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Organ-on-a-Chip Platforms for Drug Discovery and Personalized Medicine: Current Advances, Applications and Future Perspective

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ABSTRACT

Organ-on-a-chip (OOC) technology has emerged as a transformative microphysiological platform that addresses the limitations of conventional two-dimensional cell cultures and animal models in recapitulating human physiology. By integrating microfluidics, tissue engineering, biomaterials and living human cells within controlled microenvironments, OOC systems can recapitulate key structural, mechanical and biochemical features of native tissues and organs. Recent advances have enabled the development of diverse organ-specific and multi-organ platforms capable of modeling complex physiological and pathological processes, including tissue-tissue interactions, barrier function, immune responses and drug-induced toxicity. Furthermore, the integration of organ-on-a-chip technology with stem-cell-derived organoids has enhanced biological fidelity by combining self-organizing tissue architecture with precise environmental control. These platforms have demonstrated significant potential for disease modeling, predictive toxicology, efficacy screening, pharmacokinetic studies and personalized medicine through the use of patient-derived cells and disease-specific models. The emerging integration of artificial intelligence and advanced biosensing technologies further expands their capacity for automated analysis, high-content data interpretation and precision pharmacology. Despite substantial progress, challenges related to standardization, reproducibility, scalability, regulatory validation and commercialization continue to limit widespread adoption. This review examines the engineering foundations, biological applications and translational significance of organ-on-a-chip systems, with particular emphasis on their roles in drug discovery and personalized medicine. Additionally, current limitations, regulatory considerations and future perspectives are discussed to evaluate the potential of these platforms as next-generation tools for human-relevant biomedical research and precision therapeutics.

INTRODUCTION

Organ-on-a-chip technology and its translational promise: Organ-on-a-chip technology emerged to address a central challenge in biomedical research: Conventional cell culture and animal models often fail to reproduce the integrated cellular, mechanical and biochemical contexts that govern human physiology and disease[1-3]. Reviews across the field consistently describe organ chips as microfluidic devices lined with living cells and maintained under fluid flow, enabling the recapitulation of organ-level functions with greater physiological fidelity than static two-dimensional (2D) culture systems[4,5]. This translational potential is particularly significant in drug development, where discrepancies between preclinical models and clinical outcomes remain a major obstacle[6,7].

The field has progressed from a conceptual framework to a broadly applicable technology, demonstrating that chip-based systems can model disease, inter-organ communication, microbiome interactions and tissue responses to drugs, toxins,

radiation and pathogens[4,8]. At the same time, organoids-on-chips and other hybrid microphysiological systems have expanded the scope of these platforms by integrating structural self-organization with controlled perfusion and mechanical cues[9,10]. The objective of this review is to synthesize the engineering principles, biological applications and translational relevance of organ-on-a-chip platforms, while also examining their limitations, regulatory barriers and emerging applications of artificial intelligence (AI)-enabled analysis and precision medicine[11,12].

From conventional cell culture and animal models to microphysiological systems: The transition from static cell culture to microphysiological systems reflects the recognition that tissue function is shaped by fluid flow, tissue-tissue interactions and dynamic environmental regulation[1,2]. Conventional 2D culture systems can provide valuable insights into cell-autonomous behavior but they often fail to capture the intercellular communication and tissue-level interactions that regulate organ physiology and pathophysiology[1]. Animal models remain important in biomedical research; however, reviews in this field repeatedly emphasize their limited predictive value for human drug efficacy and toxicity[4,6]. Organ chips were therefore developed not merely as miniaturized cell culture devices but as human-relevant experimental systems capable of preserving key physiological contexts while permitting controlled experimental perturbation[1,13].

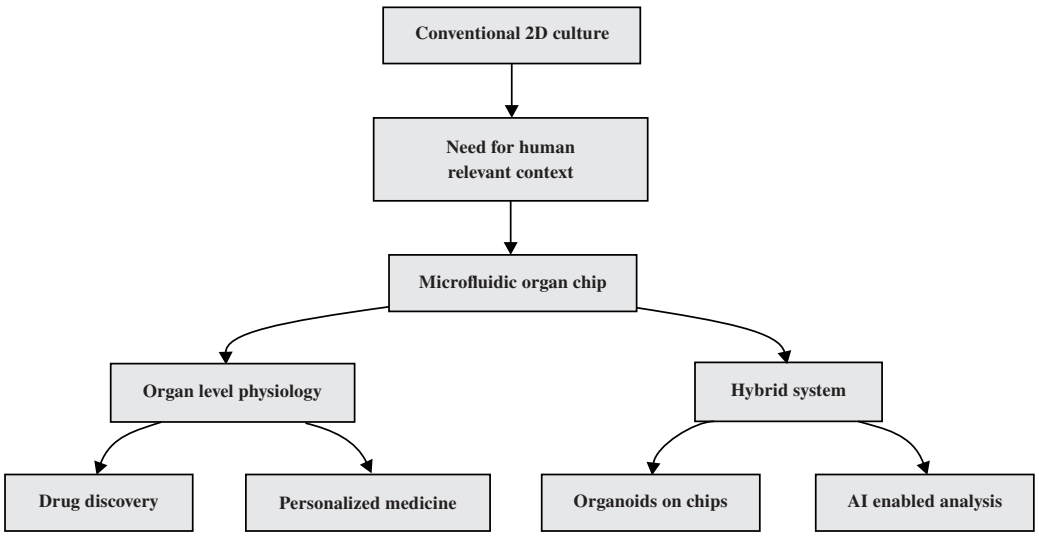
Scope, objectives and review focus: This article focuses on the design of organ-on-a-chip platforms, their ability to reproduce key aspects of human physiology and their increasing importance in drug discovery and personalized medicine[4,14]. Particular emphasis is placed on the convergence of organ chips with organoids and artificial intelligence, which has emerged as a defining trend in recent literature[9,11]. A further objective is to distinguish their robust translational potential from unresolved implementation challenges, thereby presenting organ-on-a-chip technology neither as a purely speculative innovation nor as a fully established replacement for conventional experimental models[12,13].

