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Risk Management and Risk Assessment in Physiology: Analysis of Modern Developments on their Foundation

Sidra Ghori[1], Rafi Ghori[2*], Muhammad Kashan Surahio[3], Ehsan Ali Shaikh[4]
[1]Lecturer of Department of Physiology, Indus Medical College, The University of Modern Sciences, Tando Muhammad Khan, Hyderabad, Pakistan, [2*]Professor of Medicine dean Medical and Health Sciences, Indus Medical College, The University of Modern Sciences, Tando Muhammad Khan, Hyderabad, Pakistan, [3]Department of Business Administration, Muhammad Institute of Science and Technology, Ibn-e-Sina University, Mirpurkhas, Pakistan, [4]Master Student, Department of Engineering Management, NED University of Engineering & Technology, Karachi, Pakistan
Corresponding Authors Email: drrafi_ghori@hotmail.com

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Abstract
Risk management (RM) and risk assessment (RA) are foundational tools in modern science and engineering, but their integration into the field of physiology is increasingly gaining attention. This review explores how contemporary risk science principles can enhance physiological understanding, clinical decision-making, and biomedical system resilience. Drawing upon key research developments, this paper evaluates the conceptual parallels between risk frameworks and physiological systems, such as the handling of uncertainty, adaptive decision-making, and systemic vulnerability. The review identifies emerging trends such as knowledge-based risk characterizations, dynamic modeling in high-uncertainty environments, and integrative frameworks incorporating resilience and robustness into health systems. It also highlights critical challenges in conceptual clarity, stakeholder communication, and probabilistic limitations within physiological contexts. This paper aims to encourage interdisciplinary dialogue and future research that combines physiological science with modern RM and RA methodologies to better predict, prevent, and manage health-related outcomes in complex biological systems.
Keywords: Risk Assessment, Risk Management, Physiology, Uncertainty, Resilience

Introduction
In recent years, the importance of risk management and risk assessment in the field of physiology has grown significantly due to increasing complexities in healthcare delivery, patient safety concerns, and the emergence of new health risks. Physiology, being a foundation of medical sciences, demands a systematic approach to identifying, analyzing, and mitigating risks that may compromise both research integrity and clinical outcomes. Despite

advancements in medical technologies, physiological studies often overlook structured risk protocols. This gap highlights a critical need for integrating modern risk assessment methodologies into physiological practices and research. Therefore, this study explores the evolution and implementation of risk management in physiology, with a focus on its current applications, limitations, and potential to improve decision-making and safety outcomes.

"Risk assessment" comprises scientific knowledge that quantifies the probability and consequence of harm from specific hazards, while "risk management" encompasses the strategies and actions used to mitigate or respond to such threats (Landsiedel, Sauer, & de Jong, 2017). Historically, the roots of risk thinking can be traced back over 2400 years to the Athenians, who recognized the importance of assessing and managing uncertainty in decision-making (Bernstein, 1996). In the last few decades, risk management and risk assessment (RM/RA) have matured into modern scientific fields, establishing foundational principles that are still widely used today. The importance of structured risk management frameworks in physiological settings has been emphasized in studies examining real-world occupational environments, such as the textile sector, where physiological risks due to exposure to chemicals, noise, and dust are prevalent (Sidra et al., 2025). These findings underscore the need to extend modern risk assessment approaches into physiological domains to improve worker safety and health outcomes.

Although the foundational frameworks emerged prominently in the 1970s and 1980s, the RM/RA field has undergone substantial advancements—both in theory and application. Innovative tools, statistical techniques, and risk analysis methodologies have since been adopted across diverse sectors, including engineering, ecology, security, and increasingly**, human physiology and healthcare.** Risk-based thinking is now central to areas such as **clinical diagnostics, patient safety, epidemiological modeling, physiological monitoring, and health policy development**. This intersection has led to the emergence of a physiology-informed approach to risk: using physiological data (e.g., cardiovascular markers, metabolic profiles, neural indicators) to model, predict, and manage health risks.

As modern physiology increasingly incorporates interdisciplinary approaches, educational strategies such as Case-Based Learning (CBL) have also shown promise in enhancing clinical reasoning and risk recognition among medical students (Ghori et al., 2025). When integrated into physiology curricula, CBL promotes not only engagement but also awareness of real-world risk factors and decision-making processes. This educational foundation is critical in preparing future professionals to apply risk management frameworks effectively in clinical and research settings.

