State of the art paper

Calculated courage: risk, responsibility, and the ethos of cardiac surgery in the age of artificial intelligence

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Submitted: 11 January 2026; **Accepted:** 12 April 2026
Online publication: 30 June 2026

Arch Med Sci Atheroscler Dis 2026; 11: e123–e148
DOI: https://doi.org/10.5114/amsad/220586

Abstract

The history of cardiac surgery reflects a unique interplay between technological innovation and moral responsibility. From the early era of experimental open-heart operations to the present age of data-driven precision, the discipline has continually redefined its understanding of risk, agency, and ethical duty. This review examines the historical, ethical, and philosophical evolution of cardiac surgery, focusing on how artificial intelligence (AI) and predictive modeling are reshaping the surgeon's role and professional ethos. A narrative synthesis of literature was conducted, including studies on surgical risk assessment, AI-assisted decision-making, and the ethical implications of automation. Inclusion criteria encompassed articles addressing historical development, risk quantification, moral responsibility, and algorithmic ethics within cardiac and cardiothoracic surgery. Artificial intelligence augments, but cannot replace, the ethical and interpretive dimensions of cardiac surgery. Future progress depends on aligning technological sophistication with moral wisdom, ensuring that as machines grow more intelligent, the humanity of surgical practice endures.

Key words: artificial intelligence, risk assessment, cardiac surgery, predictive modelling, surgical ethics, moral responsibility, algorithmic decision-making, calculated courage.

Introduction

Cardiac surgery can be found within a moral/intellectual context of current medical practice which has a specific relationship between technical mastery and risk wherein few clinical disciplines of modern medicine experience the intersection of the critical moment of life, death and responsibility. Few medical disciplines have been shaped so profoundly by the necessity to act under conditions of extreme uncertainty, where life, death, and responsibility converge in real time [1].

Since its inception, cardiac surgery has pushed the boundaries of human physiology as well as established ethical standards and ideas of professional bravery. The heart was considered untouchable in the first half of the 20th century, a sacred organ whose direct manipulation verged on immorality, with any attempt to operate on it required an ethical leap into the unknown in addition to technical daring [2].

Early pioneers like Michael DeBakey, John Gibbon, C. Walton Lillehei, and Clarence Dennis worked at the very edge of possibility, driven more by experimental reasoning, personal conviction, and a strong sense of moral obligation to their patients than by statistical reasoning [3, 4]. By today's standards, outcomes were uncertain, complications were common, and mortality rates were high. However, these early interventions represented a historically situated kind of professional courage in which risk was publicly and consciously accepted rather than being acts of recklessness. Although the moral and epistemic underpinnings of modern cardiac surgery were eventually established by these endeavors, the ethical rationale for such experiments was frequently shaky and disputed [5, 6]. In this early stage, risk was a lived reality that the surgeon experienced, described, and ethically owned rather than a numerical value.

The concept of risk itself evolved along with cardiac surgery. What had previously been a qualitative, experience-based assessment rooted in personal knowledge gradually became formalized, quantified, and objectified. In addition to revolutionizing the technical viability of intracardiac procedures, Gibbon's 1953 invention of cardiopulmonary bypass (CPB) made it possible to systematically observe, record, and compare results [3, 7]. This represented a significant change in epistemology since risk could now be quantified, totaled, and examined. With the development of outcome registries and risk-stratification tools, such as the Society of Thoracic Surgeons (STS) models and the European System for Cardiac Operative Risk Evaluation (EuroSCORE), risk was reframed as a comparable and calculable variable rather than a primarily moral or personal evaluation [8, 9]. This development coincided with a more general shift in medical culture from the heroic era of individual judgment to one marked by responsibility, openness, and uniformity [10, 11].

Artificial intelligence and machine-learning approaches now enable the generation of highly individualized risk estimates by analyzing vast and complex clinical datasets. These computational methods can detect patterns that would be difficult or impossible for clinicians to recognize through experience alone, thereby offering increasingly refined prognostic insights [12]. Yet the apparent analytical power of such systems also raises important philosophical and ethical questions. Even when predictions become more accurate, uncertainty in medicine cannot be fully eliminated. As algorithmic models begin to influence clinical choices – often through processes that are not entirely transparent – the question of how responsibility should be understood within technologically mediated decision-making becomes increasingly significant.

When opaque, data-driven systems increasingly inform, or subtly shape, clinical decisions, how should professional responsibility be understood? Increasing technical capability also increases moral obligation, according to philosophical reflections on technology and responsibility, particularly those of Jonas [13] and Beck [14]. This tension is especially acute in cardiac surgery, where quantification improves safety and consistency but may also separate practitioners from the irreducible uncertainty at the core of clinical decision-making by substituting proceduralized calculation and probabilistic abstraction for situated judgment [15, 16].

In light of this, cardiac surgery is at a turning point. The field must balance its historical identity, which is based on bravery, accountability, and acceptance of uncertainty, with a future that is becoming more and more shaped by predictive control and algorithmic support. From its heroic origins to its algorithmic present, this article explores the philosophical and historical development of risk in cardiac surgery and looks at how evolving ideas about risk have changed the ethical identity of the cardiac surgeon. By examining this path, we contend that the history of cardiac surgery is not just a story of technological advancement but rather a continuous struggle between bravery and reason, creativity and accountability, and, in the end, between what can be quantified and what still needs to be morally endured.

Methods

Study design

In order to investigate the changing notion of risk in cardiac surgery, this paper uses a narrative, interdisciplinary review approach that integrates historical, clinical, and philosophical sources. The analysis concentrates on key works, significant clinical advancements, and exemplary ethical frameworks that have influenced professional perceptions of risk throughout history rather than striving for comprehensive coverage.

The purpose of this study was to examine the development of the idea of risk in cardiac surgery and its philosophical, ethical, and epistemological ramifications through a narrative historical and conceptual review. The methodology integrated a philosophical examination of risk, accountability, and uncertainty in technological medicine with a historical narrative synthesis of primary and secondary medical literature. Transparency, reproducibility, and interpretative depth were prioritized in the methodology, which adhered to the guidelines for narrative reviews [17].

Data sources and search strategy

In order to assemble relevant literature published between 1950 and 2025, comprehensive searches were performed in PubMed, Scopus, Web of Science, and Google Scholar. This particular time frame was selected to present the development of modern cardiac surgery with emphasis on the emergence of cardiopulmonary bypass through presenting current information about the role of artificial intelligence (AI) in predictive risk assessment.

Search terms were combined using Boolean operators into 3 main categories. The first category is Technical and Historical Terms which includes such terms as “surgical innovation”, “cardiac surgery”, “cardiopulmonary bypass”, and “extracorporeal circulation”. The second category contains all Terms Relating to Risk such as “risk assessment”, “surgical risk”, “EuroSCORE”, “STS Risk Model”, “operative mortality”, and “risk prediction”. The final category represents all Terms Associated with Philosophy and Ethics including: “medical ethics”, “duty of care”, “uncertainty”, “philosophy of surgery”, “ethical innovation”, and “AI ethics”.

To find more pertinent research and historical accounts, the reference lists of important articles were manually screened. For theoretical framing, key works on risk theory and medical philosophy were also included [13, 14, 18].

The literature search found three primary categories: (i) historical and technical literature documenting key milestones in cardiac surgery; (ii) clinical and outcomes-based studies related to risk stratification and predictive modeling; and (iii) philosophical and ethical texts addressing responsibility, uncertainty, and technological mediation in medicine.

These main categories were analyzed together and within the context of the other categories.

Inclusion criteria

Studies were included if they met at least one of the following criteria:
- Historical relevance: Publications describing major milestones in the development of cardiac surgery, cardiopulmonary bypass, or risk evaluation models.
- Quantitative risk frameworks: Articles introducing, validating, or discussing surgical risk scoring systems such as EuroSCORE, EuroSCORE II, or the STS models.
- Ethical or philosophical analysis: Papers addressing the moral, psychological, or epistemological aspects of surgical decision-making and innovation.
- Technological risk transformation: Studies exploring data-driven or artificial intelligence–based approaches to risk prediction in cardiac or thoracic surgery.
- Peer-reviewed source: Indexed in PubMed or Scopus, published in English, and available as full-text articles.

Exclusion criteria

Publications were excluded if they:
- Focused solely on technical details or operative techniques without reference to risk, ethics, or decision-making.
- Represented conference abstracts, editorials, or non-peer-reviewed commentaries without substantive data or analysis.
- Dealt exclusively with pediatric cardiac surgery (to maintain thematic coherence).
- Discussed risk management in non-surgical or non-cardiac disciplines.
- Were non-English or inaccessible in full text.

Data extraction and synthesis

For each included publication, key information was extracted concerning:
- Historical context or timeframe (e.g., pre-bypass era, modern quantitative era, AI era).
- Conceptualization of risk (moral, statistical, algorithmic).
- Ethical and philosophical perspective (responsibility, autonomy, uncertainty).
- Key findings and implications.

To demonstrate the evolving paradigms of risk perception and management, the gathered material was arranged chronologically and thematically. In order to contextualize ethical shifts throughout historical periods, philosophical frameworks by Jonas [13], Geanellos, Ricoeur [19, 20], and Beck [14] were integrated interpretively.

Using an interpretive and comparative approach, the analysis looked at how risk and responsibility were understood in various historical eras. Risk models were examined as sociotechnical constructs embedded within larger cultural, ethical, and institutional contexts rather than as objective instruments.

Quality and validity considerations

Although this review is primarily conceptual, peer-reviewed and methodologically sound sources were prioritized for inclusion. Historical accounts were cross-checked using at least two independent sources to ensure reliability. Interpretive coherence and thematic saturation were achieved through repeated reading and synthesis of the material.

Methodological rigor and limitations

Arguments were triangulated across historical records, current clinical literature, and accepted ethical theory to improve analytical rigor. Primary sources and frequently cited models were given priority whenever possible. Converging evidence, as opposed to singular instances, served as the foundation for interpretive assertions.

Ethical considerations

The study did not require ethical approval because there were no human subjects or patient records. However, ethical guidelines for responsible scholarship and proper citation were strictly followed.

The birth of risk: early experimental cardiac surgery (1890–1950)

From taboo to experimentation

Direct surgical intervention on the human heart was considered unethical and technically impossible at the turn of the twentieth century. In medical practice, the heart represented not only a biological structure but also a significant moral boundary because it was symbolically connected to life, vitality, and emotion [2]. The idea that surgical intrusion into the cardiac domain constituted an unacceptable transgression was reinforced by both scientific limitation and cultural reverence, which upheld its inviolability. The famous claim made by British surgeon Stephen Paget in 1896 that “surgery of the heart has probably reached the limits set by Nature” summed up the general consensus of the time [5, 21, 22]. In addition to reflecting current physiological knowledge, this perspective also represented a more expansive moral imagination that saw the heart as particularly sacred. Over the course of many years, most cardiac lesions were seen as irreparable, causing physicians to hesitate as they explored options for diagnosing these problems, including pericardiocentesis. This long-standing stigma led to the development of a cadre of surgeons during the early twentieth century, who were determined to challenge the established limitations of medicine and the human body. Instead of merely seeking a technological solution, these early innovators sought to change the definition of acceptable clinical risk for patients. By creating new surgical techniques, such as Ludwig Rehn’s 1896 method to surgically repair penetrating cardiac wounds, these innovator surgeons demonstrated that hearts could be repaired with surgery. Later developments by surgeons like John Gibbon, Clarence Dennis, and C. Walton Lillehei – especially in the creation of early extracorporeal circulation – gradually converted moral prohibition into experimental investigation [3, 4, 7, 23] (Figure 1). These endeavors took place in a highly uncertain setting where survival was far from guaranteed and failure was frequent.

