

Experimental models and tools in animal research: From classical approaches to emerging trends

Dounia BKIRI

Department of Animal Physiology and Therapeutics,
Institute of Agronomy and Veterinary Medicine Hassan II,
Rabat, Morocco

Jamal HOSSAINI HILALI

Department of Animal Physiology and Therapeutics,
Institute of Agronomy and Veterinary Medicine Hassan II,
Rabat, Morocco

From invertebrates like fruit flies to vertebrates such as mice and aquatic organisms, animal models have long been central to biological discovery. Despite ethical debates and growing regulatory constraints, animal research remains a cornerstone for understanding pathophysiology and developing new therapies for both humans and animals. Significant advances have refined these models, improving their relevance in scientific research and experimental education. However, the emergence of innovative systems, including computer simulations, organ-on-a-chip technologies, and genetically modified organisms, offers promising alternatives that can complement or, in some cases, replace animal experimentation. These tools accelerate scientific progress, enhance educational training, and improve the translation of results to human biology. Yet, systematic reviews have revealed discrepancies between animal and human responses, calling into question the predictive validity of traditional models. This ongoing debate highlights the need for a balanced integration of classical and emerging approaches to strengthen scientific reliability, educational value, and ethical standards. This review aims to provide an overview of experimental models, contrasting classical and novel systems, and to discuss their applications, limitations, and the evolving regulatory frameworks that guide their use in modern research and education.

Keywords: Animal models- Education- Animal research- Emerging models- Classical models- Animal Ethics

INTRODUCTION

Since ancient times, humans have depended on animals to supply them with their demands in various fields. However, the role of animals is not just restricted to these traditional applications. Animal models have been contributing largely to scientific experiments for centuries and their use in the

pursuit of medical knowledge and research has continued for millennia (Ericsson et al., 2014). The term model is frequently used to describe an experimental system, the “animal model” derives from the Latin word anima (meaning soul or spirit) and the word model, which refers to something that imitates or resembles another (Claudia Janeth Juárez-Portilla, 2019).

Animal models are based on the principle of comparative medicine (Jota Baptista et al., 2021), serving as tools that can replicate physiological and pathological processes (Swearengen, 2018). Already in ancient Greece, animals were employed by Aristotle to study their living organisms. But it was in the 18th and 19th centuries that usage of animal models grew exponentially. Jean Baptiste Van Helmont, Francesco Redi, John Needham, Lazzaro Spallanzani, Lavoisier, and Pasteur were

among the scientists who employed experiments to ascertain the origin of life (Oparin, 1957; Andersen, 2017). It is important to recognize that traditional models are responsible for nearly 90% of Nobel Prizes in physiology and medicine, which involved animal models in their research (Andersen, 2017).

Currently, the use of laboratory animals extends across various fields, particularly in experimental teaching and scientific research. In addition, animals play a crucial role in teaching as a medium for studying students of life sciences, medicine, and veterinary medicine, by providing their first contact with laboratory animals (Carnovale et al., 2021). This helps students learn, especially anatomy, animal physiology, pathology, pharmacology, and experimental procedures, more comprehensively. It is also important to emphasize that the most of the experimental operations are still inseparable from frogs, mice, rats, rabbits, and other laboratory animals. However, in teaching and scientific research, laboratory animal welfare and ethical education have attracted significant attention from society and should be widely integrated into education (Kang et al., 2022).

Animal models have also played a crucial role in advancing biomedical science, contributing to the development of vaccines and antibiotics, as well as enhancing our fundamental understanding of human disease processes. For example, monkeys were used in the development of the polio vaccine, canines contributed to the discovery of insulin, and genetically modified mice and rats have underpinned diabetes research. Moreover, most antibiotics are tested on animals before human use (Domínguez-Oliva et al., 2023). Notably, the current pandemics' pathology, such as the 2019 Coronavirus disease, has been studied in primate, rodent, and porcine models to develop treatment strategies (Domínguez-Oliva et al., 2023). Compared to the traditional approach, the new approaches still have their place (Xu et al., 2018). In recent years, the need to find appropriate alternatives has become increasingly important for advancing experimental teaching and scientific research, particularly with the emergence of virtual simulations and 3D experimental learning. Public awareness and discussion regarding animal experiments and alternative methods have also grown significantly. In this context, the concept of the "Three Rs" - Replacement, Reduction, and Refinement of animal experiments - is central. A primary goal within the Three Rs, scientific community is to develop predictive non-animal models and to effectively integrate all available data from in vitro, in silico, and omics approaches, thereby improving both the quality of research and educational outcomes (Neuhaus et al., 2022). This review aimed to highlight the significance of classical experimental models in educational processes, and scientific investigation, and how these tools and models evolved over time, by giving a short overview on their advantages and limitations.

EXPERIMENTAL MODELS

Conventional models

While researchers most often use rodents and other mammals as animal models for scientific research, a variety of other models also exist, such as zebrafish, the nematode *Caenorhabditis elegans*, and the fruit fly *Drosophila melanogaster*. These models offer advantages in cost, efficiency and ethics (Vila et al., 2014). Wild-type or natural models refer to animals that have not undergone genetic manipulation or experimental treatment. Classical experimental models have long been the foundation of physiological investigations. Rodents (rats, mice, guinea pigs, hamsters and rabbits) are extensively used due their genetic closeness to humans, short reproductive cycles, and well-documented physiology (Robert, 1997). Other traditional Models, such as amphibians, zebrafish, *C. elegans*, and *D. melanogaster*, provide complementary advantages depending on the research objectives (Vila et al., 2014). For example, *Drosophila melanogaster* is utilized to study neurological diseases like epilepsy (Lasko and Lüthy, 2021). *C. elegans* for mechanisms underlying obesity (Benditha et al., 2021), and aquatic animals to model metabolic diseases, such as diabetes (Zang et al., 2018). To illustrate the evolution of animal model usage in scientific research, a bibliometric analysis of PubMed data from 1990 to 2024 was conducted. This analysis highlights the changing trends in publication frequency among classical models such as the mouse, rat,

rabbit, guinea pig, amphibians (*Xenopus*), and small fish (zebrafish), reflecting shifts in research priorities and ethical considerations over the past decades (Bédard et al., 2020).