This paper reviews the modern developments in RM/RA with a specific focus on their integration into physiology. Drawing from both generic risk theory and domain-specific applications, we identify major shifts in thought, the evolution of practical models, and challenges in uncertainty analysis. We also assess the Society for Risk Analysis (www.sra.org) domains that intersect with health sciences—such as dose-response, microbial risk, and occupational health—highlighting how physiological risk now benefits from these frameworks.

Two central tasks guide this paper:

(I) To explore how modern RM/RA is applied in physiology to manage specific risk-related activities (e.g., diagnostic decision-making, surgical planning, or drug-response modeling); and
(II) To investigate broader theoretical and methodological developments that inform physiological risk thinking—concepts, frameworks, and integrative methods that transcend disciplinary boundaries.

(II)

The field of risk is fundamentally about understanding the uncertain world and devising ways to assess, communicate, and manage it. In physiology, this translates into improved healthcare decisions, enhanced safety in treatment plans, and better population health strategies. We give special attention to recent contributions that adopt **integrative thinking** an approach that creatively reconciles opposing perspectives and stimulates novel insights (Martin, 2007). This is particularly vital in physiology, where competing definitions of health, risk, and outcomes can coexist and require synthesis for effective management.

By analyzing contemporary developments and foundational ideas, this paper aims to bridge traditional RM/RA frameworks with the growing demands of physiological science and medical practice.

The Failures of Risk Innovation and Technologies in Physiology

Risk, fundamentally tied to uncertainty—whether defined as probability, possibility, or likelihood has been deeply integrated into the evolution of human health and physiological science. Since ancient times, threats such as epidemics, famine, and unknown diseases have challenged societal resilience and human physiology (Sahlins, 1972; Gallant, 1991; Garnsey, 1988). With the advancement of biomedical technologies, the potential to control physiological risks has expanded—but so has the margin for unforeseen, catastrophic failures. Historically, uncertainty was attributed to forces beyond human control: fate, divine will, or ignorance. In the modern era, however, failures in biomedical innovation, risk evaluation, and health technology have proven that technological progress alone does not eliminate physiological risk and may even exacerbate it when mismanaged.

Recent clinical studies such as investigations into hematological disorders and sepsis—illustrate how risk-oriented clinical profiling can inform prognosis and early intervention strategies (Ghori et al., 2017; Shaikh et al., 2017).

One of the most tragic examples was the Thalidomide disaster (1960s), which demonstrated a critical failure in pharmacological risk assessment. Marketed as a safe sedative, even for pregnant women, thalidomide resulted in thousands of infants born with limb deformities and organ damage, due to teratogenic effects that were not identified during early clinical trials (Vargesson, 2015). The physiological toll of this risk miscalculation forced global reforms in drug safety protocols.

Similarly, the Bhopal gas tragedy (1984), though industrial, had profound physiological consequences: exposure to methyl isocyanate gas led to immediate and long-term respiratory, neurological, reproductive, and immune system damage in over half a million people (Broughton, 2005). The event underscored the failure of systemic risk controls in protecting human biology from toxic exposure.

Other high-profile technological catastrophes such as the Chernobyl nuclear disaster (1986) and the Exxon Valdez oil spill (1989) had secondary but long-lasting physiological effects on affected populations due to radiation sickness, cancer, toxic exposure, and ecological collapse (Kreitner & Almanac, 2015; The Learning Network, 2006). Each incident reflected how poor risk governance in high-stakes environments can result in wide-scale human health crises.

In more recent times, the withdrawal of the arthritis drug Vioxx (2004) revealed deep flaws in clinical trial transparency and post-marketing surveillance. The drug was linked to increased cardiovascular risks an oversight that impacted millions (Kolata, 2004). Likewise, arsenic poisoning from contaminated groundwater in Bangladesh (1990s onward) represents a failure in environmental and physiological risk assessment, with implications for liver, kidney, and neurological health (Harvey et al., 2002).

These examples illustrate that even with advances in medical diagnostics, pharmacology, and genomic screening, the underlying institutional and methodological foundations of risk management remain vulnerable to failure. Whether in terms of incomplete physiological modeling, over-reliance on limited clinical data, or insufficient ethical oversight, the intersection of human biology and technological systems is highly susceptible to uncertainty. Moreover, public policies and medical innovations that were expected to improve quality of life—ranging from hospital privatization and universal immunization campaigns to the mass production of biomedical implants have, in some cases, introduced new layers of complexity and vulnerability. The centralization of physiological decisions in large health systems or algorithms may reduce flexibility, leading to systemic blind spots.