These pioneering efforts are significant not only for their technical achievements but also for the ethical posture they embodied. Attempting surgical intervention on the human heart required an exceptional degree of moral resolve. Surgeons confronted the real possibility of fatal outcomes while acting in the hope of preserving life, accepting profound uncertainty as an inherent part of their work. Their willingness to intervene under such conditions reflected a form of professional courage grounded in responsibility toward patients despite the absence of reliable precedents or predictable outcomes [7]. These surgeons frequently operated without the assurance of previous research or accepted norms, operating at the nexus of innovation and transgression. Rather than using formalized risk assessment, they made decisions based on a sense of professional responsibility based on their own judgment. In this situation, ethical exposure was inextricably linked to experimentation, and the act of operating itself constituted a moral assertion regarding the acceptability of risk.

The moral framework of this early era, which is sometimes referred to as the “heroic era” of cardiac surgery, differed significantly from contemporary ideas of accountability and evidence-based practice. Success was determined more by the willingness to try new things and learn from mistakes than by overall results or survival statistics [3, 24]. During this initial stage, risk was perceived as an integral part of surgical identity rather than being measured or externalized. Risk served as a moral stance, a deliberate willingness to accept uncertainty, complexity, and even death as the possible price of discovery, rather than being represented as a probability or score. Albert Camus’s later concept of the “absurd hero”, a person who acts in full awareness of impossibility but refuses to give up, resonates with the surgeon’s ethos

Figure 1. Pioneers of early cardiac surgery and cardiopulmonary bypass. **A** – Ludwig Rehn (1849–1930), Professor of Surgery at the University of Frankfurt, performed the first documented successful surgical repair of a penetrating cardiac injury, demonstrating for the first time that direct surgical intervention on the human heart was feasible. Photo credit: Institut für Stadtgeschichte Frankfurt. **B** – Clarence Walton Lillehei (1918–1999), an American cardiac surgeon, was a central pioneer of open-heart surgery, contributing fundamentally to the development of surgical techniques, equipment, and prosthetic devices that enabled complex intracardiac procedures. Photo credit: University of Minnesota. **C** – Clarence Dennis (1909–2005), an American cardiothoracic surgeon, played a pivotal role in the early development of cardiopulmonary bypass. He designed one of the first heart–lung machines and, in 1951, was the first to employ such a device during an open-heart operation. Source: The Clarence Dennis Papers, Profiles in Science, National Library of Medicine. **D** – John Heysham Gibbon (1903–1973), an American surgeon, invented the heart–lung machine and achieved the first successful open-heart surgery using total cardiopulmonary bypass, establishing a technological foundation for modern cardiac surgery. Public domain

during this time, which combined technical skill with existential resolve [25].

The ethical ambiguity of early innovation

There was no official institutional governance or ethical oversight during the early stages of cardiac surgery's development. There had not yet been established mechanisms that are now thought to be essential to clinical research, such as external ethical review, standardized informed consent procedures, and institutional review boards. Patients and society rarely questioned the surgeon's paternalistic authority, and when consent was obtained, it was frequently informal and not fully documented. Therefore, rather than being governed by codified regulations or collective ethical standards, clinical decisions were primarily influenced by personal conscience, professional reputation, and an internalized sense of duty [6].

A unique moral landscape characterized by significant ethical ambiguity was created by this historical setting. On the one hand, patients were subjected to unusual and frequently poorly understood risks during early cardiac interventions, often in the absence of therapeutic alternatives. Conversely, these same interventions set the stage for later standard, life-saving treatments. Risk could not be quantified or formally communicated in an era without outcome benchmarks, validated safety data, or predictive models; instead, it was negotiated through trust, both implicitly between the surgical profession and society at large and between patients and surgeons. The individual surgeon was given both authority and moral responsibility as a result of this trust, taking on accountability for both the immediate result and the larger course of medical advancement.

In retrospect, scholars have characterized this time period as one marked by "moral gray zones", where uncertainty about the boundaries of acceptable danger coexisted with the imperative to advance knowledge [15, 26]. Innovation was not morally neutral, but it did proceed without the protections that now govern ethical discussion. Many surgeons justified their actions as morally required reactions to otherwise fatal conditions because they were well aware of the stakes involved. The localization of ethical responsibility within the individual practitioner was implied by the lack of formal oversight, not the absence of ethical reflection.

Early experimental patients' deaths were frequently seen as tragic but unavoidable outcomes of surgical advancement; by today's standards, this viewpoint would raise serious ethical concerns [5]. Not only was mortality expected, but it was also somewhat accepted as a necessary component of education. Every failed operation added to the body of knowledge, but at a human cost that was mostly unmeasured and not sufficiently examined. The fact that surgeons were able to be so open to dealing with disastrous outcomes is seen today as highly problematic, but had this openness to risk-taking not been there, cardiac surgery may never have gone beyond the realm of theory and anatomy.

The combination of early surgical procedures with the examination of our understanding of mortality has created a dichotomy between those factors that motivate surgeons to perform surgery and those that guide surgical practice. Early cardiac surgery also provided new opportunities for surgeons to explore the ethical ramifications of surgery in an environment where creativity, responsibility and harm were all inextricably linked. The conflict between these two areas has resulted in the development of ethical guidelines, risk assessment tools, and regulatory monitoring to provide guidance to surgeons regarding their surgical practices.

The epistemology of early risk

From an epistemological perspective, early cardiac surgeons worked in a setting where qualitative uncertainty predominated over quantifiable probability. Surgical decision-making was largely dependent on personal intuition, accumulated experience, and moral judgment due to the lack of institutional databases, statistical frameworks, and standardized reporting systems. Instead of using formal analysis, knowledge was created locally and gradually, frequently through trial and error and story transmission. Since probabilities were neither known nor estimable, these surgeons handled clinical situations that could not yet be classified as "risk" in the technical sense [3–5].

A helpful conceptual framework for comprehending this era is provided by philosopher Niklas Luhmann's distinction between danger and risk [18]. According to Luhmann, risk necessitates making decisions under circumstances of calculable uncertainty, whereas danger refers to circumstances in which results are essentially unpredictable and responsibility cannot be assigned or externalized. It was obvious that early cardiac surgery fell into the former category. Unfavorable results were presented as tragic consequences of necessary action or as personal failures rather than as statistical deviations. The surgeon retained complete control over responsibility; it was not shared by organizations, models, or protocols.

Only with the standardization of results, the creation of registries, and the growth of evidence-based medicine would there be an epistemic shift from danger to risk – from the unknown to the quantifiable. However, data-driven prediction did not control cardiac surgery in the early decades. Rather, it was maintained by faith in advancement, patient-surgeon trust, and a professional culture that valued accountability in the face of uncertainty. Narrative reasoning, analogical thinking, and an ethical commitment to intervening in otherwise fatal situations were used to justify decisions rather than numerical estimation.

According to Hessel [3] and Stoney [4], these early surgeons' bravery resulted from their purposeful confrontation with danger rather than from their ignorance of it. They took action knowing full well that their actions could have disastrous consequences and that their knowledge was limited. By doing this, they converted lived experience into the foundation for future understanding and turned moral fear into scientific possibility. Whether they were successful or not, every operation added to the growing understanding of what could and could not be tried.

Importantly, this groundbreaking work laid the ethical and intellectual groundwork for all later approaches to risk assessment. To have the ability to enumerate a given financial/economic risk one would need to experience the same as well as collect, log and analyze results in order to derive probability estimates from these data. Therefore, the early pioneers in cardiac surgical practices were responsible for creating not only the confidence that surgical procedures can be safe when performed within certain constraints but also establishing the baseline data which would enable the quantification, standardization, validation and regulation of those risks in the future. As a result, their influence goes beyond technological advancement to include the epistemological transformation of uncertainty.

Quantifying risk: the technological and statistical turn (1950–1990)

The rise of cardiopulmonary bypass and the birth of measurable risk

In addition to being a technical turning point in the history of cardiac surgery, John Gibbon's invention of cardiopulmonary bypass (CPB) in 1953 also significantly altered the way surgical risk was understood, expressed, and controlled. The epistemic status of cardiac intervention was significantly changed by CPB, which made the previously inaccessible interior of the heart visible and functional under controlled circumstances. According to Hessel [3], surgeons were able to control circulation, oxygenation, and temperature by temporarily replacing cardiac and pulmonary function. This reduced physiological variability and improved procedural reproducibility. It was now possible to observe, record, and progressively systematize risk, which had previously been seen as an irreducible uncertainty.

The artisanal and heroic tradition of early cardiac surgery gave way to a more experimental and data-driven field as a result of this technological breakthrough. It is possible to classify complications, compare results, and repeat procedures under similar circumstances. The ability to track flow, pressure, temperature, and oxygenation in real time changed the cardiac operating room into a living laboratory where physiological reactions were measured directly rather than inferred, as Stoney highlighted [4]. The surgeon's relationship to uncertainty changed as a result of this ongoing feedback: objective parameters and measurable thresholds gradually supplemented – and in certain situations replaced – subjective anticipation of danger.

In the 1960s and 1970s, institutional reporting and outcome registries grew, and this evidence-based reasoning emerged at the same time. Systematic data collection made it possible to measure, aggregate, and compare mortality, morbidity, and length of hospital stay among surgeons, institutions, and populations as cardiac surgery became more common [27]. As a result, risk gained a collective dimension, becoming ingrained in institutional memory and professional benchmarking rather than being limited to the experience of a single surgeon. In addition to facilitating accountability and quality improvement, this development quietly shifted accountability from the lone practitioner to systems, protocols, and norms.

Risk was no longer primarily an expression of moral courage or personal exposure for the first time in the discipline's history. Rather, it evolved into a variable that could be measured, optimized, and somewhat predicted. Numerical estimates of benefit and harm were increasingly used in surgical decision-making, bringing cardiac surgery into line with the overall growth of evidence-based medicine. This shift mirrored the rise of the contemporary "risk society", where uncertainty was reframed as a technical issue of calculation and control rather than as a question of fate, virtue, or existential resolve, as noted by Beck [14] and Luhmann [18] in their sociological analyses.

However, this changed the nature of uncertainty rather than eradicating it. While CPB and early statistical techniques decreased some risks, they also created new risk categories, such as population-level trade-offs, systemic complications, and technological failure. Therefore, risk quantification was a reconfiguration of the understanding, management, and ethical distribution of uncertainty in cardiac surgery rather than an end in itself. This reconfiguration would intensify in the decades that followed, as statistical modeling and predictive frameworks became increasingly central to clinical judgment.

