

Review Article

Digital Twin Models for Personalized Surgical Risk Assessment

Mette Fischer^{1*}, Marek van der Meer² and Claire Steiner³

¹Department of Anesthesiology and Pain Management, Nordfjord University of Health Sciences, Norway

²Department of Surgical Sciences, Northmoor School of Anesthesia, United Kingdom

³Department of Surgical Sciences, Northmoor School of Anesthesia, United Kingdom

ABSTRACT

Population-derived surgical risk calculators such as the ACS NSQIP tool estimate a patient's complication risk from the aggregated outcomes of similar patients, while digital twin modeling proposes instead building a continuously updated, patient-specific computational representation of an individual's physiology to simulate how that patient will respond to a proposed operation.

This review examines where that ambition currently stands in perioperative and surgical practice, from the architectural proposals for a multi-organ perioperative human digital twin to its most mature clinical application in cardiac and structural heart surgery.

Digital-twin-guided modeling of patient-specific atrial substrate has been used to stratify and prevent postoperative atrial fibrillation after cardiac surgery, and patient-specific anatomic simulation now informs device selection and procedural rehearsal in transcatheter and aortic interventions, representing the field's most externally grounded applications to date.

Extension to trauma, general, and noncardiac surgery currently takes the form of continuously updating multimodal predictive analytics rather than the fully mechanistic multi-organ twins described in foundational proposals, and is constrained by the difficulty of acquiring longitudinal multimodal patient data, the computational cost of clinically timed simulation, and the absence of validation and regulatory pathways suited to continuously adapting models.

We conclude that digital twin methods are a promising complement to, rather than yet a replacement for, externally validated population risk calculators in most surgical settings, with cardiac and structural heart applications furthest along the path toward routine clinical use.

Keywords: digital twin; surgical risk assessment; perioperative medicine; personalized surgery; predictive analytics

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Corresponding Author: Mette Fischer

E-mail Address: m.fischer@nuhs.no

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INTRODUCTION

Surgical risk prediction has long relied on population-derived scoring systems: the ASA physical

status classification, the Revised Cardiac Risk Index, and more granular calculators such as the American College of Surgeons National Surgical Quality Improvement Program (ACS NSQIP) risk calculator, which regresses a patient's demographic and comorbidity variables against outcomes pooled from hundreds of thousands of prior operations. These tools have real value, and successive validation studies have confirmed that the NSQIP calculator predicts postoperative complications with reasonable discrimination across colorectal, laparotomy, and orthopedic trauma populations [1,2,3,4]. But a calculator built from population averages necessarily answers a population question — what happened, on average, to patients who looked like this one — rather than a mechanistic question about how this specific patient's physiology will actually respond to this specific operation.

The digital twin concept, borrowed from aerospace and manufacturing engineering, proposes a different architecture entirely. Rather than a static regression equation, a digital twin is a continuously updated, patient-specific computational model — built from imaging, genomic, physiological, and real-time monitoring data — that simulates how an individual's organs and systems will behave under a defined intervention, and that keeps recalibrating itself as new data about that patient arrives. Applied to surgery, the idea is to move from asking "what is this patient's percentile risk of a given complication" to asking "what does a virtual instantiation of this patient's cardiovascular, coagulation, or wound-healing physiology predict will happen if we perform this specific procedure this specific way, and how does that prediction change if we adjust the plan" [5,6].

This review surveys where that ambition currently stands in perioperative and surgical practice: what has been built and validated, what is closer to concept demonstration than clinical tool, and where the evidentiary and implementation gaps remain widest. We organize the discussion around the perioperative human digital twin as a unifying architecture, its cardiovascular applications in cardiac and structural heart intervention, its extension into trauma and general surgical risk stratification, and the practical barriers — data, computation, validation, and regulatory — that stand between the current state of the field and routine clinical deployment.

THE PERIOPERATIVE HUMAN DIGITAL TWIN AS AN ARCHITECTURE

The clearest articulation of what a perioperative digital twin should actually contain comes from proposals describing a multi-organ physiological model — cardiovascular, respiratory, renal, and coagulation compartments coupled together — that is parameterized from a given patient's preoperative labs, imaging, and monitored vital signs, and that can then be driven forward in simulated time through a

proposed anesthetic and surgical plan before the actual operation occurs [7]. The appeal of this architecture is that it does not treat "surgical risk" as a single output number; it generates a trajectory of predicted hemodynamic, respiratory, and metabolic states throughout the case, which in principle allows the anesthesia and surgical teams to test alternative plans — a different fluid strategy, a different anesthetic technique, a staged rather than single-stage procedure — against the same simulated patient before committing to one in the operating room.