Ultimately, the increased awareness of these shortcomings combined with the growing recognition that risk in physiology is not only technical but also social and ethical has prompted a reassessment of how we define, manage, and communicate risk in health sciences (Taylor-Gooby & Zinn, 2006). This reassessment is urgently needed in a world where precision medicine, AI in diagnostics, and synthetic biology are accelerating faster than regulatory or ethical frameworks can adapt.

The Science of Risk in Physiology

Over the past few decades, the discipline of risk science has matured significantly, particularly in its application to fields like engineering, economics, and environmental systems. More recently, this framework has been extended to health-related domains such as **physiology**, where uncertainty and risk are intrinsic to biological variability, diagnosis, treatment outcomes, and systemic responses.

Risk science can be broadly categorized into two domains:

- **Level I: Application-Specific Risk** – practical, domain-specific techniques used in fields like medical physiology, pharmacology, and systems biology.
- **Level II: Generic Risk Science** – foundational principles that apply across disciplines and provide epistemological and methodological support for Level I.

While physiology traditionally relies on deterministic models and empirical experimentation, the **increased complexity and unpredictability of biological systems** demand more nuanced approaches. The integration of **probabilistic risk assessment (PRA)**, **Bayesian inference**, and **decision theory** into physiological systems represents a shift from purely empirical evaluation to a structured, knowledge-based methodology for **handling uncertainty and variability**.

As discussed in Hansson & Aven (2014), risk science offers a robust structure to assess how certain we are about a given physiological outcome, how confident we are in treatment protocols, and how we might **quantify and manage adverse events**, such as medication side effects, organ failure probabilities, or surgical risks. These concepts become particularly useful when developing **personalized medicine models**, where risk must be assessed individually.

Several recent studies have emphasized the need to bridge the gap between foundational science and application-oriented risk in physiology. For instance, the use of **supply chain risk models** has been adapted in healthcare settings to manage drug delivery systems and pandemic preparedness (Fahimnia et al., 2015; Tang & Zhou, 2012). Although these models originate from logistics, they provide insights into how risk structures can be translated across fields including physiology where **the delivery of oxygen, nutrients, or pharmaceuticals** functions as an internal supply chain.

The literature also draws parallels between **biological regulation** and **system reliability theory**, suggesting that physiological systems exhibit fault tolerance similar to engineered systems (Heckmann, Comes, & Nickel, 2015). This analogy helps in modeling **organ redundancy**, **homeostasis**, and **feedback control** using risk-based approaches.

Furthermore, Aven and Reniers (2013a) demonstrate that challenges arising in high-stakes environments like offshore safety have generated new concepts of **risk conceptualization**. These can be translated into physiological contexts such as the assessment of cardiovascular failure or neurodegenerative disease progression where uncertainty is high, and decisions must be made under time-sensitive conditions.

Several scholars, including Goerlandt & Montewka (2015) and Aven & Renn (2015), have shown how even application-specific problems (e.g., maritime safety, climate modeling) can rest on generic risk theory foundations. Likewise, in physiology, **risk modeling of epidemics**, **clinical trial uncertainties**, and **predictive diagnostics** requires a blend of empirical data and theoretical frameworks.

This fusion of Level I and Level II risk in physiology is not without its challenges. Biological systems are inherently more variable than engineered ones, making it difficult to establish generalizable models. However, insights from physiology-specific data such as heart rate variability, blood pressure dynamics, or pharmacokinetics can **inspire new approaches to generic risk modeling**.

Physiology stands as a promising domain where **modern developments in risk science can be actively applied and further developed**. The methodological insights from generic risk theory not only support practical applications in medicine and biology but also offer new perspectives on uncertainty, variability, and control that may redefine the future of physiological research and healthcare decision-making.

Risk Management and Risk Assessment in Physiology: Analysis of Modern Developments on Their Foundation

In physiology, risk management and risk assessment involve a complex relationship between scientific knowledge, values, and decision-making. These processes connect empirical facts with value judgments to guide safety decisions (Hansson & Aven, 2014). Information and data gathered through analysis and testing form the evidence base that supports scientific understanding (Arthur R. Burgess, 1985). However, this knowledge is not purely objective; it consists of both established facts and expert opinions developed through ongoing research. While knowledge and evidence are ideally free from subjective values at early stages, risk evaluation and final judgments inevitably incorporate value-based considerations alongside scientific evidence. This is particularly important in physiology, where even thoroughly tested products or procedures cannot fully rule out rare or long-term adverse effects. Thus, expert interpretation of available evidence is crucial.