The emergence of surgical risk models

Advances in technology and statistical methods allowed researchers to synthesize data from multiple institutional databases into a single mathematical model of surgical risk in the 1990s. This was an important development, marking a transition away from merely measuring the outcomes of surgical procedures to predicting the outcome before a surgical procedure occurred. EuroSCORE is one of the first predictive models based on the EuroSCORE methodology for how to use a defined set of variables to determine the risk of surgery. Instead of depending upon the thoughts and memories of individual surgeons or hospitals to assess their patients' risk before surgery, EuroSCORE created a reference standard for determining the risk of surgery that could be used across the board by anyone [28].

Shortly after EuroSCORE's initial publication, the Society of Thoracic Surgeons (STS) developed risk estimates that refined and built upon EuroSCORE's initial approach by incorporating risk estimates on a procedure-specific basis, such as coronary artery bypass surgery, valve surgery, and combination surgeries [29]. STS-created risk models relied on an even wider variety of granular clinical data, which involved demographic data; physiologic measurements, and surgical variables, to determine a predicted risk for mortality and morbidity [11, 30]. Over time, iterative validation and recalibration improved their discriminatory performance. As demonstrated by Hogervorst *et al.*, such tools achieved high predictive accuracy and became embedded in routine clinical practice, shaping preoperative counseling, shared decision-making, and institutional benchmarking [31].

Surgical risk models have changed the way uncertainty is communicated and managed. The risk estimates that were previously implicit and based on experience are now explicitly quantified and documented. This change created greater transparency and made it possible for surgeons, hospitals, and policymakers to evaluate results across populations and institutions. It has also given way to an additional epistemic authority, numerical prediction has begun to assume a normative role and therefore influences decisions not only about clinical care but also the professional reputations of surgeons and the organizational reputation of hospitals.

However, this quantitative paradigm was not ethically neutral. As noted by Wasfy *et al.* [16] and Shahian *et al.* [32], publicly reported surgical outcome data and the use of standardized surgical risk scores have established a culture of aversion to risk. Surgeons are increasingly pressured externally to enhance their performance on various risk metrics and, in certain instances, this has caused surgeons to forgo treating complex/high-risk patients or high-risk cases, which could adversely impact publicly reported results. The unintended consequence of the development of instruments to promote safety, accountability, and quality in surgical care could restrain innovation by causing surgeons to avoid taking morally permissible risks on behalf of their most vulnerable patients.

In this context, the quantification of risk reshaped not only practice patterns but also professional identity. The cardiac surgeon of the late twentieth century evolved from the archetype of the "heroic craftsman", whose authority rested on personal judgment and technical daring, into a "manager of probabilities", navigating between scientific rationality, institutional expectations, and bureaucratic oversight [5]. Decision-making became increasingly mediated by scores, benchmarks, and comparative data, redistributing responsibility from individual agency toward systems of measurement and evaluation. This transformation set the stage for the subsequent emergence of algorithmic and artificial intelligence-based risk prediction, in which numerical authority would become even more pervasive and less transparent.

The ethics of measurable risk

The increasing reliance on numerical prediction profoundly reshaped the moral framework of surgical practice. Where early cardiac surgeons bore direct and personal moral responsibility for their judgments under uncertainty, late twentieth-century practitioners increasingly operated within an institutionalized environment of shared and distributed accountability. Decisions were no longer grounded solely in individual expertise but were mediated by scores, benchmarks, and performance indicators. As McKneally argued, the diffusion of responsibility through statistical systems and quality controls carries the risk of attenuating individual ethical agency, as accountability becomes embedded in processes rather than persons [15].

This transformation was particularly evident in the public reporting movement, which sought to enhance transparency and patient empowerment by making surgical outcomes visible and comparable. Brown *et al.* had put all heart surgeons under the scrutiny of comparative performance report cards on several levels. These performance ratings were for institutions and by individual surgeons, with a goal of increasing accountability of institutions and increasing the rights of patients; however, they also resulted in heart surgeons being held to much greater scrutiny based on performance. The professional autonomy of surgeons, which was previously largely based on their own discretion, was now being diminished by external evaluation and reputational risk. Therefore, the professional and moral weight of clinical decision-making had shifted away from bedside interactions between surgeons and patients and was now being assessed and evaluated based on reports. Thus, practice patterns and identity as a surgeon had changed [33].

In parallel, the evolution of informed consent practices reflected this changing ethical landscape. As analyzed by Hanson *et al.*, risk communication moved away from a paternalistic model toward a framework emphasizing patient autonomy and shared decision-making [34]. This newfound accountability for surgeons also extended to patients. Reports provided patients with statistical data on the risk of injury and mortality and encouraged patients to utilize statistical probabilities to help them make informed decisions about their care. While this opened up lines of communication and made it easier for many patients to make informed decisions regarding their care, it also created new barriers between patients and their healthcare providers. Even though numerical risk data «represented» an apparent level of objectivity, it also risked creating a false sense of security in patients about the real uncertainty, variability, and context associated with statistical information, thus creating confusion on behalf of patients who are not adequately equipped to understand the implications of such information.

By the end of the twentieth century, risk in cardiac surgery had thus acquired a dual function. It became both a moral language through which responsibility, consent, and accountability were articulated, and a statistical instrument used to govern uncertainty through calculation and comparison. These parallel roles did not always align. While quantification promised control and fairness, it also risked reducing complex ethical judgments to numerical thresholds. In this sense, measurable risk functioned not only as a clinical tool but as a mirror reflecting the evolving relationship between the surgeon, patient, and society – a relationship increasingly shaped by data, regulation, and expectations of transparency. This ethical reconfiguration would become even more pronounced with the advent of algorithmic and artificial intelligence–driven risk prediction.

Taken together, these developments illustrate a profound epistemological shift in how risk is understood, managed, and morally distributed in cardiac surgery. From an early era in which uncertainty was borne directly by the individual surgeon, through a period of statistical abstraction and institutional benchmarking, surgical risk has progressively moved away from lived experience toward formalized calculation. This historical trajectory, and its ethical implications, are schematically summarized in Figure 2.

Beyond calculation: the age of predictive modeling and artificial intelligence (1990–today)

Risk in the era of big data

The increase of digital health technology starting in the 1990s and the use of large-scale clinical

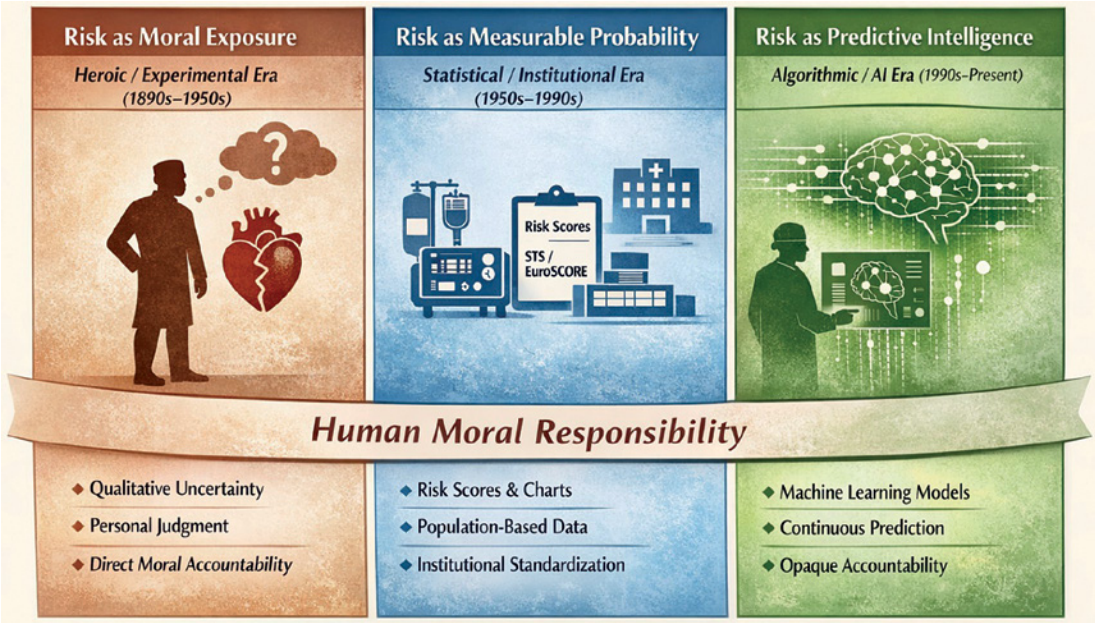

Figure 2. The evolution of risk in cardiac surgery across three epistemological eras. This schematic diagram illustrates the historical and conceptual transformation of surgical risk in cardiac surgery. In the early experimental era, risk was experienced as qualitative uncertainty and borne directly by the individual surgeon as a moral burden. With the advent of cardiopulmonary bypass and outcome registries, risk became quantifiable, standardized, and institutionally mediated through statistical models. In the contemporary era, artificial intelligence and predictive analytics redefine risk as a continuously updated, data-driven construct, introducing new ethical challenges related to opacity, automation bias, and distributed responsibility. Across all eras, however, moral accountability remains irreducibly human, forming the ethical core of surgical decision-making

databases to manage healthcare has dramatically impacted the way we assess and manage surgical risk. The way we assess risk has changed from a set of discrete evaluations to a continuous process that is supported by technology-based infrastructures. As described by Shahian and Normand, the implementation of risk modeling systems into hospitals has shifted the performance evaluation from an event-based approach to an ongoing, technology-supported evaluation process integrated into daily clinical workflows [10]. The assessment of surgical risk is no longer limited to a pre-operative assessment but is now a continuous measure that is updated as new data are available.

The widespread adoption of high-fidelity electronic health records (EHRs), advanced multimodal imaging, and fully automated monitoring instruments (both intraoperatively and postoperatively) have created a large amount of data that contain vast amounts of volume, velocity, and heterogeneity. Not only do the datasets contain traditional clinical variables (i.e., clinical information), they also contain extremely precise physiological data signals derived from imaging, longitudinal laboratory trend data, and medical imaging-diagnosis formulas. This complexity is greater than the analytical ability of classical statistical approaches and has created an environment that requires machine-learning methodologies to identify non-linear, high-dimensional relationships and data socio-historical factors that are difficult to detect through direct human observation [35].

Within this context, artificial intelligence–based predictive models began to emerge as powerful tools for surgical risk estimation. Previously published studies estimated that machine learning algorithms demonstrate superior predictive ability for post-operative complications, duration of ICU stay and mortality than previously used risk assessment models (such as EuroSCORE II and STS) which utilized logistic regression [12]. Computational approaches have also shown the ability to synthesize and apply thousands of diverse inputs, including hemodynamic data, biochemistry, echocardiographic data, and contextual history to create predictions of risk that can continually be recalibrated as the patient receives treatment [36, 37]. Rather than utilizing static estimates, predictive algorithms have produced indefinite probabilities in a continual manner as patients proceed with their medical care.