That same architecture is what underlies the more recent framing of digital twins as central to an era of genuinely personalized surgery, in which the operative plan itself, not just the risk estimate attached to it, is derived from patient-specific simulation rather than from guideline-based population reasoning [5]. Reviews taking stock of where this stands describe digital twins moving surgical planning from a reactive posture — responding to complications as they occur — toward a genuinely anticipatory one, in which adverse trajectories are identified in simulation and the plan is adjusted before the patient ever enters the operating room [6]. It is worth being explicit, though, that most of what is described in this literature remains architectural and conceptual: full, continuously updated multi-organ twins validated against actual perioperative outcomes at any scale do not yet exist, and the honest state of the field is closer to component-level proof of concept than to an assembled, clinically deployed system.

A comprehensive review of digital twins across healthcare more broadly situates the perioperative use case within a wider set of applications — chronic disease management, drug dosing, implant design — and makes the point that the perioperative setting is in some ways the most demanding proving ground for the technology, because the relevant physiology changes on a timescale of minutes rather than months, and because the cost of a wrong prediction is immediate rather than diffuse [8]. That combination of high stakes and fast dynamics is precisely why cardiac and cardiovascular surgery has become the area where digital twin modeling has advanced furthest.

CARDIOVASCULAR AND CARDIAC SURGICAL APPLICATIONS

Postoperative atrial fibrillation remains one of the most common and costly complications of cardiac surgery, and it is also one of the clearer targets for digital twin modeling because the relevant substrate — atrial geometry, fibrosis distribution, and conduction properties — can be reconstructed from preoperative imaging and used to drive electrophysiological simulation. A recent digital-twin-guided virtual clinical trial approach built patient-specific atrial models from imaging data, simulated the arrhythmogenic substrate each patient's atria would present after surgery, and used the resulting risk stratification to test prophylactic

interventions in silico before applying the most promising strategy to actual patients, reporting that this approach identified higher-risk patients and informed prevention strategies more precisely than standard clinical risk factors alone [9]. This is one of the more mature examples in the literature of a digital twin doing something a population risk score cannot: not just flagging a patient as high-risk, but simulating why, at the level of the actual arrhythmogenic mechanism, and testing candidate interventions against that specific substrate before the intervention is chosen.

Multimodal deep learning approaches aimed at perioperative cardiovascular risk stratification represent an intermediate step toward the fuller digital twin architecture, integrating imaging, waveform, and structured clinical data into a single predictive model of cardiovascular risk that updates as new perioperative data becomes available [10]. These models are not full physiological twins in the mechanistic sense — they are data-driven predictive models rather than simulations grounded in cardiovascular physics — but they share the digital twin's core ambition of continuously updated, patient-specific risk estimation rather than a single preoperative score fixed at the time of consultation.

Structural heart and transcatheter intervention has produced some of the most visually compelling digital twin work in the field, using patient-specific anatomic reconstruction from CT or MRI to simulate device deployment, predict paravalvular leak or coronary obstruction, and rehearse the procedure computationally before it is performed on the actual patient [11]. Aortic disease management has followed a similar trajectory, with patient-specific models integrating computational hemodynamics and, increasingly, immune and inflammatory profiling to inform the timing and type of endovascular intervention for a given patient's aneurysm or dissection rather than relying solely on diameter thresholds derived from population data [12]. Both applications illustrate a pattern that recurs throughout this literature: digital twin modeling has advanced furthest where the relevant anatomy and physics can be captured from a single high-quality preoperative scan, and least far where the relevant physiology is diffuse, dynamic, and poorly captured by any single imaging modality — which is precisely the situation in general and noncardiac surgery.

EXTENSION TO TRAUMA, GENERAL, AND NONCARDIAC SURGERY

Outside cardiac and structural heart procedures, digital twin and closely related predictive-analytics approaches have been applied to trauma and general surgical populations with a somewhat different emphasis: less on simulating a specific anatomic intervention and more on continuously updating a patient's postoperative trajectory as monitoring data accumulates. Artificial-intelligence-driven predictive

analytics applied to postoperative management in trauma patients have been used to flag deteriorating trajectories — evolving coagulopathy, occult hemorrhage, impending organ dysfunction — earlier than conventional vital-sign thresholds would trigger clinical concern, by continuously recalibrating a patient-specific risk model against the trauma patient's own evolving physiological data stream [13]. This is a narrower and more immediately actionable version of the digital twin concept: not a full mechanistic simulation, but a continuously updating, patient-specific predictive layer sitting on top of standard monitoring.

A narrative review specifically addressing digital twin technology across surgical specialties more broadly catalogs applications spanning surgical planning, intraoperative navigation, and postoperative outcome prediction, while being candid that the evidence base for most of these applications remains at the level of single-center feasibility studies and retrospective model validation rather than prospective trials demonstrating that twin-guided care changes outcomes [14]. That review's implementation-challenges discussion is arguably as important as its applications catalog: it identifies the difficulty of acquiring sufficiently rich, longitudinal, multimodal data on individual patients, the computational cost of running physiologically detailed simulations at the pace clinical decision-making requires, and the absence of regulatory pathways specifically suited to continuously adapting patient-specific models, as the central obstacles standing between current digital twin research and routine surgical deployment.