Risk evaluation involves assessing uncertainties and making judgments about potential risks, carefully distinguishing between scientific proof and practical decision-making needs (Terje Aven, 2014). This process often operates in the space between science and policy, where differing values can create challenges (Hansson, 2014). Decision-makers must integrate risk assessments with broader information and societal values beyond pure science. Knowledge in this context includes practical skills as well as justified beliefs based on current evidence, recognizing that it is often provisional and probabilistic rather than absolute truth (SRA, 2015a). Risk assessment moves beyond the traditional scientific goal of certainty by explicitly addressing uncertainties and identifying knowledge gaps (Aven, 2011a; Terje Aven & Heide, 2009). Modern approaches also focus on the resilience of physiological systems and lessons from past successes and failures to improve risk management (Hansson & Aven, 2014).

This integrative perspective shifts the role of risk assessment from solely quantifying hazards to managing uncertainty and supporting policy decisions under incomplete knowledge, which is essential for protecting health and advancing medical science.

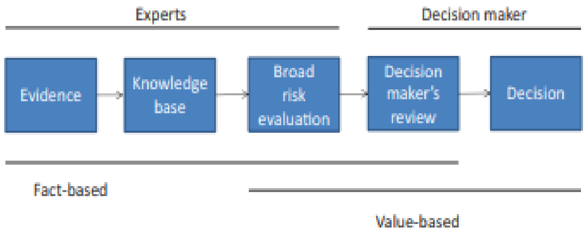

Fig. 1. The various stages link this model to risk-informed decision-making (based on Aven & Hansson, 2014).

Conceptualizing Risk in Physiology: Foundations and Contemporary Perspectives

In physiology, risk conceptualization involves understanding the potential for adverse outcomes arising from biological processes, environmental exposures, or medical interventions that affect the human body's normal function. Unlike purely mechanical or technological risks, physiological risks must account for complex, dynamic, and adaptive systems within the body, where variability and uncertainty are inherent (Aven, 2011;

Hansson, 2014). Risk in this context is often linked to the probability and severity of physiological dysfunctions, diseases, or failures triggered by internal or external stressors (Cumming, 1981; Weinberg, 1981).

Modern physiological risk assessment integrates data from molecular biology, clinical diagnostics, and patient-specific factors to create a comprehensive understanding of potential health threats. For example, cardiovascular risk models combine genetic markers, lifestyle information, and biochemical data to estimate the likelihood of adverse cardiac events (Aven & Heide, 2009). This multidimensional approach reflects a shift from deterministic views of health risk toward probabilistic models that embrace uncertainty and variability inherent in living systems (Burgess, 1985; Hansson & Aven, 2014).

Furthermore, physiological risk is closely tied to homeostatic balance and the body's capacity to respond to stress through compensatory mechanisms. The breakdown or overwhelming of these mechanisms marks an increased risk for pathological conditions. Hence, risk assessment in physiology must consider both immediate factors and long-term adaptations, accounting for latent vulnerabilities and resilience (Aven, 2011; Terje Aven & Heide, 2009).

The evolving perspective on risk in physiology also acknowledges the role of knowledge gaps and uncertainties, as biological systems often present non-linear responses and emergent behaviors that challenge traditional risk frameworks. This necessitates integrative models that combine empirical data with theoretical constructs, supporting more robust predictions and personalized interventions (Hansson & Aven, 2014).

In summary, conceptualizing risk in physiology requires a nuanced understanding of biological complexity, the interplay of multiple factors, and the limitations of current knowledge. Modern developments emphasize probabilistic, systems-based approaches that align with advances in biomedical research and clinical practice, aiming to improve health outcomes through informed decision-making and risk management.

Uncertainty in Risk Assessment of Physiological Systems

Uncertainty is a fundamental concept in risk assessment, particularly in the complex domain of physiological systems, where inherent biological variability and incomplete knowledge often complicate risk evaluations. Understanding and managing uncertainty is crucial for accurate risk assessments related to human health, disease progression, and physiological responses to environmental or therapeutic interventions.

Historically, from the 1970s and 1980s onwards, risk assessment methodologies have evolved to better address uncertainty, mainly through probabilistic frameworks relying on relative frequency interpretations of probability (Flage et al., 2014). However, physiological systems often exhibit epistemic uncertainty uncertainty due to lack of knowledge stemming from limited data on individual variability, mechanisms, or long-term effects (Dubois, 2010). This type of uncertainty challenges traditional probability methods, as it cannot always be adequately captured by single numerical probabilities.