Flowchart 1 illustrates the conceptual rationale underlying organ-on-a-chip technology, highlighting the recognition that tissue function is shaped by fluid flow, tissue-tissue interactions and dynamic environmental regulation, which conventional two-dimensional (2D) cell culture and animal models cannot adequately reproduce[1,2]. Organ chips were developed not merely as miniaturized culture systems but as human-relevant experimental platforms that preserve key physiological contexts while allowing controlled experimental perturbation[1,13].

Engineering principles and core platform designs: Organ-on-a-chip platforms are defined by the integration of tissue engineering, microfabrication and microfluidics into devices capable of exerting biologically meaningful control over the cellular microenvironment[3,5].

Their engineering value lies in their ability to independently manipulate and subsequently integrate variables that are normally difficult to separate *in vivo*, including fluid flow, nutrient transport, tissue geometry and physical stimulation[8,15]. Across the literature, this level of control is consistently identified as a key factor contributing to the greater physiological relevance of organ chips compared with conventional static assays[6,13].

Microfluidics, tissue architecture and dynamic mechanical cues: Microfluidic architecture enables the precise handling of minute fluid volumes and supports physiologically relevant flow conditions that more closely approximate the *in vivo* milieu[5,8]. Flow serves not only as a



Flowchart 1: The problem the chip solves: why static culture and animal models fall short

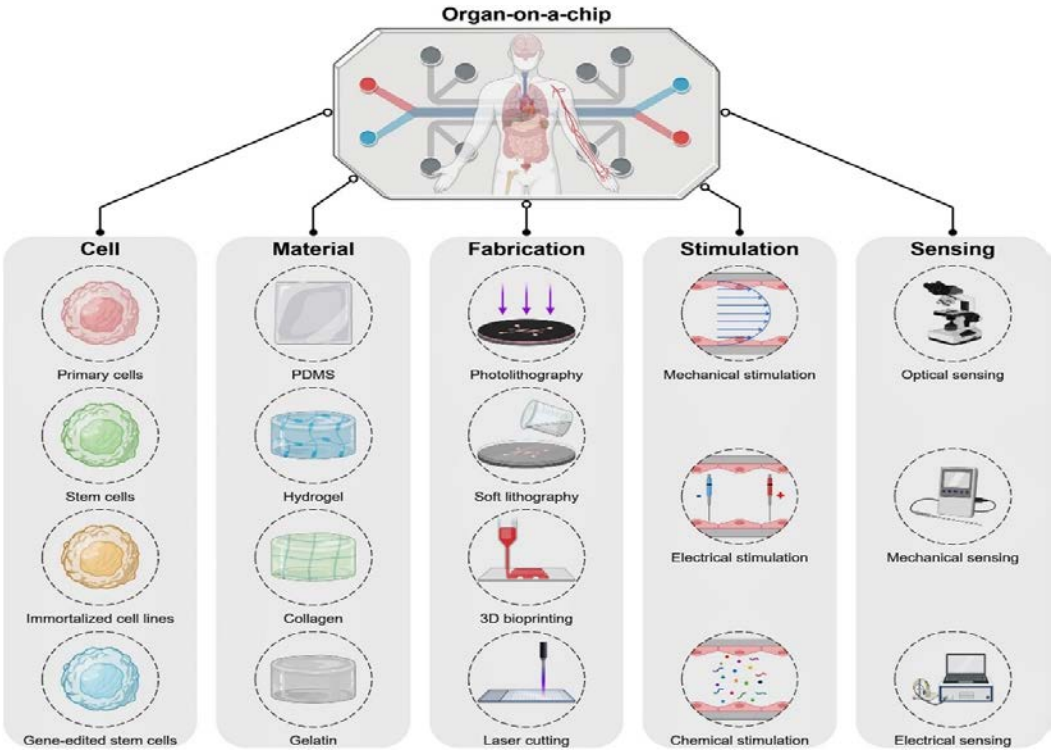


Fig. 1: Schematic representation of the key components involved in organ-on-a-chip engineering

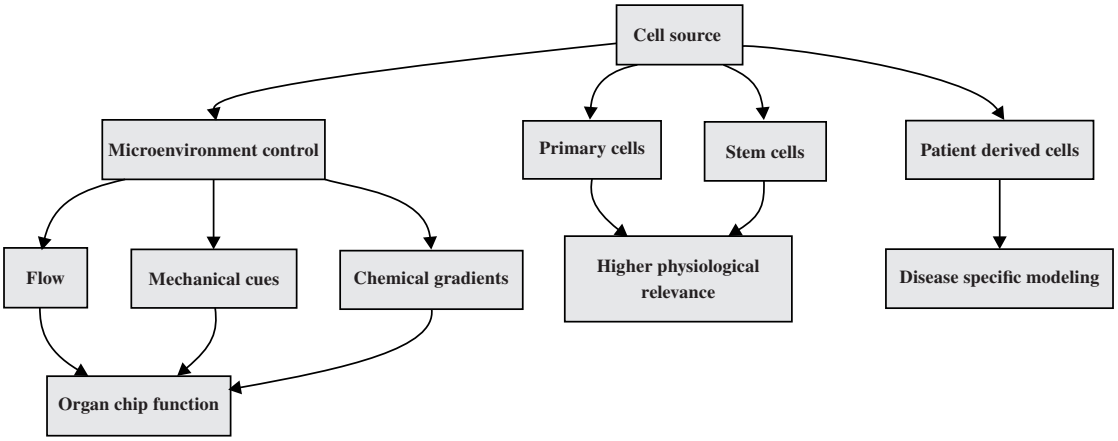
transport mechanism but also as a regulatory cue, influencing epithelial differentiation, barrier function and communication between adjacent tissue compartments[4,15]. Several reviews have noted that organ chips can incorporate mechanical and electrical stimulation, thereby extending their modeling capabilities beyond passive culture systems to organs whose functions depend on stretch, contraction, or electrophysiological activity[10,15]. In practice, this design approach enables the organ-specific reconstruction of intestinal, pulmonary, hepatic, cardiac and neuromuscular phenotypes under dynamic conditions[8,13,16].