The ability to continually update predictive probabilities is a vast improvement over previous predictive technologies and represents an epistemological transformation. Risk is no longer assessed at distinct points but instead inferred on a continual basis using automated algorithmic functions that operate behind the scene during clinical interventions. As such, clinical decision-making occurs collaboratively with these evolving algorithmic sys-

Table I. Historical evolution of risk and responsibility in cardiac surgery

Era	Approximate time period	Dominant technologies/practices	Conceptualization of risk	Primary locus of responsibility	Ethical characteristics
Experimental/ Heroic Era	1890–1950	Direct cardiac repair, early experimental extracorporeal concepts, individual technical innovation	Qualitative, experiential, largely unquantified uncertainty	Individual surgeon	Moral courage, personal accountability, acceptance of uncertainty, experimental transgression
Technological Transition Era	1950–1970	Cardiopulmonary bypass, physiological monitoring, early outcome reporting	Observable but incompletely quantified risk	Surgeon supported by emerging institutional structures	Shared learning, procedural standardization, emerging collective responsibility
Statistical/ Institutional Era	1970–1990	Outcome registries, standardized reporting, early risk stratification models	Quantified, population-based probability	Institutions, professional societies, healthcare systems	Benchmarking, transparency, risk standardization, accountability through metrics
Predictive/ Algorithmic Era	1990–present	Artificial intelligence, machine learning, electronic health records, continuous monitoring systems	Dynamic, probabilistic, continuously updated prediction	Distributed across clinicians, institutions, and algorithms	Opacity, automation bias, diffusion of responsibility, governance challenges
Ethical Synthesis (Calculated Courage)	Contemporary	Human–AI co-piloting frameworks, ethical governance structures	Contextualized uncertainty integrating data and judgment	Human moral agent within sociotechnical systems	Responsible action under uncertainty, ethical humility, interpretive authority, moral stewardship

tems, which provide an increasingly "intelligent" means of risk assessment through machine learning. In this new paradigm, the surgeon is not the only holder of knowledge, nor is he or she the final authority. Instead, the surgeon operates within an environment where both clinical experience and machine learning will shape clinical decisions. This shift provides a pathway to addressing many of the critical ethical implications associated with contemporary cardiac surgery (e.g., authority, accountability, and what is meant by "risk"). The historical transformation of surgical risk and the corresponding shifts in moral responsibility across successive eras of cardiac surgery are summarized in Table I.

The problem of algorithmic authority

While advances in artificial intelligence have substantially improved predictive accuracy in cardiac surgery, they have also introduced new and unresolved ethical tensions. Central among these is the increasing opacity of machine-learning systems. A major concern surrounding contemporary machine-learning systems is their limited interpretability. Complex models – particularly deep neural networks – often produce predictions without providing a clear explanation of how specific variables contributed to the result. This opacity creates a phenomenon sometimes described as algorithmic authority, where clinicians may place undue confidence in computational outputs even when the reasoning behind those outputs cannot be fully examined or validated. In such circumstances, decision-making risks are shifting subtly from human judgment toward algorithmically generated suggestions [38–41].

The emergence of algorithmic authority represents a qualitative shift in the structure of clinical decision-making. Historically, debates surrounding authority in medicine focused on the balance between physician paternalism and patient autonomy. The advancement of artificial intelligence, and the role of these technologies in society, has changed the way modern society looks at the ethical dimension of human decision-making (and those who provide healthcare) working together with machine intelligence (AI). Machine intelligence produces probabilistic output that can be interpreted by society as neutral, objective or superior to scientific. Because of that, the machine has the power to affect people's decisions without the person necessarily being aware of the influence, which is a significant risk [40, 41].

Although AI-driven tools can reduce diagnostic variability, enhance consistency, and support safety, scholars have cautioned against the phenomenon of "automation bias", whereby human expertise is diminished through habitual over-reliance on computational systems [42]. In such cases, clinicians may give disproportionate weight to algorithmic outputs, discounting contradictory clinical signs or experiential knowledge. In cardiac surgery, where intraoperative conditions can change abruptly and unpredictably, blind adherence to probabilistic forecasts may suppress intuitive, experience-based decision-making – the very essence of surgical judgment developed through years of embodied practice [43]. What is lost is not merely autonomy, but the capacity for moral discernment under uncertainty.

Beyond epistemic concerns, algorithmic authority also complicates traditional notions of accountability. As emphasized by Morley *et al*., when AI-driven recommendations contribute to patient harm, responsibility becomes distributed across multiple actors, including the surgeon, software developers, healthcare institutions, and regulatory bodies [44]. The challenge of the changing ethical dimension of healthcare is that the person has traditionally been the moral agent responsible for the outcome of their actions; thus all ethical codes assume that there is a person responsible for their moral agency. In the case of machine intelligence, there is no known person responsible for the outcome of the machine; therefore, there will always be an unknown, unidentifiable, source of moral ambiguity in relation to the ethical accountability of artificial intelligence and its impact on people's individual choice regarding life-and-death decisions.

Therefore, not only are there the positive aspects of greater precision in medical treatment by means of machine intelligence, but there is also the negative aspect of increased confusion regarding moral responsibility due to the loss of transparency in decision making. In order to create a new type of ethical framework that maintains the value of human moral agency and accountability, it will take more than developing better technology – it will take a change in the overall philosophy of creating a new ethics framework. The differences

Table II. Comparison of traditional surgical risk models and artificial intelligence–based predictive systems in cardiac surgery

Dimension	Traditional risk models (e.g., EuroSCORE, STS)	AI-based predictive systems
Primary purpose	Preoperative estimation of operative mortality and morbidity	Continuous prediction of perioperative and postoperative outcomes
Data structure	Structured, predefined clinical variables	High-dimensional, multimodal data (clinical, imaging, physiological, longitudinal)
Temporal scope	Static; calculated at a single preoperative time point	Dynamic; continuously updated throughout the care pathway
Methodological basis	Statistical regression models	Machine learning and deep learning architectures
Interpretability	High; variable contribution generally transparent	Variable; often limited due to "black box" behavior
Adaptability	Periodic recalibration using new datasets	Continuous learning and real-time model updating
Clinical integration	Established in guidelines and routine practice	Increasingly embedded in electronic health records and monitoring systems
Decision-making role	Advisory; supports but rarely overrides clinician judgment	Influential; may subtly shape or bias clinical decisions
Primary ethical concern	Risk aversion and avoidance of high-risk cases	Diffuse accountability, automation bias, opacity
Responsibility attribution	Clearly human and institutional	Distributed across clinicians, systems, developers, and institutions
Strengths	Transparency, standardization, comparability	Precision, personalization, responsiveness to change
Limitations	Limited individualization; reduced sensitivity to complex interactions	Reduced explainability; governance and accountability challenges

between traditional surgical risk models and contemporary artificial intelligence–based predictive systems are summarized in Table II.

The ethics of predictive medicine

The current emphasis on prediction is a manifestation of the society's desire to decrease uncertainty, improve outcomes and control the biological uncertainties of existence. This is particularly true in the field of cardiac surgery because of the critical nature of decision-making and the ethical responsibility to prevent harm from occurring. Yet, as Jonas famously reminded, every technological advance expands the scope of human responsibility rather than diminishing it [13]. The increasing availability of precise risk probabilities may therefore create an illusion of control, suggesting that uncertainty has been mastered, while in reality it has merely been reframed in computational terms.

AI-supported predictive medicine can unintentionally blur the distinction between statistical probability and ethical judgment. Although predictive models provide estimates of likely outcomes, these probabilities should not be mistaken for deterministic conclusions or moral guidance regarding the best course of action. Even with the best models available today, there is still a significant amount of unpredictability associated with the outcomes produced from these models when using mathematical precision to predict. The unpredictability associated with various aspects of intraoperative decision-making (i.e. the effect of provider judgement), the patient's unique capabilities to cope with stress, and the occurrence of unforeseen events, all impact ultimately upon the outcome of the surgical procedure. When we understand prediction as determinism, the ethical implications for decision making are postponed rather than remedied [40–42].

Emanuel and Wachter caution that algorithmic medicine may inadvertently privilege numerical abstraction over the relational and narrative dimensions of clinical care [45]. Because the informed consent process increasingly utilizes quantifiable morbidity and mortality estimates to inform the patient of the risks associated with a surgical procedure, we are losing sight of the non-quantifiable aspects of risk i.e. the emotional components of fear, hope, trust and vulnerability. We may provide a patient with their estimated probabilities of risk without adequately ensuring that he/she has the ability to adequately process the significance of these probabilities within the context of his/her own life experience. In such contexts, ethical communication requires more than accurate data; it demands interpretive guidance and empathic engagement.

For McKneally, genuine surgical wisdom does not consist in the elimination of uncertainty but in the capacity to act responsibly within it [15]. From this perspective, courage in the digital age is not defined by resistance to technological assistance, nor by uncritical acceptance of algorithmic output, but by discernment – the ability to integrate data-driven insight with contextual judgment, moral reflection, and professional responsibility. The surgeon's task is not to compete with predictive systems, but to contextualize them within the irreducibly human dimensions of care.

Ethically, the central challenge of predictive medicine is therefore to reconcile artificial intelligence's growing epistemic power with the preservation of human moral agency. While algorithms can assist in the decision-making process as well as enhance the capabilities of professionals in several different areas of health care, they cannot bear moral accountability or take responsibility for their actions. Moral accountability and human intentionality must remain linked. Therefore, the evolution of the practice of cardiac surgery is reliant upon the establishment of balanced paradigms that utilize computational intelligence as tools to support human intervention by way of clinical judgment without compromising ethical responsibility. This experience provides an opportunity to create an equilibrium between prudence and prediction within the present-day model of calculated courage.

Philosophical reflections on risk and responsibility

The nature of surgical risk

In surgery, risk has always been more than a statistical abstraction; it constitutes an existential condition that defines the very act of intervention. Every surgical decision involves acting in the face of uncertainty, where outcomes cannot be fully predicted and consequences may be irreversible. As Paul Ricoeur proposed, human action is intrinsically bound to uncertainty, because every decision unfolds within a horizon of incomplete knowledge and unforeseeable effects [19, 20]. Cardiac surgery, perhaps more than any other medical discipline, transforms this philosophical insight into lived reality: every incision embodies a wager between necessity and danger, intervention and restraint.

In the pre-quantitative era, as earlier sections have shown, risk was experienced primarily as a moral burden, carried by the surgeon's conscience and personal courage. Responsibility was immediate, visible, and deeply individualized. With the advent of statistical models and, later, algorithmic prediction, this moral dimension has been progressively externalized and mediated through numbers, probabilities, and technological systems. Risk has become something that can be calculated, communicated, and compared, often creating the impression that uncertainty has been domesticated.

Yet, as Jonas compellingly argued, technological progress does not diminish human responsibility; on the contrary, it amplifies it [13]. The expansion of predictive power enlarges the sphere of moral obligation, because the ability to foresee potential outcomes entails a duty to reflect on their ethical implications. In this sense, predictive tools do not absolve clinicians from uncertainty but relocate it within a more complex decision-making environment.

The modern-day cardiac surgeon is not removed, liberated or absolved from engaging in moral accountability as a result of technology. However, the surgeon has been given a more significant duty of understanding the potential and limitations of predictive algorithms as well as responsibly incorporating those predictive algorithms into his or her clinical judgment. Surgical risk will continue to be inherently human even though it can be modeled accurately. The significance of surgical risk, and its moral significance, will remain with the individual making the decision to proceed with surgery. Being aware of this tension is critical to continuous ethical agency in a world increasingly focused on calculation and prediction.