Bayesian subjective probability approaches are commonly applied to express expert beliefs about uncertain physiological outcomes (Flage et al., 2014). These methods allow integration of prior knowledge and new evidence but can be limited when information is sparse or ambiguous. Alternative approaches such as possibility theory, interval probabilities, and qualitative assessments have been proposed to complement probabilistic models by better representing uncertainty and ignorance in physiological risk contexts (Flage et al., 2014; Aven, 2010).

A critical aspect of uncertainty characterization in physiological risk assessment involves combining quantitative probabilities with qualitative measures of knowledge strength. The pairing of probability with the strength of knowledge (SoK) enables decision-makers to interpret risk estimates with an understanding of their epistemic confidence (Flage & Aven, 2009; Aven, 2014). This is particularly important in physiology, where model assumptions, data limitations, and biological complexity can greatly affect the reliability of risk predictions. Frameworks such as NUSAP (Numeral, Unit, Spread, Assessment, Pedigree) have been developed to systematically evaluate the quality and robustness of scientific information used in risk assessments (Kloprogge, van der Sluijs, & Petersen, 2011; Laes, Meskens, & van der Sluijs, 2011). These tools are useful in physiological studies to assess uncertainty arising from data quality, measurement variability, and expert judgment.

Spiegelhalter and Riesch (2011) proposed a hierarchical approach to classify uncertainties, including model uncertainty, parameter uncertainty, and event uncertainty, alongside meta-level concerns such as model framing and adequacy. This multi-layered understanding is vital when dealing with physiological systems, where uncertainties may propagate through complex biological pathways.

Recent studies have emphasized the importance of identifying and prioritizing sources of uncertainty that most impact physiological risk assessments (Borgonovo, 2007; Borgonovo & Plischke, 2016). Sensitivity analysis and uncertainty quantification techniques help elucidate how variability in physiological parameters influences overall risk estimates, guiding more focused data collection and model refinement (Aven & Nøkland, 2010).

Moreover, the development and validation of physiological models require careful consideration of model uncertainty—differences between model predictions and true physiological states. Approaches to quantify and reduce model uncertainty have been addressed in various engineering and biological risk contexts (Reinert & Apostolakis, 2006; Droguett & Mosleh, 2013; Aven & Zio, 2013). These methodologies are increasingly applied in physiological modeling, such as pharmacokinetics, cardiovascular simulations, and systems biology, where accurate representation of uncertainty is essential for reliable risk management.

Managing uncertainty in risk assessments of physiological systems demands integrating probabilistic, possibilistic, and qualitative methods to capture the multifaceted nature of biological variability and knowledge gaps. Advancements in uncertainty quantification and expert judgment frameworks provide a robust foundation for improving risk-informed decisions in physiology and healthcare.

Risk Management Strategies and Principles in Human Physiology

Risk management in human physiology involves the systematic identification, assessment, and mitigation of biological risks that can affect the body's normal functioning. Similar to traditional risk management frameworks used in engineering and organizational contexts, physiological risk management applies strategies such as precautionary measures, risk-informed decisions, and adaptive responses to maintain homeostasis and prevent adverse health outcomes (Renn, 2008; SRA, 2015b). The precautionary strategy in physiology often manifests as immune system strengthening, redundancy in critical biological pathways, and flexibility in physiological responses to environmental stressors or injuries (Terje Aven, 2015a). Risk-informed approaches utilize quantitative and qualitative data, such as biomarker analysis and patient history, to assess the probability and severity of potential health threats, guiding clinical decisions regarding prevention and treatment (Zio, 2007a; Thierry Meyer & Genserik Reniers, 2013). The process includes context establishment—defining the physiological goals and health status, risk identification through diagnostic methods, consequence analysis via clinical monitoring, and risk evaluation to prioritize interventions (ISO 31000, 2009). Moreover, discursive strategies are important in patient-centered care, fostering communication and trust between healthcare providers and patients to navigate uncertainties and personalize treatment plans (Renn, 2008). Overall, applying these risk management principles in physiology supports resilient health systems capable of adapting to internal and external challenges, enhancing patient outcomes and safety.