Cell sources, extracellular matrix and biosensing integration: Cell sourcing is a major determinant of platform relevance because the predictive value of a chip depends on whether it incorporates primary cells, stem-cell-derived populations, or patient-derived cells that retain disease-specific characteristics[4,16,17]. Reviews of organoids-on-chips emphasize that combining organoid self-organization with chip-level environmental control can enhance cellular fidelity while maintaining experimental accessibility[9,10]. Extracellular matrix and scaffold selection are also important because these components influence tissue organization, polarity and long-term function, although the supplied sources discuss these considerations primarily at a conceptual rather than highly technical level[3,15].

Sensor integration represents another important design principle because real-time monitoring of pH, oxygen, metabolites and functional responses can transform organ chips from endpoint assays into systems capable of continuous monitoring[5,15]. This combination of controlled biological environments and integrated sensing is central to the potential of organ chips to support high-content translational research[13].

Organoids-on-chips and hybrid microphysiological systems: Hybrid systems combine the self-organizing capacity of organoids with the controlled perfusion and mechanical conditioning provided by microfluidic chips[9,18]. The literature suggests that these integrative approaches can improve structural fidelity, throughput, reproducibility and scalability while preserving lineage complexity that may be difficult to maintain in monolayer culture[9,10]. Importantly, the need for such integration is not solely technical but also biological: Organoids can recapitulate aspects of tissue architecture, whereas chips provide vascular-like transport and external mechanical or biochemical stimulation that organoids alone often lack[8,15]. Studies and reviews have also highlighted implementation challenges, including determining the appropriate differentiation stage at which organoids should be incorporated into chips and establishing perfusable vascular networks within these systems[10]. These unresolved design considerations represent an important frontier between proof-of-concept systems and broadly deployable microphysiological platforms.

Flowchart 2 illustrates how key engineering principles are integrated within a single organ-on-a-chip platform, combining tissue engineering, microfabrication and



Flowchart 2: The anatomy of an organ chip: core engineering building blocks

microfluidics to create devices capable of exerting biologically meaningful control over the cellular microenvironment[3,5].

Applications in disease modeling and human physiology: A major strength of organ-on-a-chip systems is their ability to model physiology at the organ level rather than focusing solely on isolated cellular behavior[1,4]. This capability makes them particularly valuable for studying diseases in which barrier function, tissue-tissue signaling, immune interactions, or biomechanical forces play central roles in pathogenesis[8,16]. Accordingly, the field has progressed beyond generic tissue models toward disease-specific and even phenotype-specific modeling across multiple organ systems[4,13].

Modeling organ-level physiology and pathophysiology: Human Intestine Chips exemplify how microfluidic control can reproduce physiological properties that are not readily captured by conventional culture systems, including sustained coculture with microbiome components and the controlled isolation of individual physical and chemical variables[9]. This capability is important because intestinal biology depends on epithelial barrier regulation, luminal exposure and microbial interactions that are difficult to maintain in static culture systems[4,8]. Similarly, Liver-Chip studies have shown that physiologically relevant flow and multicellular composition can reveal hepatocellular injury, steatosis, cholestasis and fibrosis phenotypes[17]. Together, these findings demonstrate that organ chips can model not only tissue structure but also the dynamic pathophysiological processes underlying disease progression and drug responses[4,13].

Multi-organ interactions and cross-talk in integrated platforms: The human body functions as an interconnected network and multi-tissue chip systems are designed to capture this physiological interdependence[4,18]. An integrated three-tissue system linking the liver, heart and lung demonstrated that drug responses can depend on interactions among these tissues, underscoring why isolated models may fail to capture clinically relevant effects[18]. Review literature similarly emphasizes that whole-body physiology and inter-organ cross-talk are important targets for next-generation microphysiological systems[4,13]. These platforms are therefore particularly valuable when pharmacological effects in one tissue alter drug exposure, metabolism, or toxicity in another tissue[17,18]. From a translational perspective, multi-organ integration is significant because it more closely approximates the sequential and systemic nature of human drug disposition than single-organ assays[6,18].

Modeling specialized tissues and complex phenotypes: Organ-on-a-chip systems have also been used to reconstruct specialized tissues that are difficult to study using conventional culture approaches[13,16]. The neuromuscular chip described in protocol form provides a three-dimensional (3D) motor unit model in which motor neurons and skeletal muscle interact through functional neuromuscular junctions, enabling live imaging of axonal outgrowth, neuromuscular junction formation and muscle maturation[16]. The same platform can reproduce disease-related phenotypes, including axonal regression, motor neuron death and muscle atrophy and can be developed using patient-derived induced pluripotent stem cells[16]. More broadly, reviews of organ chips have reported applications in brain, retina, heart, pancreas, tumor and barrier models, demonstrating the flexibility of these platforms for investigating complex phenotypes and specialized tissues[10,13]. This diversity is important because precision medicine requires models that reflect not only the organ of interest but also the relevant disease architecture.

Flowchart 3 illustrates the biological foundation of organ-on-a-chip platforms, demonstrating how these systems model physiology at the organ level rather than as isolated cellular behavior, with particular emphasis on barrier