The surgeon as a moral agent

Historically, the surgeon's role has oscillated between heroism and humility, between bold intervention and sober acknowledgment of limitation. The early pioneers described in previous sections embodied a form of "calculated transgression", acting at the threshold between what was technically possible and what was ethically permissible [5]. Their courage was rooted in personal conviction and experiential judgment, and their accountability was largely self-contained, borne by the individual practitioner who both decided and acted.

In contrast, the contemporary moral landscape of cardiac surgery is markedly more complex. As Beck argues in his theory of the risk society, modernity tends to replace visible and immediate danger with systemic risk – risk that is diffuse, managed through institutions, and distributed across bureaucratic and technological structures [14]. Within such systems, individual action is increasingly embedded in networks of protocols, teams, and decision-support tools. The cardiac surgeon's responsibilities are shared among various individuals and systems, thus clouding their ethical role. The cardiac surgeon can no longer consider themselves an independent moral agent, rather they operate within the larger system of multidisciplinary teams, healthcare systems, regulatory agencies, and increasingly, computerized decision-making.

Jonas warned that such fragmentation of agency risks severing moral responsibility from individual intention, particularly in technologically advanced societies where outcomes emerge from complex systems rather than discrete acts [13]. This concern becomes especially salient in the context of AI-assisted surgery, where recommendations may be generated by opaque models that clinicians neither fully understand nor directly control [44].

Therefore, as part of the larger system of shared responsibility, the role of the cardiac surgeon has evolved away from that of the heroically autonomous individual to that of a member of a team acting as a reflective steward of the communal and technological framework of understanding, risk, and accountability. Moral agency is preserved not through isolation, but through active engagement with uncertainty, transparency about limitations, and a continued willingness to assume responsibility for decisions that no system can fully automate [45].

Courage, uncertainty, and the meaning of responsibility

Courage remains the moral center of surgical practice, yet its meaning has changed. In the mid-twentieth century, courage meant daring to operate when others would not. In the twenty-first century, courage may instead mean resisting overconfidence in technology – daring to question the algorithm and assume responsibility for human judgment [3–5].

Using Heidegger's concept of being-toward-death, one could say that the surgeon's ability to confront risk exemplifies the authentic human condition: the ability to make decisions in the presence of finality [46]. Similarly, Camus, in *The Myth of Sisyphus* [25], describes the absurd hero as one who engages in meaningful action despite the impossibility of achieving success. In this way, the surgeon embodies the same existential approach: acting without total control of the outcome and confronting an uncertain future.

The philosophy of Ricoeur further illuminates this duality: responsible action requires both conviction and prudence. In cardiac surgery, this means balancing the imperative to innovate with the humility to acknowledge limits [19, 20]. Courage is thus redefined – not as defiance of risk, but as the moral strength to bear uncertainty consciously.

From heroic individualism to ethical systems

Cardiac surgery today exists in an environment where ethics, institutions, technology have merged to dominate a large part of clinical decision making. These large systems include government regulations, quality metrics, digital platforms, algorithmic tools, all intended to mitigate the uncertainty inherent in the performance of a cardiac surgery through standardized approaches to surgery, ongoing monitoring, and feedback. As Luhmann described, such systems are self-referential: they reduce complexity by translating uncertainty into manageable categories and processes [18]. While these systems are extremely sophisticated, they do not eliminate the risk associated with the human element in cardiac surgery, the unpredictable outcomes resulting from the combination of biological variability, situational judgement, and contingent circumstance that characterize cardiac surgery.

Therefore, the ethical challenge of cardiac surgery today is not to replace the individual ethical agent with systems; rather, to reintroduce the individual ethical agent within the context of the institutional systems developed to support cardiac surgeons and their patients. While systems can guide, constrain, and support decision-making, they cannot assume responsibility or moral intent. As Jonas emphasized, ethical responsibility must extend beyond immediate outcomes to encompass long-term and intergenerational consequences – a principle that becomes increasingly salient as AI-driven technologies reshape surgical practice and influence future standards of care [13].

As these systems continue to transform, so too must the role of the surgeon evolve. The surgeon must no longer function as a mere executor of technical support; rather, the surgeon is now an ethical curator of innovation. An ethical curator of innovation evaluates the potentialities of technology, continually questions these potentialities and places them in context. As the ethical curator of innovation, the surgeon must always ensure that efficiency, precision, and predictive capacity do not become more important than empathy, accountability, and reflective judgement.

Consequently, by evaluating risks in the context of an ethical curator of innovation, we can see risk as a place where we have the opportunity to grow as ethical beings, where we can learn about our ethical intention and the capacity to evaluate technology. Preserving this space is essential if cardiac surgery is to remain not only technologically advanced, but also ethically grounded in an age of mechanized precision.

Toward an ethics of calculated courage

Re-defining courage in the technological age

Innovation and accountability have always been at the core of cardiac surgery. Courage before was interpreted as operating under extreme conditions of unknown results and embracing failure. In contrast, contemporary surgical practice confronts a different challenge. Courage today can be interpreted as intervening when the patient's best interests are at stake by deciding with known risk, quantified outcomes, algorithms, published benchmarks from peer-reviewed journals, and regulatory bodies approving interventions. Calculated courage may be defined as the capacity to act decisively under irreducible uncertainty by integrating probabilistic knowledge, experiential judgment, and ethical responsibility.

Digitalization has increased our ability to provide modern surgical techniques with more accuracy and predictability than ever; however, the increased reliance on numerical measurements includes falling victim to the loss of authority in interpreting human patient care. To practice courage within this environment requires reclaiming clinical decision-making as a profoundly human act, one that resists both technological determinism and defensive passivity. Courage, in this sense, involves the willingness to question models, to recognize their limits, and to assume responsibility for decisions that cannot be fully delegated to systems or scores [47]. The ethical position advanced in this review is captured schematically in Figure 3. The concept of calculated courage is presented as a dynamic equilibrium between human clinical judgment, predictive intelligence, and ethical humility. While artificial intelligence and statistical models enhance the precision of risk estimation, they do not replace the surgeon's responsibility to interpret data within clinical context, acknowledge uncertainty, and assume moral accountability. Calculated courage thus represents the capacity to act decisively under irreducible uncertainty, integrating technological insight with experiential knowledge and ethical reflection.

Modern surgical courage is therefore best understood as calculated – not because it seeks to abolish uncertainty, but because it consciously integrates it into ethical deliberation. Calculation provides orientation, but it does not replace judgment. As Ricoeur argued, responsible action emerges from the union of conviction and prudence: the capacity to act decisively while remaining open to reflection and doubt [20]. In cardiac surgery, this ethical posture manifests as the ability to weigh probabilistic risk models against lived clinical experience, to interpret data without

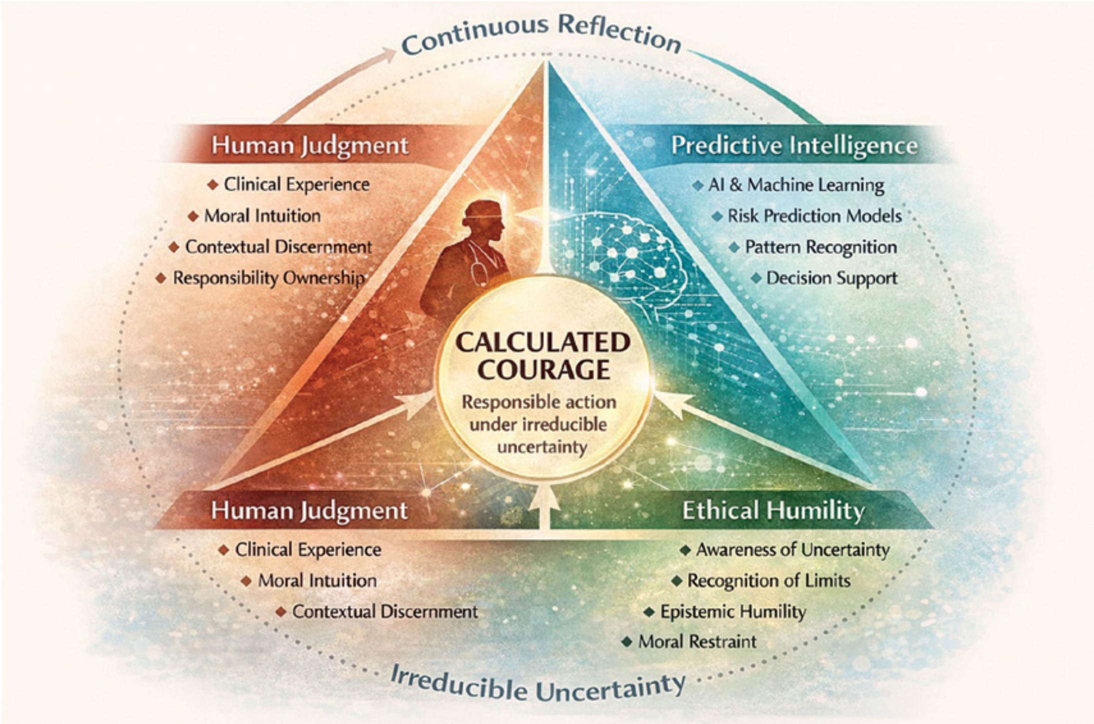

Figure 3. Calculated courage as an ethical equilibrium in contemporary cardiac surgery. This conceptual diagram illustrates calculated courage as a dynamic ethical balance between human clinical judgment, predictive intelligence, and ethical humility. Human judgment provides experiential insight, contextual awareness, and personal accountability. Predictive intelligence contributes data-driven risk estimation and pattern recognition but lacks moral agency. Ethical humility anchors decision-making by acknowledging uncertainty and the limits of prediction. Calculated courage emerges at the intersection of these domains, representing the surgeon's capacity to act responsibly and decisively within technologically mediated, yet irreducibly uncertain, clinical environments

being governed by it, and to attend not only to metrics but also to the patient's narrative, vulnerability, and values.

Under this redefined framework, courage is no longer confused with defiance or technical bravado (the bravado that comes from technological capability). Rather, courage becomes a form of moral clarity that is exercised under constraint as a commitment to perform one's duties and responsibilities in an environment that may be influenced by prediction, pressure and complexity. A calculated courage ethos (principle or belief) provides a pathway to the future for cardiothoracic surgery within the technological era by preserving the ethical agency of the practitioner and embracing the technological capabilities available through modern medical equipment.

Restoring moral agency in an algorithmic system

AI will increasingly take center stage, in surgical practice, bridging the gaps in predictive analytics and also supporting clinicians with clinical decision-support systems. The emergence of these technologies represents a shift in how we view medical decision-making. It poses a significant threat to the propriety of our profession in that it will diffuse moral agency amongst algorithms, protocols, and institutional hierarchies. Rather than having a single person responsible for every decision made in surgical contexts, there may not be a clear decision-maker. Morley *et al*. [44] and Emanuel and Wachter [45] caution that algorithmic medicine, while designed to enhance safety and efficiency, may unintentionally diminish professional responsibility by interposing technological systems between judgment and action. This phenomenon, sometimes described as "moral buffering", occurs when reliance on automated recommendations attenuates the perceived need for individual ethical reflection.