The Precautionary Principle in Physiological Risk Management

In physiological risk management, the precautionary principle remains a fundamental yet sometimes debated guideline for handling uncertainties related to human health and biological systems (Renn, 2008; Peterson, 2017; Cox, 2011). This principle can be understood in two key ways within the context of physiology (Strategic Risk Analysis [SRA], 2015a). First, it suggests that when the outcomes of an intervention or exposure may pose significant harm to the body and there are systemic uncertainties, precautionary measures should be implemented, or the action should be deferred. Second, it allows for preventive administrative or clinical actions to be taken even if conclusive scientific evidence about potential adverse effects is lacking, especially when dealing with emerging physiological risks such as new drugs or environmental toxins.

This approach is particularly relevant in managing complex biological uncertainties where deterministic models of human responses may be limited or unavailable (Aven, 2011b). For example, in immunology, the decision to initiate or withhold a novel vaccine often relies on precautionary judgments due to incomplete data on long-term effects. The distinction between precautionary and cautionary approaches is critical: precautionary actions are often justified by scientific uncertainty and the need to prevent potential harm proactively, while cautionary strategies may emphasize robustness and resilience in physiological systems, such as enhancing immune function or providing redundant protective mechanisms (Aven, 2011b). A physiological illustration can be drawn from managing inflammatory responses; while inflammation is a protective mechanism, unchecked or excessive inflammation can cause damage. The precautionary principle would guide clinicians to carefully monitor and modulate inflammation even if the exact risk thresholds are not fully established, to avoid severe outcomes. Similarly, in designing medical devices or pharmacological interventions, precautionary policies may enforce strict safety margins despite the absence of definitive risk quantification. Overall, effective physiological risk management combines a thorough understanding of biological risks with precautionary strategies that prioritize patient safety in the face of uncertainty, supporting resilient health outcomes.

Robustness in Physiological Systems Risk Management

Robustness, as a concept in risk management, refers to the ability of a system to maintain its functions despite uncertainties and variations in internal and external conditions (Baker, Schubert, & Faber, 2008; Ben-Haim, 2012; Gabrel, Murat, & Thiele, 2014). In physiology, robustness is crucial because biological systems constantly face environmental stressors, genetic variability, and unpredictable perturbations. Roy (2010) describes robustness as the capacity to withstand "vague estimates" and "ignorance zones," reflecting incomplete knowledge of physiological parameters or disease mechanisms. Robust physiological systems can adapt to or compensate for such uncertainties, thereby preventing functional degradation or failure.

Recent advances in robust optimization techniques (Gabrel et al., 2014) have provided strategies for managing uncertainties in complex systems, including biological networks. For example, in cardiovascular physiology, robustness can be observed in how the heart maintains output despite variations in blood pressure or oxygen demand. Ben-Haim (2012) emphasizes that decision-making under risk requires conceptual tools that integrate robustness to optimize system design or therapeutic interventions when exact parameters are unknown. Joshi and Lambert (2011) illustrate this with robust management strategies in engineered systems, which can be extrapolated to physiological contexts such as drug dosing regimens designed to accommodate patient variability.

A key challenge in robustness is determining how to balance system performance and protection against uncertainty. Gabrel et al. (2014) discuss worst-case scenario analysis to evaluate robustness, which can be applied in physiology when considering the most extreme environmental or pathological stresses an organism might face. For instance, immune system robustness involves maintaining defense mechanisms without triggering autoimmune damage under uncertain pathogenic challenges.

Furthermore, Aven and Hiriart (2013) highlight that robustness analysis in decision-making should be accompanied by sensitivity checks and qualitative evaluations to support flexible and resilient management strategies. In physiology, this approach could involve continuously assessing patient responses to treatments and adjusting interventions based on emerging data, ensuring a robust therapeutic outcome.

In summary, incorporating robustness into physiological risk management involves designing systems and interventions that remain effective across a range of uncertainties, thereby enhancing resilience and safeguarding health despite incomplete knowledge or unpredictable conditions.

Resilience in Physiological Systems

Resilience strategies are critical in managing risks, potential failures, and uncertainties within physiological systems. The resilience of a biological system or an organization managing physiological health is defined by its capacity to maintain or restore essential functions when subjected to stressors such as injury, disease, or environmental challenges (Hollnagel & Woods, 2006). Resilient physiological systems exhibit the ability to:

- Respond adaptively to both regular and irregular stressors while maintaining robustness,
- Continuously monitor ongoing internal and external states beyond mere performance metrics,
- Learn from previous experiences and accumulated biological or clinical knowledge,
- Anticipate future risks and opportunities to prevent adverse outcomes.