Institutional efforts to operationalize digital twins in clinical care, such as those described at academic medical centers building dedicated computational and digital health infrastructure, illustrate what building toward this capability actually requires in practice: substantial investment in data integration across previously siloed systems (imaging, laboratory, monitoring, and electronic health record data), computational infrastructure capable of running patient-specific simulations at clinically useful speed, and multidisciplinary teams spanning clinicians, computational biologists, and software engineers working on a shared patient model [15]. Broader surveys of digital twin applications and challenges across the healthcare domain echo the same conclusion from a different angle, cataloging use cases in chronic disease and drug development alongside surgery and noting that interoperability and data standardization remain the most persistent obstacles across all of them [16]. Market analyses tracking the commercial trajectory of digital twin technology specifically in surgery suggest substantial anticipated growth in adoption over the coming years, driven largely by imaging-based planning and intraoperative navigation applications rather than by

the more ambitious continuously updated physiological twins described in the foundational architecture papers [17].

VALIDATION, DATA, AND IMPLEMENTATION BARRIERS

The gap between what a digital twin can in principle offer and what has actually been validated against real surgical outcomes is the central honest finding of this review. Population-based risk calculators such as ACS NSQIP have the advantage of having been externally validated across many surgical populations and settings, even where that validation reveals imperfect calibration in specific subgroups such as incisional hernia risk after midline laparotomy or complication prediction in resource-limited settings [18,4]. Digital twins, by contrast, mostly lack this kind of external validation at scale; the atrial fibrillation work in cardiac surgery is a partial exception because it has been tested against actual postoperative arrhythmia outcomes in a defined cohort, but the more architecturally ambitious multi-organ perioperative twin remains, at this point, closer to a research proposal than a validated clinical tool [9,7].

Preprint and industry-adjacent literature describing AI-powered digital twins for predictive modeling in treatment and surgical planning illustrates a related concern: enthusiasm for the concept has outpaced peer-reviewed validation in a meaningful fraction of the published material, with some of the more expansive claims about digital twins predicting individualized surgical outcomes appearing in venues that have not subjected those claims to the same scrutiny as, for example, a NSQIP calibration study [19]. This is not a reason to dismiss the underlying concept, but it is a reason for surgical and anesthesia readers to distinguish carefully between digital twin applications that have cleared prospective or retrospective outcome validation — largely concentrated in cardiac imaging-based applications so far — and those that remain conceptual demonstrations of what the architecture could eventually do.

Data requirements are the most concrete barrier. A physiologically grounded digital twin needs longitudinal, multimodal data — serial imaging, continuous monitoring waveforms, laboratory trends, and often genomic or proteomic data — on an individual patient, most of which is not routinely collected preoperatively in current practice, and which becomes available at meaningfully increased volume only once a patient is already under continuous intraoperative or intensive care monitoring. This creates an awkward mismatch for the preoperative risk-assessment use case specifically: the richest data a twin needs typically becomes available only after the moment at which a preoperative risk estimate would be most useful for shared decision-making about whether to operate at all. Computational cost compounds this: running a physiologically detailed simulation with

enough fidelity to be clinically trustworthy, fast enough to inform a same-day decision, remains a genuine engineering constraint rather than a solved problem, and is one of the implementation challenges explicitly flagged in the surgical narrative review discussed above [14].

CONCLUSION

Digital twin modeling offers a conceptually compelling alternative to population-based surgical risk scoring: rather than placing a patient on a probability curve derived from thousands of other people, it proposes building a computational instantiation of that specific patient's physiology and simulating how it will respond to a proposed operation. The evidence supporting that ambition is real but narrow, concentrated almost entirely in cardiac and structural heart applications where high-quality anatomic imaging can be translated directly into mechanistic simulation, with the atrial fibrillation prediction and prevention work in cardiac surgery standing out as one of the field's more rigorously validated examples. Extension to general, trauma, and noncardiac surgery is underway but currently takes the form of multimodal predictive analytics layered onto conventional monitoring rather than the fully mechanistic, continuously updated multi-organ twin described in foundational architecture proposals. Data integration, computational cost, and the absence of regulatory and validation pathways suited to continuously adapting patient-specific models remain the central obstacles. For clinicians evaluating this literature now, the reasonable position is neither dismissal nor uncritical adoption: digital twins are likely to earn an expanding role in surgical risk assessment as validation studies accumulate, but for the great majority of noncardiac operations performed today, externally validated population calculators remain the tool with an actual evidence base behind it, and digital twin methods should be understood as a promising complement still working toward, rather than already possessing, that same evidentiary footing.

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Conflict of Interest

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Author Contributions

Mette Fischer conceived the review topic, performed the literature search, and drafted the manuscript. Marek van der Meer contributed to literature synthesis, critically revised the manuscript for intellectual content,

and prepared the final reference list. Claire Steiner contributed to the manuscript's structure and clinical framing and critically reviewed the final draft. All authors read and approved the final manuscript.

Ethics Statement

This is a literature review that did not involve new human or animal data collection and did not require ethics committee approval.

Data Availability

No new data were generated or analyzed in this review. All sources discussed are cited and publicly available through their respective publishers.

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