In order to mitigate this risk, any use of AI in surgical practice should be enveloped in an explicit governance framework to ensure accountability, transparency, and the audit trails of decisions [48]. Therefore, these frameworks should outline the responsibilities of the clinician, developer, institution, and regulatory body, and the algorithmic outputs should always be viewed as support rather than authorship. Without such protections, we risk losing professional integrity and patient trust due to the diffusion of responsibility.

To thrive in this environment, surgeons must exercise calculated courage and take back their interpretive responsibilities. This involves critically engaging with algorithmic recommendations, recognizing their assumptions and limitations, and remaining willing to override them when clinical context or moral judgment so requires. As Jonas argued, the ethics of technological civilization depend fundamentally on foresight – on an awareness of how present decisions shape future practices, norms, and consequences [13]. In this sense, the cardiac surgeon emerges not only as a technical expert, but also as a steward of innovation, mediating thoughtfully between human judgment and computational intelligence to preserve ethical agency in an increasingly algorithmic system.

Ethical humility and the limits of prediction

Although there is remarkable precision and breadth of the predictive analytics available in the present day, it must be remembered that uncertainties abound with biological complexity; the variability of individuals; and the synergistic effects of other environmental variables. Thus, no matter how sophisticated a model may be, it cannot encapsulate or replicate the continuous dynamic of physiology, environment, and human response that constitutes surgical practice. As Beck cautioned, the modern preoccupation with safety may evolve into a culture of "safetyism", in which deviation from standardized pathways is discouraged and innovation becomes constrained by fear rather than guided by judgment [14]. In such settings, algorithmic overconfidence risks generating false reassurance, masking residual uncertainty behind the appearance of control and precision [49].

Ethical response to AI is not to stop using technology, but to develop epistemic humility; that is, an understanding of the inherent limitations of our ability to predict certain events and the use of limited evidence, or knowledge, to generate those predictions. In AI-assisted cardiac surgery, ethical humility adds a critical view on the authority of algorithms and indicates to clinicians that the output of predictive algorithms is a best guess of how patients will respond and not an absolute fact. Ethical humility provides a buffer against physicians placing too much importance on the statistical accuracy of AI algorithms when making medical decisions.

Philosophy supports the concept of ethical humility in medicine. Heidegger's being-toward-death discusses the fact that all people eventually die and that we are obligated to act when we feel uncertainty or limitation [46]. Camus' Absurd Hero epitomizes that a person can take actions that have meaning and value even if there is no certainty or ultimate control [25]. Ethical humility, therefore, is about respecting the unpredictability of patients (and how they will respond) and accepting the notion that every individual patient, heart, and surgical procedure cannot be completely controlled.

The concept of humility provides a foundation for how to conduct practice; it does not diminish or undermine the professional authority of a surgeon, but establishes that authority. Surgeons' ability to recognize the limits inherent in their ability to predict things allows them to create the ethical space in which they will make their moral decisions, innovate, and be compassionate to their patients/clients. As such, ethical humility is a prerequisite to the calculated courage that accompanies the technological precision of surgical care; without ethical humility, the technological precision of surgical care will not match the realities of how we care for each other.

Integrating systems, virtues, and futures

We as professionals must develop an ethical paradigm that can combine increasingly sophisticated technology with ethical depth and understanding. As predictive systems, automation, and artificial intelligence move towards becoming central to surgical care, the need for ethical reflection cannot remain a secondary consideration. Hospitals, professional societies, and academic centers must actively embed virtue-based ethics – such as reflection, empathy, and accountability – into both surgical training and AI governance structures [50, 51]. Technical proficiency alone is insufficient; as McKneally has emphasized, the cultivation of surgical wisdom is as essential as the mastery of operative skill [15].

In developing a paradigm for ethical calculated courage, we must, through our reflection on the interplay of ethics and technology, articulate three principles that are mutually dependent upon one another. First, epistemic clarity requires a clear understanding of the capabilities and limitations of predictive technologies, we must resist uncritical acceptance of algorithmic authority. Second, moral responsibility requires that we maintain human accountability in ever-complex algorithmic systems, and that ethical ownership of decision-making in respect to patient care persists, rather than being supplanted by algorithmic procedures. Third, ethical humility affirms the need to act decisively and also to acknowledge the unavoidable presence of uncertainty as an essential condition for biological life and the caring of other humans.

The aforementioned principles modify how we think of surgical professional conduct in relation to digital technologies and therefore have changed the position of "the surgeon" from a pure operator of sophisticated technological tools to an ethical agent who employs judgement and caution to guide patients through times of uncertainty. Furthermore, risk should not only be viewed as something to be mitigated; it has become a shared moral space where courage, empathy, and the ability to assess one's own values coexist [4, 5, 18].

Thus, as we look at the area of cardiac surgery, it has consistently been, at its very essence, both an example of technological advancement and an incredible showing of what the application of science and the principles that provide for human welfare can create together.

Discussion and future perspectives

This review has described the history, epistemology and ethics of cardiac surgery, tracing this development through the exemplary courage displayed by early pioneers and their ability to apply moral principles in practice through the present day's application of quantitatively defined risk using CSS models. A major thread running through all of these developments is that with each technological advancement, uncertainty was increased rather than eliminated, and the ways in which we construct, define, and ultimately allocate moral responsibility for risks associated with surgical interventions continues to transform.

Surgeons today define their ethical and professional identities at the intersection of human judgment and artificial intelligence. Increasingly, the applications of predictive analytics and decision support are shaping how clinicians formulate clinical reasoning, how they communicate risk, and how they will be held accountable at the level of institutions; and furthermore, the ways in which technology can enhance a surgeon's ability to accurately assess a patient's risk of death or complications, will redefine the boundaries between expertise, autonomy, and governance. Dr. Eric Topol has indicated that the proper use of artificial intelligence has the capacity to enhance the standard of clinical care when implemented in a manner that protects the agency and trust of the clinician [52]. Similarly, Shahian and Normand have emphasized that risk models and performance metrics, while essential for quality improvement, inevitably shape behavior and professional norms in ways that extend beyond their technical intent [53].

This transformation reflects a broader shift in medicine toward data-driven decision-making, in which numerical representations of risk acquire normative authority. As indicated by Emanuel and Wachter, algorithmic approaches to medicine are generating new ethical issues concerning accountability, transparency and the maintenance of professional accountability for the application of algorithmic approaches to medical care [45]. In cardiothoracic surgery, where the effects of surgical decisions are often irreversible, the introduction of predictive approaches to the assessment of patients' risks will exacerbate the historical challenges faced by physicians as they seek to balance their desire for innovation with their commitment to caution, their desire to develop standard practice with their obligation for personal clinical judgment, and their commitment to a safe outcome with their desire to demonstrate the moral courage required to take on risky surgery.

Thus, this is an analysis of the primary ethical challenges presented by the shift from traditional to algorithmic risk, and how these ethical issues can be addressed moving forward. Rather than viewing artificial intelligence as a break from surgical tradition, we believe that artificial intelligence is a continuation of the long-standing tension between the technological capabilities of surgeons and the ethical obligations of surgeons. An understanding of the historical tension between the technological advancements in cardiac surgery and the ethical challenges facing surgeons will be essential to building the necessary regulatory structures, educational policies, and professional norms to ensure that the development of these innovations is consistent with the core human values that underlie the practice of cardiac surgery.

Moral agency and systemic delegation

One of the most significant challenges in modern cardiac surgery is the progressive diffusion of moral agency. In the past, way before the invention of artificial intelligence or machine learning, pioneers of surgical practice made all of their own clinical decisions based on how ethical or feasible the procedure was. They were responsible for all of their decisions and all clinical aspects, and this responsibility was based on their personal belief, judgement and experience. Today, the practice of cardiac surgical care happens in the context of various forms of institutionalization, regulatory compliance and technological infrastructure, with responsibility now increasingly being divided among multidisciplinary teams of highly skilled professionals, hospital organizations, metrics of performance, and the use of algorithms in decision-making. The level of delegation of this responsibility may change even further with the advent of artificial intelligence into the clinical workflow of the surgical profession.

Most contemporary AI systems function as "black boxes", generating outputs that may equal or even outperform human reasoning, yet lack transparent or readily interpretable rationales. While such systems can enhance consistency and predictive accuracy, their opacity introduces new ethical tensions. As Emanuel and Wachter have described, this dynamic can result in "moral buffering", whereby accountability is subtly displaced from individual clinicians to technological systems or institutional processes, weakening the link between decision-making and moral ownership [45].

In cardiothoracic surgery, where decisions frequently involve irreversible consequences, the ethical implications of such displacement are especially consequential. Scholars have emphasized that the deployment of AI in high-risk medical domains must be accompanied by robust ethical governance, including mechanisms for traceability, auditability, and human oversight [54]. Morley *et al.* [44] and Horgan *et al.* [55] similarly argue that transparency and explainability are not optional technical features, but ethical prerequisites for responsible AI implementation. Without these safeguards, algorithmic recommendations risk acquiring de facto authority without corresponding accountability.

Empirical and conceptual work in medical ethics further supports this concern. London has argued that opaque algorithmic systems threaten professional responsibility by undermining clinicians' capacity to justify and defend their decisions [56]. Likewise, Grote and Berens have highlighted that meaningful human control over AI systems is essential to preserve moral agency in safety-critical domains such as medicine [57]. In the surgical environment, it is necessary for the surgeon to maintain the ability to assess algorithm-generated output critically instead of accepting them as absolute truths or unquestionable authority.

Therefore, the role of the cardiac surgeon is not to eliminate the use of algorithms but to avoid the practice of relying solely on the logical conclusions made by algorithms. Thus, "calculated courage" is found in maintaining interpretive power and moral responsibility while utilizing technological devices effectively. The surgeon must remain the final moral agent – capable of integrating algorithmic insight with contextual judgment, patient values, and professional accountability. Only through this active engagement can systemic delegation coexist with the preservation of ethical agency in contemporary cardiac surgery [58].

The illusion of certainty and the persistence of uncertainty

Predictive analytics promise accuracy, anticipation, and control, yet their growing influence risks fostering an illusion of certainty in domains that remain inherently uncertain. As Beck warned, the modern pursuit of absolute safety can evolve into a culture of "safetyism", in which procedural compliance and technical assurance displace moral judgment and reflective decision-making [14]. In cardiac surgery, where biological variability and intraoperative complexity are irreducible, no algorithm, however sophisticated, can fully eliminate uncertainty. The danger lies not in prediction itself, but in the assumption that prediction equates to mastery.

Overconfidence in algorithmic outputs may generate false reassurance among clinicians and contribute to progressive deskilling, particularly when decision-support systems are treated as authoritative rather than advisory [59–61]. Research shows that automation bias is common in safety-critical environments such as medicine, where clinicians tend to rely more on automated system suggestions than their own clinical judgment [62]. When clinicians rely on predictive systems too much, they may lose the ability to detect unusual patient presentations, creatively deal with unforeseen events, or dispute incorrect predictive system outputs. This is especially problematic in the field of cardiac surgery, where the dramatic physiological changes that occur during surgery can require a healthcare provider to be aware of conditions that cannot be predicted from preoperative or real-time data.

