1002/wjs.12265
36. Lin T-H, Wang C-W, Shen C-H, et al. Clinical outcomes of multivessel coronary artery disease patients revascularized by robot-assisted vs conventional standard coronary artery bypass graft surgeries in real-world practice. Medicine 2021; 100(3): e23830. https://doi.org/10.1097/MD.0000000000023830
37. Mastroiacovo G, Manganiello S, Pirola S, et al. Very long-term outcome of minimally invasive direct coronary artery bypass. The Annals of Thoracic Surgery 2021; 111(3): 845–52. https://doi.org/10.1016/j.athoracsur.2020.06.025
38. Ilcheva L, Häussler A, Cholubek M, et al. Thirteen Years of Impactful, Minimally Invasive Coronary Surgery: Short-and Long-Term Results for Single and Multi-Vessel Disease. Journal of Clinical Medicine 2024; 13(3): 761. https://doi.org/10.3390/jcm13030761
39. Fortunato GA, Davierwala PM. The current role and future perspectives of minimally invasive coronary artery bypass grafting. Journal of Visualized Surgery 2023; 9. https://doi.org/10.21037/jovs-22-41
40. Guo MH, Toubar O, Issa H, et al. Long-term survival, cardiovascular, and functional outcomes after minimally invasive coronary artery bypass grafting in 566 patients. The Journal of Thoracic and Cardiovascular Surgery 2024; 168(4): 1080–8. e2. https://doi.org/10.1016/j.jtcvs.2023.07.047
41. Ilcheva L, Risteski P, Tudorache I, et al. Beyond conventional operations: embracing the era of contemporary minimally invasive cardiac surgery. Journal of Clinical Medicine 2023; 12(23): 7210. https://doi.org/10.3390/jcm12237210
42. van der Merwe J, Casselman F. Minimally invasive surgical coronary artery revascularization—Current status and future perspectives in an era of interventional advances. Journal of Visualized Surgery 2023; 9. https://doi.org/10.21037/jovs-22-40
43. Oishi K, Nagaoka E, Kawabata T, et al. Coronary Artery Bypass Grafting in the Era of

Evidence-Based Medicine Advancing Techniques and Their Integration into Future Guidelines. Journal of Coronary Artery Disease 2025; 31(2): 52–8.
https://doi.org/10.7793/jcad.31.25-00010
44. Hou H-T, Chen H-X, Wang Z-Q, et al. Integrative Multi-omics Approach Reveals the Molecular Characterization and Differences of ECM-PI3K-Akt Pathway among Coronary Artery Bypass Grafting Conduits with Clinical Implications. medRxiv 2024: 2024.08. 11.24311581.
https://doi.org/10.1101/2024.08.11.24311581
45. Hou H-T, Chen H-X, Wang Z-Q, et al. Arterial and venous grafting biomaterials in coronary Surgery: Integrative multi-omics approach reveals ECM-PI3K-Akt pathway as Key Regulator of different patency. Chemical Engineering Journal 2025; 511: 161829.
https://doi.org/10.1016/j.cej.2025.161829
46. Khan MA. Ethical implications of AI (artificial intelligence) in healthcare mainly focus on surgical procedures: identification of ethical issues of AI in surgical procedures and ranking of ethical issues based on criticality. 2024.
47. Jayabal R. Nanomaterials in Regenerative Medicine: Advancing the Future of Tissue Engineering. Regenerative Engineering and Translational Medicine 2025: 1–19.
https://doi.org/10.1007/s40883-025-00416-x