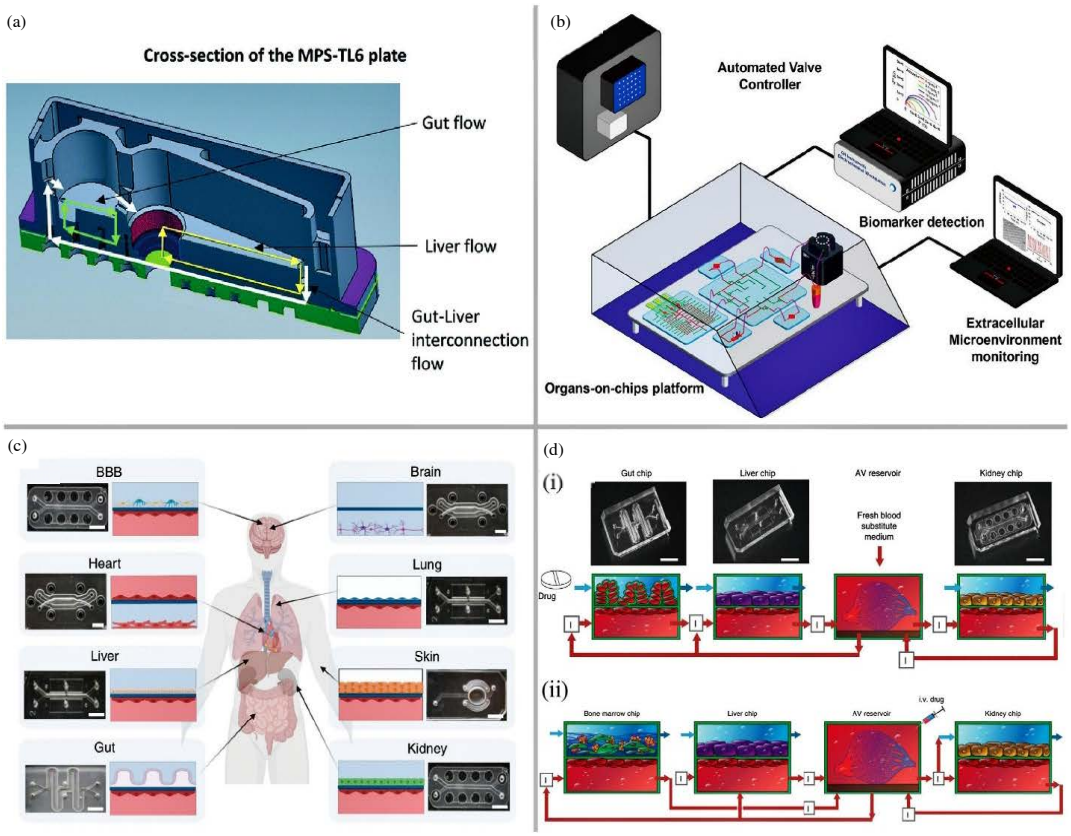


Fig. 2: The multi-organ-on-chip system[20]

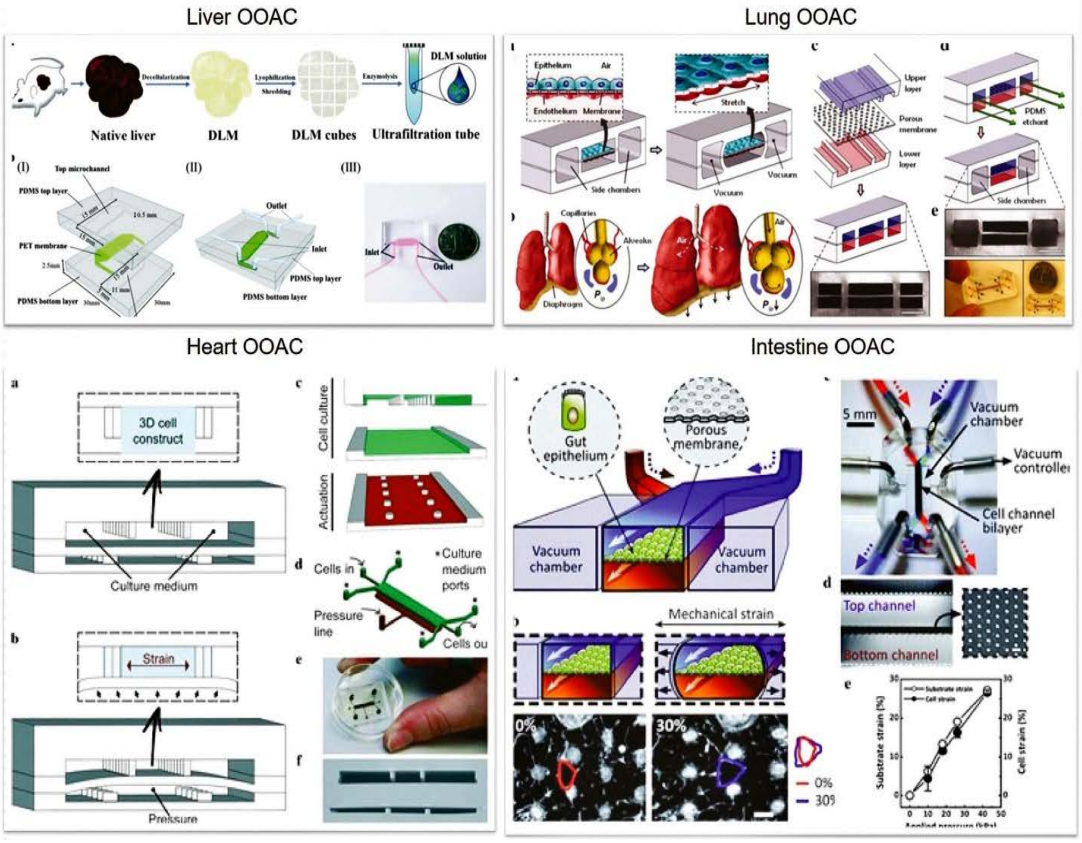
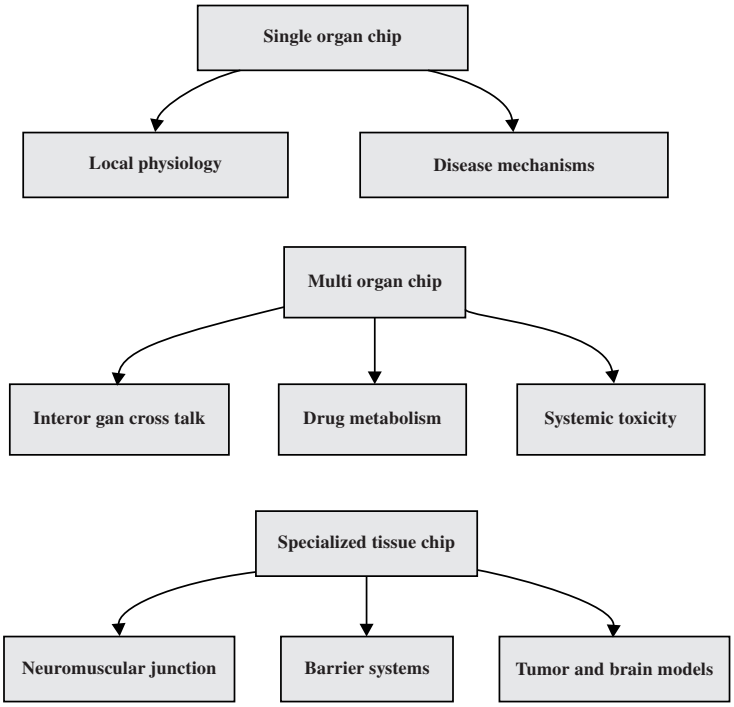