Many clinical studies have been undertaken recently to clarify the potential promise of these predictive technologies and also their limitations. Using technology such as a machine-learning based hemodynamic monitoring system (e.g., the hypotension prediction index, (HPI), used in the field of cardiac anesthesia) has shown improvement in the ability to effectively and successfully control blood pressure during surgery when utilized in a controlled trial setting. For example, randomized studies have shown reductions in hypotensive episodes when clinicians proactively responded to HPI alerts [63]. However, subsequent investigations revealed variable effectiveness across patient populations, surgical contexts, and institutional settings, highlighting challenges related to generalizability and clinical integration [64]. These findings underscore that predictive systems are highly context-dependent and that their performance is contingent upon appropriate interpretation and human response.

Beyond technical limitations, these observations reaffirm a deeper epistemological point: algorithms do not abolish uncertainty; they reframe it. As Kelly *et al.* have argued, the translation of machine-learning models into clinical practice often exposes gaps between statistical performance and real-world utility, particularly when sociotechnical factors are neglected [65]. Similarly, Wynants *et al.* have cautioned that even high-performing predictive models may fail when deployed outside their development context, reinforcing the need for continuous validation and skepticism toward claims of certainty [66].

In this light, Ricoeur's ethical insight remains highly relevant. Responsible action, he argued, does not consist in eliminating uncertainty, but in acting prudently within it – balancing knowledge with humility, and conviction with reflection [20]. Thus, the ethical duty of a cardiac surgeon is not to use technology to avoid uncertainty, but rather, to acknowledge and accept responsibility to interpret it correctly. Even when the predictive tools are available to assist clinical judgment, they will never replace the moral responsibility that will always be necessary when dealing with the unpredictability associated with human life.

Transparency, trust, and the doctor–patient relationship

The integration of artificial intelligence into cardiac surgery does not only reshape clinical decision-making; it also alters the moral fabric of the doctor–patient relationship. Traditionally, surgical risk has been communicated through narrative explanation, professional judgment, and empathic dialogue. Risk assessment in the modern-day presentation still remains an evolving practice, yet today the presentation of risk has been replaced with numerical estimates and algorithmically generated probabilities. This can lead to an increase in the ability to analyze risk accurately, however this focus on numerical estimates can also be detrimental to the patient's understanding and emotional response to clinical uncertainty. Meaningful informed consent is not obtained through disclosure alone, as emphasized by Hanson and Pitt, but through open dialogue that allows patients to place the information obtained in the context of their own values, beliefs, fears and expectations [34].

When an algorithmic tool is being used within the clinical space, the ethical requirements for informed consent change due to the need to educate the patient not only on the risks and benefits of the procedure they are considering but also about how the use of artificial intelligence may impact how the provider determines whether or how often they recommend a certain treatment to a particular patient. This includes clarity regarding the degree of human oversight, the advisory nature of algorithmic assistance, and the inherent limitations of predictive models [44, 55, 67]. Without such contextual explanation, numerical risk estimates may be misinterpreted as deterministic truths rather than probabilistic guidance, potentially undermining patient autonomy. Research on risk communication has long demonstrated that numerical data alone are often poorly understood and can mislead rather than inform when not carefully translated into accessible terms [68].

Empirical work on shared decision-making further underscores the importance of interpretive mediation. Elwyn *et al*. have shown that trust and patient engagement are strengthened when clinicians actively contextualize probabilistic information within meaningful narratives that reflect patients' lived experiences and priorities [69]. Conversely, uncontextualized statistical framing may increase anxiety or foster false certainty. This challenge is amplified in AI-assisted care, where the opacity of algorithms complicates explanation. Watson *et al.* have argued that clinical trust in machine learning depends not merely on technical accuracy but on the capacity of clinicians to explain how and why algorithmic recommendations are used [70].

Transparency, therefore, cannot be reduced to technical explainability alone. A review by Brown *et al.* on transparency in cardiac surgery underscored that openness enhances trust only when accompanied by compassion, professional accountability, and contextual interpretation [33]. Algorithmic transparency must thus be paired with ethical translation: surgeons interpreting predictive outputs not as authoritative verdicts, but as one source of insight among many, framed within the patient's unique clinical and personal context. As Topol has argued, the promise of artificial intelligence lies not in replacing the human relationship, but in restoring time, empathy, and attentiveness to patient care [52]. At the same time, Grote and Berens emphasize that preserving meaningful human control over algorithmic systems is essential to sustaining trust in high-stakes medical domains [57].

Patient-centered research further supports this view. Studies on patient attitudes toward medical AI suggest that trust is contingent on the visible presence of human judgment and accountability; patients are often resistant to AI involvement when it appears to displace clinician responsibility rather than support it [71]. Taken together, these findings indicate that trust in the doctor–patient relationship is not generated by data alone, but by the assurance that technology remains subordinate to human care.

The ethical use of AI in assisting with cardiac surgery means the need for transparency in the decision-making process. This will require the clinician to act as a bridge between the computational insight provided by an algorithm and the understanding that the patient has of his/her condition; predictive medicine must also be rooted in intuition, understanding, and accountability for medical professionals.

Validation, safety, and implementation

As the technology continues to advance, and with appropriate governance and validation of AI technology, the relational component of providing quality surgical care should be enhanced rather

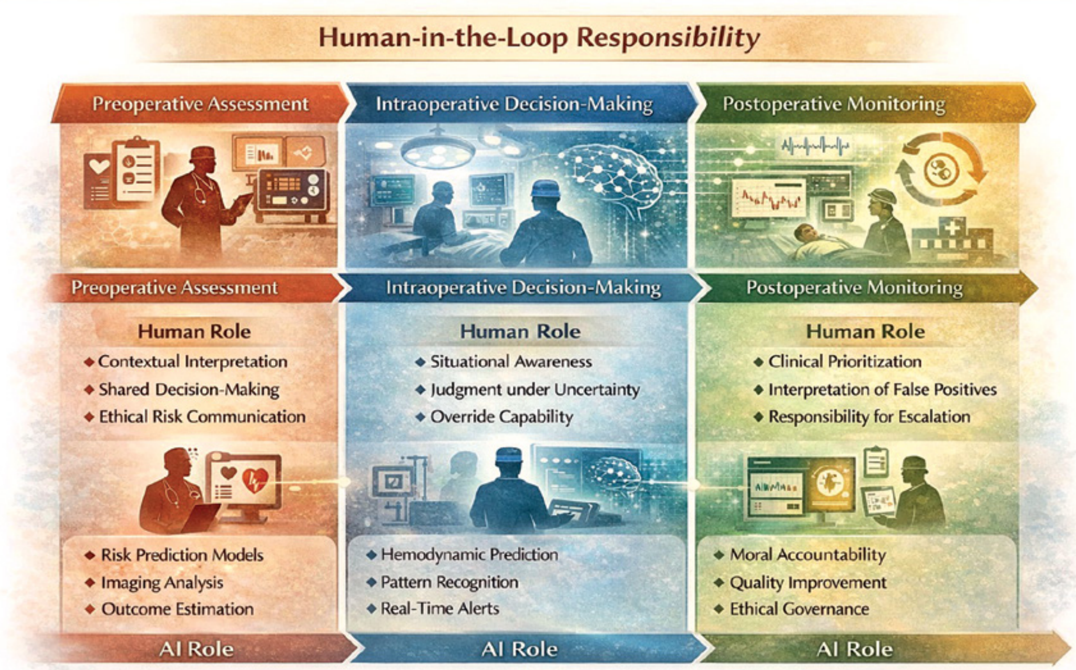

Figure 4. Decision-making in contemporary cardiac surgery: Human–AI co-piloting across the surgical timeline. This schematic diagram illustrates the integration of artificial intelligence across the preoperative, intraoperative, and postoperative phases of cardiac surgery within a human-in-the-loop framework. Predictive systems support clinical care through risk estimation, imaging analysis, real-time monitoring, and outcome analytics. At each stage, however, clinicians retain interpretive authority, contextual judgment, and moral accountability, including the capacity to override algorithmic recommendations. The model emphasizes co-piloting rather than automation, highlighting that responsibility for clinical decisions remains fundamentally human despite increasing technological mediation

than diminished through advances in technology. Many published algorithms have been derived from retrospective datasets, trained in single institutions, or evaluated only through internal validation. As a result, relatively few have undergone prospective clinical testing, external validation across diverse populations, or formal regulatory assessment [43, 55]. This gap between technical performance and clinical readiness represents one of the major barriers to responsible implementation. The practical implications of this ethical framework are illustrated in Figure 4, which depicts a human–AI co-piloting model across the surgical timeline. While artificial intelligence contributes predictive analytics, real-time monitoring, and pattern recognition at each phase of care, interpretive authority and moral responsibility remain anchored in the clinician. This human-in-the-loop approach emphasizes that algorithmic systems function as decision-support tools rather than autonomous agents, ensuring that accountability is preserved throughout preoperative assessment, intraoperative decision-making, and postoperative management. The ethical challenges introduced by AI-assisted decision-making, along with corresponding human responsibilities across the surgical timeline, are summarized in Table III.

The experience gained from traditional risk modeling remains instructive. As Nashef *et al.* demonstrated in the development and iterative refinement of EuroSCORE, model credibility depends not only on discrimination, but also on reproducibility, calibration, and continuous updating across different clinical contexts [8]. These principles are equally – if not more – essential for machine-learning models, which are vulnerable to dataset shift, overfitting, and performance degradation when deployed outside their development environment. Methodological research has repeatedly shown that models performing well in development cohorts may fail when externally validated, underlining the necessity of independent testing before clinical adoption [72].

To achieve the safe integration of AI into existing practice, additional pathway evaluation mechanisms are needed that span the technical, clinical and ethical dimensions of application in cardiothoracic surgery. In this regard, it has been proposed that ethical frameworks will augment the measures of conventional performance by including related issues such as transparency and explainability, as well as addressing issues of bias and accountability (in addition to predictive accuracy). Such frameworks recognize that safety in AI-assisted surgery is not solely a function of

Table III. Ethical challenges and human responsibilities across the cardiac surgical timeline in AI-assisted care

Surgical phase	AI contributions	Human responsibilities	Key ethical risks	Ethical safeguards and mitigation strategies
Preoperative assessment	Risk prediction, imaging analysis, outcome estimation, patient stratification	Contextual interpretation of predictions, patient-centered risk communication, shared decision-making, informed consent	Over-reliance on numerical risk scores, deterministic interpretation of probabilities, erosion of patient autonomy	Narrative-based risk explanation, clinician-led consent process, explicit acknowledgment of uncertainty
Intraoperative decision-making	Real-time physiological monitoring, predictive alerts, pattern recognition	Situational awareness, judgment under uncertainty, override of algorithmic recommendations, accountability for action	Automation bias, delayed human response, suppression of experiential judgment	Clear override authority, continuous human supervision, training in critical AI engagement
Postoperative monitoring	Trend detection, early warning systems, complication prediction	Clinical prioritization, validation of alerts, proportional response to warnings	Alert fatigue, false positives, diffusion of responsibility	Clinical validation protocols, escalation criteria, human-led decision confirmation
System-level learning and governance	Outcome analytics, performance benchmarking, model retraining	Ethical oversight, accountability attribution, governance of deployment and use	Moral buffering, opacity of responsibility, institutional blame shifting	Human-in-the-loop governance, transparency requirements, auditability, ethical review structures

algorithmic precision, but of how systems interact with human users and institutional workflows [73]. Without these safeguards, even technically robust models may introduce new forms of risk.