Early detection and timely responses are fundamental in preventing system failures, such as organ failure or systemic inflammation (Weick, Sutcliffe, & Obstfeld, 2008; Sahebjamnia, Torabi, & Mansouri, 2015). Sutcliffe and Weick's concept of cooperative mindfulness, developed in the context of High-Reliability Organizations (HROs), is applicable to physiological systems, emphasizing five principles: reluctance to oversimplify complex biological signals, deference to expert knowledge (e.g., specialist clinical judgment), a commitment to resilience, vigilance toward potential system failures, and acute sensitivity to operational states (Weick et al., 2008).

Resilience engineering approaches have been increasingly applied in healthcare risk assessment and accident analysis, including diagnostic errors and treatment failures (Righi, Saurin, & Wachs, 2015). Traditional risk assessments, often based on linear cause-effect models and historical failure data, fall short in capturing the complexity and nonlinear dynamics inherent in physiological systems. Therefore, resilience provides a framework that emphasizes adaptability, learning, and proactive anticipation to better manage the complexities of human health and disease.

Managing Deep or Large Uncertainties in Physiology

Certain physiological challenges such as emerging infectious diseases, complex chronic conditions, or climate-related health impacts are characterized by deep or large uncertainties, where traditional statistical and predictive models may be insufficient (Cox, 2012). In such cases, precautionary and resilient approaches, coupled with robust systems, are vital for decision-making and policy formulation.

Cox (2012) discusses adaptive methods and robust decision-making frameworks that improve predictions and management in highly uncertain environments. These include tools like subjective expected utility theory, scenario modeling, robust optimization, reinforcement learning, and Bayesian model averaging. Such approaches allow healthcare decision-makers to identify strategies that remain effective across a broad range of plausible models and uncertain data.

In physiology, these methods translate into adaptive treatment plans, personalized medicine, and dynamic monitoring strategies that adjust to new patient information or shifting environmental conditions. By embracing uncertainty rather than attempting to eliminate it, health systems can become more flexible and resilient to unknown future challenges.

Black Swans and Surprises in Physiological Risk

The concept of "Black Swan" events—highly improbable but impactful surprises—was popularized by Nassim Nicholas Taleb (2007) and has since influenced risk thinking in many domains, including physiology and healthcare. Black Swan events in physiology could be unexpected disease outbreaks, rare adverse drug reactions, or sudden system failures (Taleb, 2007; Aven, 2015a).

While the metaphor has gained public attention, researchers emphasize that its utility depends on theoretical rigor around concepts such as probability, risk, and knowledge (Aven, 2015b; Paté-Cornell, 2012). Black Swans challenge traditional risk models that rely on historical data and expected probabilities (termed “Mediocristan” by Taleb), pushing focus toward rare but extreme events (“Extremistan”) that can overwhelm physiological or healthcare systems.

Improving management of such surprises requires enhanced risk assessment quality, broader knowledge capture, and resilient (or even antifragile) system designs those that not only withstand shocks but improve because of them. This mindset encourages building health systems and physiological models that are not only robust but capable of learning and adapting in the face of extreme uncertainty (Aven & Krohn, 2014; Feduzi & Runde, 2014).

The Concepts of Risk Criteria and Integrative Risk Management Perspectives to Physiology

The criteria for risk acceptance and the integrative perspectives in risk management closely parallel essential principles in physiology, particularly in how biological systems maintain homeostasis and adapt to stressors. Just as risk management balances competing priorities such as safety, reputation, and operational goals while imposing constraints to minimize harm (Rodrigues, Arezes, & Leão, 2014; Vanem, 2012), physiological systems regulate internal conditions through feedback loops that restrict deviations in vital parameters like temperature, pH, and blood pressure to maintain well-being (Sterling & Eyer, 1988). The responsibility assigned to supervisors for recognizing and managing risks aligns with the role of central regulatory organs, such as the hypothalamus, which monitors bodily states and coordinates responses to preserve stability (Cannon, 1932). Furthermore, integrative perspectives on risk, incorporating resilience and antifragility (Renn, 2008; Taleb, 2007), reflect how organisms not only resist damage but can improve function following challenges, as seen in processes like immunological memory and cellular repair mechanisms (Kitano, 2004). The emphasis on knowledge building, learning, and system thinking in risk frameworks (Deming, 2000; Terje Aven & Krohn, 2014) resonates with physiological plasticity, where adaptive changes at molecular and systemic levels optimize survival amid changing environments. Thus, risk management’s structured approach to uncertainty and evolving threats parallels physiological processes that dynamically balance stability and adaptability to sustain life