Fig. 3: Different methodologies for developing organ-on-a-chip models of the liver, lung, heart and intestine[21]



Flowchart 3: Disease modeling on a chip: from organ-level physiology to multi-organ cross-talk

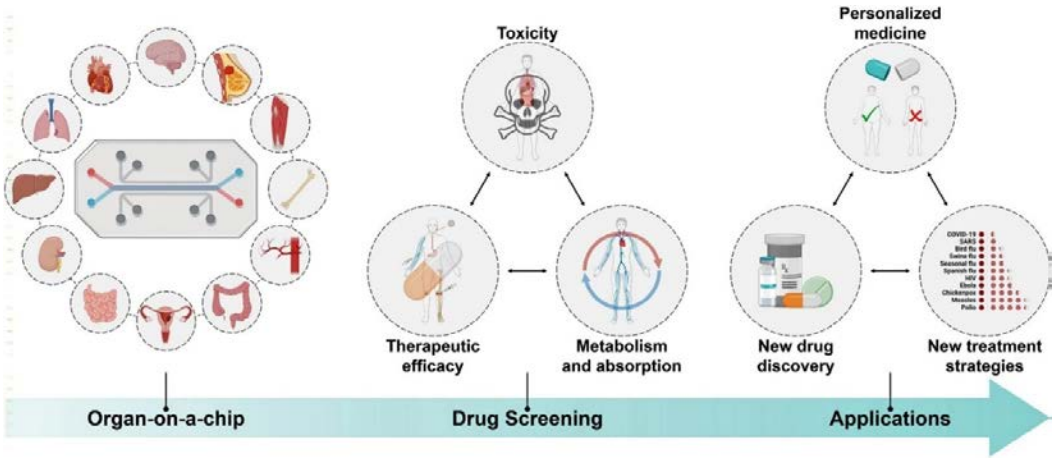


Fig. 4: Scheme of organ-on-a-chip for drug screening[9]

function, tissue-tissue signaling, immune interactions and biomechanical forces that contribute to disease pathogenesis[4,8,16]. The flowchart progresses from single-organ disease models, including intestinal and liver chips, to integrated multi-organ systems linking the liver, heart and lung and ultimately to specialized tissue models, such as neuromuscular chips[16-18].

Organ-on-a-chip platforms in drug discovery and safety assessment: Drug discovery remains one of the most prominent translational applications of organ-on-a-chip technology because these platforms were specifically developed to improve human relevance in efficacy and safety testing[2,6]. Reviews in this field consistently associate the high attrition rate in clinical development with the limitations of preclinical models in accurately reproducing human responses[7,13]. Accordingly, organ chips are increasingly being evaluated not merely as experimental model systems but also as decision-support tools that may inform and potentially reshape go/no-go decisions within drug development pipelines[4,19].

Efficacy screening, dose response and mechanism-based testing: The major advantage of organ chips in efficacy testing is that they provide a dynamic three-dimensional (3D) environment in which candidate compounds can be evaluated against more physiologically relevant tissue responses[6,7]. Reviews emphasize that these systems can

enhance the assessment of pharmacodynamics and pharmacokinetics because they permit controlled exposure, tissue-specific readouts and repeated sampling under flow[5,13]. Mechanism-based testing is particularly valuable when efficacy depends on barrier function, tissue maturation, or multicellular organization rather than on simple receptor engagement[8,16]. In this context, organ chips serve as a bridge between reductionist cell-based assays and *in vivo* experimentation by preserving sufficient biological complexity to reveal context-dependent effects[1,3].

Predictive toxicology and cross-species relevance: Predictive toxicology represents one of the clearest demonstrations of the value of organ-on-a-chip platforms. A human Liver-Chip reproduced multiple forms of liver toxicity, including hepatocellular injury, steatosis, cholestasis and fibrosis, while a multispecies version enabled comparisons among rat, dog and human tissues under controlled conditions[17]. This finding is important because it directly addresses a longstanding translational challenge: Toxicity signals observed in animal models may not reliably predict human risk[4,17].

Cross-species comparison is not merely descriptive; it provides a framework for distinguishing conserved toxic effects from species-specific liabilities[17]. Review and economic-analysis studies further suggest that such predictive platforms could reduce late-stage attrition and improve the interpretation of animal findings within a human-relevant context[6,19].

The same rationale applies to organ chips developed for other safety domains, including the gut, lung, skin, kidney and vascular systems, which are repeatedly highlighted in reviews addressing drug administration routes and organ-specific testing[7,13]. Because many adverse drug reactions arise from tissue-specific metabolism or barrier exposure, organ chips offer a particularly promising approach for earlier safety de-risking[5,13].

Performance, throughput and economic value in development pipelines: Beyond biological fidelity, organ chips must also be evaluated in terms of their practical performance within drug development workflows. A performance assessment and economic analysis of the human Liver-Chip concluded that predictive Organ-Chips could improve development efficiency and contribute to bringing safer and more effective medicines to market in less time and at lower cost[19]. This conclusion is consistent with broader reviews suggesting that organ-on-a-chip platforms may accelerate early-stage drug discovery and reduce dependence on animal testing[2,16]. At the same time, the literature does not suggest that organ chips have already displaced standard methods; rather, they are positioned as complementary tools whose value depends on assay robustness, reproducibility and adoption by industry and regulatory authorities[4,12].