The advent of AI-assisted tools and techniques that utilize machine vision, motion tracking and intraoperative data analysis in cardiothoracic surgery offers great promise for improving precision with respect to surgical techniques, assessing the skill of surgeons, and enhancing the process of training new surgeons. Early studies suggest that these technologies can augment performance and reduce variability, provided that human oversight remains central and that AI outputs are interpreted as supportive cues rather than prescriptive commands [74, 75]. These findings reinforce the importance of maintaining the surgeon's interpretive authority within technologically augmented environments.

In today's cardiothoracic surgery environment, it is critical that any algorithms being integrated into the surgical process are based upon a "co-piloting" philosophy. In this way, AI is an assistive partner rather than an autonomous decision-maker. This philosophy ensures that human moral agency is preserved and also maximizes the computational strengths inherent in AI, so that all responsibility for clinical decisions continues to be assigned to individual human practitioners. Both regulatory agencies and professional societies are becoming increasingly involved with the implementation of AI-based medical devices. Thus, to continue to promote advances in the fields of surgery, it is necessary to align the standards for validation with the principles of ethical governance to ensure that the development of new technologies does not negatively impact the safety of patients or the integrity of the profession [76].

From a clinical perspective, the framework of calculated courage offers practical guidance for surgeons navigating AI-assisted decision-making. By positioning predictive systems as decision-support tools rather than authoritative agents, clinicians can preserve interpretive judgment, maintain meaningful informed consent, and retain moral accountability across the surgical timeline. This human-in-the-loop approach supports responsible innovation while safeguarding professional agency and patient trust in increasingly data-driven clinical environments.

Future perspectives

Explainable and transparent AI

The development of interpretable models, commonly referred to as explainable artificial intelligence (XAI), is essential for maintaining clinician trust, accountability, and safe clinical adoption [77, 78]. Transparent algorithms allow surgeons to understand the factors influencing predictions, facilitate ethical and regulatory review, and enable meaningful clinical contestability when algorithmic outputs conflict with human judgment. Moreover, explainability has been linked to improved error detection and mitigation, particularly in high-risk clinical environments, thereby strengthening patient safety [79, 80].

Integrating ethics from design to deployment

The ethical basis for any AI system must not be developed once the system has been implemented, but rather maintained throughout the life cycle of development, validation and implementation. Horgan *et al*. [55] and Emanuel and Wachter [45] illustrate the importance of having multidisciplinary co-design teams which include ethicists, data scientists, clinicians, and patients as soon as possible in order to identify any hidden biases, value conflicts, or unintended consequences. Such participatory approaches align technological innovation with societal values and have been shown to improve acceptance and legitimacy of AI tools in healthcare settings [81].

Moral reflexivity and education

The next generation of cardiac surgeons must be trained not only in data interpretation and technical proficiency, but also in moral reasoning about technology, automation, and responsibility. As McKneally stresses, surgical wisdom must evolve to include ethical literacy regarding AI-assisted decision-making and the limits of prediction [15]. Educational curricula that integrate ethics, systems thinking, and reflective practice alongside technical training are increasingly recognized as essential for preparing clinicians to navigate algorithmically mediated care [82].

Continuous validation and regulation

AI systems are dynamic and can deteriorate in performance due to changes in data distribution, as well as become subject to bias or other safety issues that were previously unknown. Therefore, these systems need to be monitored continuously once they have been deployed to perform optimally; this will entail auditing and recalibrating. Evaluation of AI systems on a prospective basis (similar to what is done with pharmaceutical phase IV trials) has been suggested as one method for conducting long-term evaluation of AI technology; it would assist with early identification of any adverse effects of a particular application of AI technology and maintain performance monitoring at a mass scale or organizational level [83].

Human oversight as ethical core

It is important to note that while technology evolves, it cannot replace the surgeon as the ultimate decision-maker and accountable person in this process. As noted by Jonas, the increase in the use of technology will not lessen your responsibility as the surgeon; rather, it will add to your responsibility [13]. For this reason, future regulations and systems for managing AI-generated insights must clearly specify how they fit into clinical practice; they should not dictate how physicians conduct their work but serve as an aid in decision-making. Maintaining this principle is essential for ensuring that accountability, trust, and ethical practices are upheld throughout the surgical discipline.

Virtue-based institutional culture

In addition to technical safeguards, the environment of hospitals and educational training programs must be established where moral dialogue, ethical contemplation and mentoring are an integral part of surgical education and the development of surgical professionals. Ricoeur’s concept of reflective responsibility [20] and Heidegger’s thought of authentic action that is grounded in the awareness of one’s own finitude [46] suggest that, in order for ethical practices to flourish, they should not only rely on skills or competencies, but rather on the ongoing integration of reflection with action.

Digital twins and closed-loop systems

The advent of emerging technologies, such as patient-specific digital twins and closed-loop perfusion/hemodynamic control systems, has the potential to transform the future of cardiac surgery as well as the perioperative care [12]. The promise of these solutions to provide unparalleled personalization and automation raises new ethical issues which go beyond just the individual human-machine interface-scale accountability, data governance, and accountability in an interconnected technological ecosystem. It will be critical to anticipate and to develop methods to address these ethical challenges as these technologies come closer to being implemented clinically in the future.

Concluding remarks

Over the last century, cardiac surgery has evolved significantly in how we manage risk; how risk was formerly managed by a surgeon based upon their intuition, experience and courage, has now become a computationally driven process based upon predictive analytics and algorithms.

When we compare how risk is managed today (computationally driven) vs. historically (by a surgeon), although technology is taking over the management of risk, moral responsibility continues to be a human responsibility. No matter how "advanced" the technology is, the moral burden of making decisions regarding when and how to intervene on behalf of a patient remains with the clinician making the decision.

If we want to see cardiac surgery develop successfully into a future with advanced technology we need to create a way to give clinicians a structure of both technical precision and human judgment. Predictive technologies can help identify patterns, improve risk estimates and facilitate decision-making; however predictive technologies do not have the ability to take on the burden of moral responsibility for each patient's unique life. As multiple scholars have emphasized, the central challenge of artificial intelligence in medicine lies not in its accuracy alone, but in preserving accountability, trust, and professional integrity in increasingly automated environments [84, 85].

Within this context, the concept of calculated courage offers a guiding ethical orientation. Qualified courage does not ignore the uncertainty that comes with medicine, and it also does not succumb to the idea that technology should determine the way a clinician practices medicine. Qualified courage is the ability for a clinician to take responsibility for their decisions when presented with complex data. Qualified courage is the combination of probabilistic knowledge and the experiential wisdom of the clinician, along with ethical reflection and compassion. Qualified courage means taking responsibility for how the clinician interprets and applies data about a patient's medical conditions.

In the age of artificial intelligence, cardiac surgeons must be equally committed to both technical proficiency and ethical awareness. Technologically advanced devices will enhance the accuracy with which machines are able to perform complex tasks, however, these machines cannot replicate or substitute for the combined power of human judgment, empathy, and ethical reasoning. In order to ensure that advances in technology will be accompanied by corresponding ethical growth, it will be essential for cardiac surgeons to understand that their role is more profound than creating longevity through innovation; cardiac surgeons also need to care for people when they are at their most vulnerable [86–94].

Limitations

This review, while broad in scope and depth, has certain limitations that should be acknowledged. This publication employs an interpretative/narrative method (historical, ethical and philosophical) to study how the fields of surgery, bioethics and philosophy intersect, instead of using a systematic/quantitative method. The result of producing deep, analytically comprehensive narratives can help create a better picture or awareness of the fields being studied, but the process increases the likelihood of bias from selections made when creating the narratives as well as reducing the ability to reproduce results and find them in systematic reviews and meta-analyses.

Interdisciplinary methodology combines interpretational reasoning with empirical data. Therefore, the results of this manuscript do not present proven or statistically supported hypotheses; rather, they present a collection of literature and philosophical paradigms, along with an exploratory review of the concepts of risk, accountability and moral agency. Thus, this document serves as a platform upon which to gain an understanding of these concepts, but it does not encompass every single or complete study performed to date in these fields.

Similarly, because many of the studies/technological advancements discussed herein are only in an initial/investigative phase of research, few AI/CV models of cardiac/thoracic surgery have been validated and continue to be developed solely via retrospective analyses or as part of a researcher's experience within individual centers. Thus, while this manuscript has pointed out and highlighted current ethical and procedural trends, the extent to which these will continue to develop safely, effectively or with a positive influence on practice has yet to be evaluated.

A further limitation lies in the normative nature of ethical reasoning. The discussions of accountability, transparency, and virtue ethics are interpretive and theoretical rather than empirically tested. This means that while ethical recommendations are grounded in established philosophical principles, their practical implementation will depend on evolving institutional frameworks, technological capabilities, and regulatory oversight.

Finally, the philosophical perspective adopted in this work draws predominantly from Western traditions of thought, including phenomenology and deontological ethics. Perspectives rooted in other cultural or relational paradigms of medical morality are not extensively represented here but would provide valuable future contributions to a more pluralistic understanding of surgical ethics in the AI era.

Although this review has limitations in that it does not address all historical issues concerning cardiac surgery nor provide solutions for all current and future ethical dilemmas surrounding the practice, it does provide a unified and cohesive framework that relates the development of cardiac surgery throughout history to the ethical challenges facing surgeons today. In addition, this framework encourages practitioners to reflect on how they define courage, responsibility and wisdom in the context of their profession when making surgical decisions using intelligent systems.

Conclusions

The ongoing dialogue regarding innovation and responsibility has progressed over time from the "heroic" era of open-heart surgery pioneers to the present reliance on AI for data-driven precision. In recent years, the way we measure and manage surgical risk has changed due to technological advances; however, regardless of the advances made, it is conclusive that the moral weight of surgical decision-making will continue to exist. In this rapidly evolving environment, the ultimate challenge for surgeons will be to maintain ethical agency and discernment when faced with ever-increasing levels of technological complexity such as systems of prediction and automation. The idea of "calculated courage" captures the essence of how surgeons must conduct themselves with technical competence, prudent judgement and humility in today's environment. This requires surgeons to take advantage of the benefits provided by AI, yet maintain the benefit of human judgement which gives surgical practice its moral authority. Future research should explore how calculated courage can be operationalized in surgical education, AI governance frameworks, and multidisciplinary decision-making models. The future of cardiac surgery will not only rest on the intelligence of the technologies but also on the wisdom, integrity and courage of the people using them.

Funding

No external funding.

Ethical approval

Not applicable.

Conflict of interest

The authors declare no conflict of interest.

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