The Future of Risk Management and Assessment — A Physiological Analogy

The future of risk management and assessment, as discussed by SRA (2015b), Aven and Zio (2013), Pasman and Reniers (2014), and others, increasingly emphasizes managing uncertainty and complexity over purely probabilistic forecasts. This evolution mirrors developments in human physiology, where biological systems must constantly adapt to unpredictable internal and external stimuli to maintain homeostasis and long-term viability. Rather than relying on fixed, static responses, the body uses dynamic systems—such as the autonomic nervous system and endocrine feedback loops—to interpret incomplete signals and enact flexible strategies. Similarly, risk frameworks now shift toward adaptive, knowledge-based models in response to unknown or emerging threats, akin to how the immune system handles novel pathogens with anticipatory and learned responses (Flag & Aven, 2015).

Emerging risk concepts resemble biological ideas of latent vulnerabilities and systemic fragility, where small disturbances can cause cascading failures if compensatory mechanisms are insufficient (Taleb, 2007). For example, the inability of a damaged organ to recover can be compared to society’s exposure to "black swan" events in a fragile risk environment. Bayesian models, while mathematically elegant, fall short in high-uncertainty scenarios just as oversimplified physiological models fail to predict nonlinear biological reactions. Thus, integrating cautionary and learning-based strategies is as vital in risk science as it is in medical diagnostics and adaptive physiology.

Moreover, the growing emphasis on inclusive, intergenerational risk governance parallels ethical and developmental considerations in physiology—where the health of future offspring depends on present genetic, environmental, and behavioral decisions. Issues like how to communicate uncertainty, evaluate knowledge robustness, and design systems that can “fail safely” are central to both physiological resilience and sustainable risk management (Fahimnia et al., 2015; Giannakis & Papadopoulos, 2016). Just as clinicians must interpret symptoms, genetic predispositions, and lifestyle factors across timescales, risk professionals must translate incomplete or emerging data into actionable insights without overstating confidence. The near-miss concept, widely used in safety science, also mirrors physiological “pre-symptomatic” events where early markers signal potential dysfunctions before full pathology develops. Recognizing such patterns, and mapping causal proximity across complex systems, remains a shared challenge in both domains.

Significant of the Study

This study is significant for several reasons. First, it bridges a gap in existing literature by systematically analyzing how risk management frameworks can be applied in physiological contexts. Second, the findings offer practical insights for researchers, educators, healthcare professionals, and policy-makers who rely on physiological data to inform decisions. By understanding the utility and effectiveness of risk assessment tools in physiology, stakeholders can improve experimental design, reduce errors, and enhance patient safety in clinical applications. Ultimately, the study contributes to building more resilient and scientifically sound health systems.

Conclusion

Risk management (RM) and risk assessment (RA), when examined through the lens of physiology, reveal deep and meaningful parallels that can significantly enhance both fields. Physiological systems inherently manage risk—whether through immune responses, hormonal regulation, or homeostatic mechanisms by navigating uncertainty and dynamically adapting to threats. Despite this natural alignment, the scientific foundation of RM and RA still faces theoretical gaps and conceptual ambiguities that, if not addressed, may misguide clinical and biological decision-making. For instance, interpreting physiological risk purely through probabilistic distributions—similar to expected value models—can overlook critical aspects such as biological complexity, emergent behavior, and inter-individual variability.

Recent developments in integrative risk science have proposed broader frameworks that more accurately reflect physiological realities. These include redefinitions of core concepts such as probability, vulnerability, and knowledge gaps, along with approaches that emphasize resilience, robustness, and system-level adaptively. Such concepts are not only applicable but essential in physiological modeling, especially when dealing with chronic diseases, systemic inflammation, or unpredictable medical outcomes.

This review identifies growing concerns and ongoing efforts to build a stronger conceptual foundation for RM and RA in physiology. Encouragingly, this convergence is spurring interest in new methodologies, including real-time risk analytics, adaptive models, and the integration of expert judgment within biological risk decision-making. As uncertainties in health systems and medical technologies continue to grow, especially under global pressures like pandemics and demographic shifts, further interdisciplinary research is crucial. A new generation of researchers must be cultivated one that is both scientifically grounded and innovative to elevate risk-based physiological modeling into a robust, predictive, and preventative science.

Data Availability
Data and materials can be provided as needed.

Conflict of Interest
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