A concise comparison of the principal development functions identified in the literature is presented below:

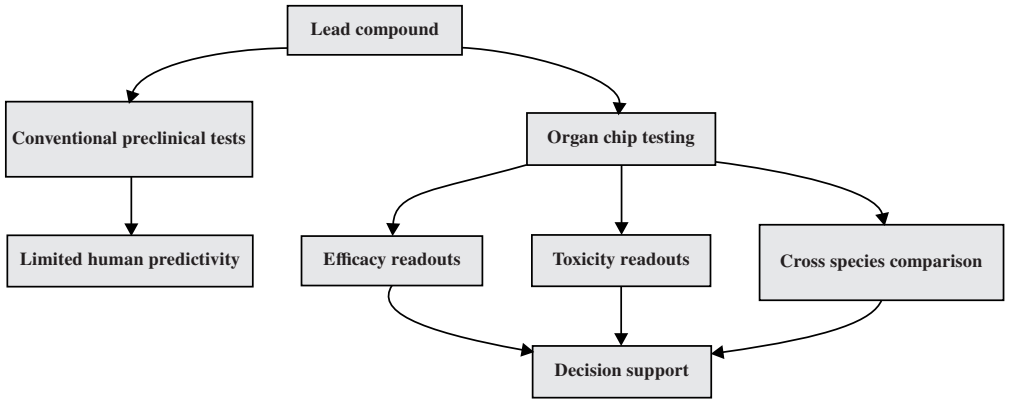
Development function	Organ-chip contribution	Supporting evidence
Efficacy screening	Human-relevant tissue responses under flow	5,7
Cross-species interpretation	Parallel human and animal-chip comparisons	17
Translational decision support	Better alignment with human outcomes	4,6
Translational decision	Better alignment with	4,6

The broader implication is that organ chips are evolving from experimental proof-of-concept systems into tools with increasing relevance to drug development pipelines, provided that they can consistently demonstrate predictive value beyond that of existing conventional systems[12,19].

Flowchart 4 summarizes the role of organ-on-a-chip platforms as decision-support tools within drug development pipelines, encompassing efficacy screening and dose-response testing in dynamic three-dimensional (3D) environments, mechanism-based testing in which barrier function and tissue maturation are important and predictive toxicology incorporating cross-species comparisons among rat, dog and human models[7,8,17]. The flowchart concludes with performance and economic evidence indicating that predictive organ chips may reduce late-stage attrition and development costs[6,19].

Personalized medicine, precision pharmacology and ai-enabled analysis: Personalized medicine is one of the most compelling translational applications of organ-on-a-chip systems because these platforms can incorporate patient-derived cells and disease-specific tissue architectures[4,16]. Unlike population-level assays, these systems can be designed to reflect individual genetic, epigenetic and functional differences that influence therapeutic responses[4,9]. The literature increasingly presents organ chips not only as disease models but also as living avatars for precision pharmacology[4,14].

Patient-derived cells, organoids and disease-specific chips: Patient-derived induced pluripotent stem cells have been used in neuromuscular chip models to generate motor neurons and skeletal muscle cells from disease-relevant material[16]. Reviews of organoids-on-chips suggest that combining patient-derived organoids with chip-level environmental control can enhance biological analysis and genetic manipulation while preserving tissue-specific properties[9,10]. This approach is particularly important for disorders in which the patient's own cellular state is a major determinant of phenotype or treatment response[4]. Disease-specific chips therefore provide a pathway toward individualized preclinical testing that is more tailored than conventional population-based screening[4,12].



Flowchart 4: From assay to decision: organ chips in drug discovery and safety testing

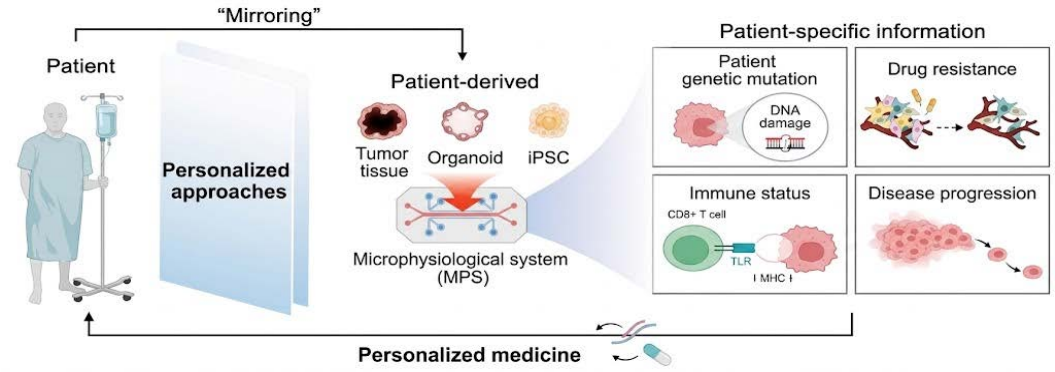


Fig. 5: Patient-derived microphysiological system for precision medicine[22]

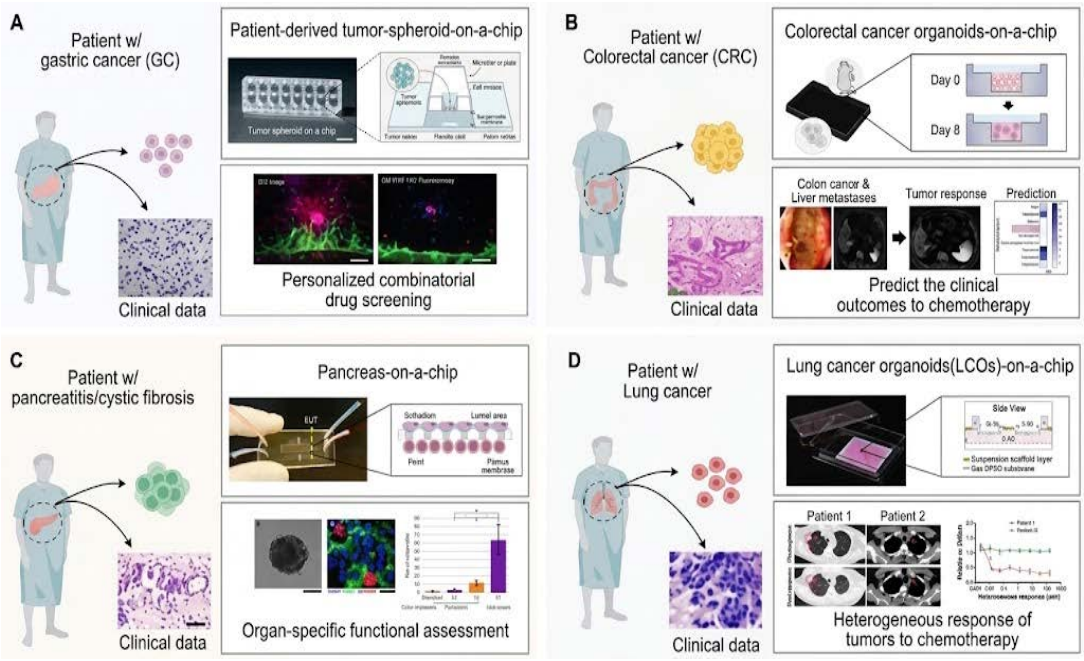


Fig. 6: Representative examples of patient-derived cell- and Organoid-Based Microphysiological Systems (MPS)

Stratifying drug response and supporting rare or complex diseases: Precision pharmacology depends on the capacity to distinguish responders from non-responders and to model rare or complex diseases that are poorly represented in standard experimental platforms[4,13]. The organ-on-a-chip literature explicitly describes applications

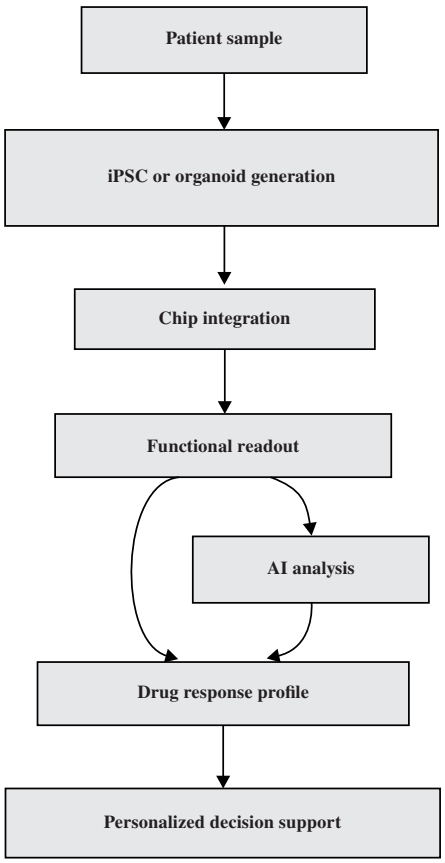
in rare genetic disorders, neuromuscular diseases and other conditions in which patient-specific tissue behavior is central to disease phenotype and therapeutic response[4,16]. Because many of these diseases involve complex tissue interactions or barrier dysfunction, a human-relevant engineered microenvironment can reveal responses that may remain undetected in simpler assays[8,18]. This approach also supports the ethical and scientific rationale for reducing dependence on animal models when relevant human samples are available[4,12].

Artificial intelligence for design, automation and data interpretation: AI has emerged as a complementary technology because organ chips generate complex, high-dimensional datasets that can be difficult to interpret manually[11]. Reviews in this area suggest that AI can enhance platform design, automation and data processing, thereby addressing challenges related to reproducibility and the analysis of large datasets generated by chip-based evaluations[11,12]. The most immediate value of AI is likely to lie in pattern recognition, integration of functional readouts and experimental optimization rather than in replacing biological interpretation[11]. In this context, AI is best understood as an enabling layer that can help organ-on-a-chip platforms progress from technically sophisticated experimental systems to scalable analytical tools[11,13].

Flowchart 5 illustrates how organ-on-a-chip platforms can progress from generalized models toward individualized testing by incorporating patient-derived cells and disease-specific tissue architectures, enabling these systems to function as "living avatars" for precision medicine[4,16]. The flowchart further demonstrates how artificial intelligence provides an enabling layer for platform design, automation and high-content data interpretation, facilitating the transformation of complex datasets generated by organ chips into scalable analytical tools[11,12].

Current limitations, regulatory challenges and future directions: Despite their strong translational potential, organ-on-a-chip platforms remain constrained by challenges related to standardization, validation and implementation[4,12]. The field is advancing rapidly but its long-term success will depend on whether experimental complexity can be translated into reproducible, standardized and regulatory-compliant workflows[11,13]. These limitations are not peripheral considerations; rather, they will determine whether organ chips remain specialized research tools or evolve into routinely used decision-support systems[12,19].

Standardization, reproducibility and validation across laboratories: Reproducibility is repeatedly identified as a major barrier because chip performance can be influenced by cell source, batch-to-batch variability, differentiation stage and device configuration[10,11]. Reviews of organoid-



Flowchart 5: Patient-specific chips and ai-enabled precision pharmacology: from patient cells to personalized therapy

chip integration specifically highlight uncertainties regarding the optimal stage at which organoids should be introduced into devices and the strategies required to establish perfusable vasculature within these systems[10]. The same literature also emphasizes the difficulty of comparing data across laboratories when platforms are highly customized[12,13].

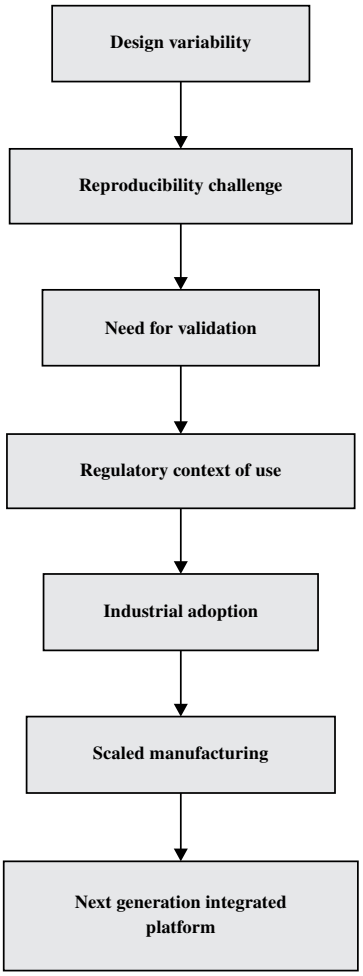
Validation therefore requires not only proof-of-concept studies but also rigorous benchmarking studies demonstrating that specific chip-derived readouts can predict clinically meaningful outcomes more accurately than existing experimental models[4,19].

Regulatory acceptance, translational pathways and FDA modernization act 2.0: Regulatory adoption depends on evidence demonstrating that organ chips are reliable, scientifically robust and suitable for informing drug development decisions[4,12]. Recent reviews highlight the FDA Modernization Act 2.0 as an important policy development because it reduced the emphasis on mandatory animal testing and increased the visibility of advanced *in vitro* models, including organoids and organ-on-a-chip systems[12]. However, policy changes alone do not establish regulatory

acceptance; regulatory agencies still require standardized performance metrics, transparent validation procedures and clearly defined contexts of use[12,1]. In practice, translation will likely progress initially through niche applications in which organ chips can demonstrate measurable advantages over existing assays[4,17].

Scalability, commercialization and next-generation integration: Commercial adoption will depend on manufacturability, throughput and compatibility with industrial workflows[6,19]. Reviews suggest that the next generation of systems will likely be more modular, sensor-rich and deeply integrated with organoids and AI-assisted analysis[9,11]. These platforms may also incorporate additional organ systems, advanced vascularization strategies and closed-circuit multi-organ configurations to better recapitulate whole-body physiology[4,18]. The future of organ-on-a-chip technology therefore lies not in a single universal chip but in a family of interoperable platforms tailored to specific scientific, therapeutic and regulatory applications[12,13].

Flowchart 6 illustrates the remaining challenges and the projected path forward, including standardization, reproducibility and validation across laboratories; regulatory acceptance, including the FDA Modernization Act 2.0 and the scalability and commercialization required for broader industrial adoption[10-12]. The future outlook encompasses modular, sensor-rich, multi-organ systems integrated with organoids and AI, positioning organ chips as potential routine tools for predictive toxicology, rare-disease modeling and individualized therapy selection[4,18,19].



Flowchart 6: Barriers and beyond: Standardization, regulation and the future of organ chips

Future of organ-on-a-chip platforms in biomedicine: Organ-on-a-chip technology has matured into a substantive platform for modeling human physiology, disease and inter-organ communication[4,18]. Its central contribution is to restore biological context to experiments that have historically relied on simplified monolayers or species-mismatched animal models[1,2]. Across the literature, organ chips have demonstrated value in reproducing organ-specific pathophysiology, detecting toxicities, supporting efficacy testing and enabling patient-relevant modeling for precision medicine[4,16,17]. The convergence of organ chips with organoids and AI further strengthens this trajectory by incorporating greater cellular complexity and computational scalability[10,11].

Synthesis of key contributions to drug discovery and personalized care: In drug discovery, organ chips offer a more human-relevant bridge between target validation and clinical testing, particularly in contexts where toxicity and inter-organ effects limit therapeutic success[6,19]. In personalized care, they provide a platform for patient-specific experimentation that can incorporate disease-derived cells and reveal individualized pharmacological responses[9,16]. These are not separate achievements but interconnected outcomes of the same engineering principle: when the tissue environment is more accurately reproduced, biological inference becomes more clinically informative[3,15]. This principle underlies the increasing characterization of organ chips as living avatars and translational microphysiological systems[4,14].

Outlook for clinical translation and precision therapeutics: Future progress will depend on addressing challenges related to reproducibility, validation and regulatory acceptance while preserving the biological complexity of these platforms[10,12]. If these challenges are successfully addressed, organ-on-a-chip systems could become routine tools for predictive toxicology, mechanism-based screening, rare-disease modeling and individualized therapy selection[4,19]. The most plausible path forward is likely to be incremental but transformative, beginning with broader adoption in specific high-value applications and

progressing toward deeper integration into industrial and regulatory workflows[12,13]. Along this trajectory, organ-on-a-chip platforms have the potential to become important enabling technologies for precision therapeutics and human-relevant biomedical research[4,11].

CONCLUSION

Organ-on-a-chip (OOC) technology represents a promising next-generation approach for developing more physiologically relevant models of human tissues and organs and addressing important limitations associated with conventional two-dimensional cell cultures and animal models. The integration of microfluidics, tissue engineering, biomaterials, living human cells and stem-cell-derived organoids has substantially improved the ability of OOC platforms to reproduce key structural, mechanical, biochemical and functional characteristics of native tissues. Their applications in disease modeling, drug discovery, predictive toxicology, efficacy screening, pharmacokinetic assessment and personalized medicine highlight their considerable potential to enhance the translational relevance of biomedical research and therapeutic development. The incorporation of patient-derived cells, advanced biosensing and artificial intelligence further expands the capabilities of OOC systems by enabling more precise disease-specific modeling, automated analysis, high-content data interpretation and precision pharmacology. However, widespread clinical and industrial adoption remains constrained by challenges involving standardization, reproducibility, scalability, regulatory validation and commercialization. Addressing these challenges will require interdisciplinary collaboration, harmonization of experimental and analytical standards, rigorous validation against clinical outcomes and the development of appropriate regulatory frameworks. Continued advances in organoid integration, biosensing, artificial intelligence and multi-organ platforms are expected to further enhance the biological fidelity and translational utility of OOC systems. Collectively, OOC technology has substantial potential to become an important component of human-relevant biomedical research and precision therapeutics, particularly by improving the prediction of therapeutic responses and supporting more efficient, personalized and clinically relevant drug development.

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