Rodents

To date, rodents remain the predominant species used teaching and scientific research (Domínguez-Oliva et al., 2023; Makowska and Weary, 2019; Robinson et al., 2019), they have been employed in teaching, scientific, veterinary, and comparative medical research to investigate physiological mechanisms and gene mutations. Rodents, particularly (*Mus musculus*) and rats (*Rattus norvegicus*), have long been central to each research owing to their genetic tractability, cost-effectiveness and practicality in laboratory settings (Ferreira et al., 2025). Over the past 25 years, the laboratory mouse has become the dominant model in biomedical research, while the use of most non-rodent mammals has steadily declined (Ericsson et al., 2014). Rodent models play a vital role in evaluating the early-stage therapeutic effects of new drugs and remain essential for advancing translational research (Ericsson et al., 2014). Rabbits also hold great value in both education and research due to their biological and physiological characteristics, which are comparable to those of humans. As intermediate models, they combine the ease of handling of smaller species with greater physiological relevance than rodents (Ferreira et al., 2025). They are used in various biomedical fields, including cardiovascular, immunological, ophthalmological, and neurological studies, as well as in toxicology testing, vaccine development, and behavioral research. In educational settings, rabbits are frequently utilized in practical laboratory classes, particularly in physiology and pharmacology. Readily available and generally docile, they represent a practical model, when ethical guidelines and research protocols are carefully respected (Thomas et al., 2012).

The Guinea pig

The term 'guinea pig' has become synonymous with scientific experimentation. Classified as a non-rodent (Noguchi et al., 1994), *Cavia porcellus* has been used in research for approximately 200 years. Historically, guinea pig were pivotal in the study of infectious diseases such as tuberculosis and diphtheria, efforts that contributed to Nobel Prizes winning discoveries (Padilla-Carlin et al., 2008). Today, guinea pig remain valuable models for investigating bacterial infections of the lungs, reproductive tract, eyes, ears, as well as viral infections, including influenza (Lowen et al., 2014). They also play a key role in the development of vaccines and other preventive measures to combat these infections (Padilla-Carlin et al., 2008). Despite their contributions, guinea pigs are less frequently used than other animal models, largely due to higher costs and limited availability of immunological reagents (McMurray, 2001). Notably, they are considered essential in asthma research, especially for pharmacological studies, where their physiological responses are closer to humans than those of mice (Adner et al., 2020). Guinea pigs are also used in educational settings to teach immunology and pharmacology, allowing students to observe physiological responses in a live mammalian model.

Amphibians

Amphibians have long been a cornerstone in the study of physiology. Early physiologists favored them due to their small body size, local availability, and tolerance of surgical procedures. This diverse group of tetrapods has been instrumental in advancing our understanding of musculoskeletal, cardiovascular, renal, respiratory, reproductive, and sensory system physiology (Burggren and Warburton, 2007). Amphibians offer several advantages for experimental studies (Bédard et al., 2020), including accessibility, ease of handling, and suitability for detailed physiological investigations, making them highly valuable for generating new insights in fundamental physiological research aimed at generating new insights, and strong applicability in physiological research. Amphibians are still widely used in educational laboratories to demonstrate physiological principles, such as nerve-muscle function, heart activity, and respiratory mechanisms, providing students with hands-on learning experiences (Rees et al., 2025).

Fish

Over the past decade, small fish such as zebrafish (*Danio rerio*) and medaka (*Oryzias latipes*) have increasingly been used as animal models for studying human diseases, due to the high degree of conservation in genome organization and physiology with humans. A major advantage of these models is their suitability for real-time live imaging of various biological processes, including skeletal development and repair, which has contributed to a significant increase in publications involving teleosts in biomedical research (Lleras-Forero et al., 2020). Today, zebrafish remain the predominant small fish model species in laboratories worldwide, with medaka being used to a lesser extent (Parichy et al., 2009; Wittbrodt et al., 2002). Their short life cycles allow researchers to generate large numbers of subjects in a short period, facilitating high-throughput experiments (Vila et al., 2014). Beyond fundamental research, zebrafish have provided valuable insights for the pharmaceutical industry (Patton et al., 2021). They serve as comparative models in a wide range of fields, including cardiovascular research, bone biology, immunology, and cancer studies (Van Rooijen, 2017; Lleras-Forero et al., 2020; Tessadori et al., 2018). Several characteristics make these small fish especially suitable as laboratory models: external fertilization, rapid embryonic development, small body size, ease of handling, low maintenance costs, and optical transparency of embryos and adult fish (Bauer et al., 2021). Despite their aquatic nature and differences from terrestrial mammals, teleosts can faithfully replicate many important aspects of human physiology and disease phenotypes (Lleras-Forero et al., 2020). Small fish models are increasingly integrated into educational laboratories, allowing students to observe embryogenesis, organ development, and disease phenotypes in real time, enhancing hands-on learning experiences (Gladys et al., 2015; Wilk et al., 2018).

Non-Human Primates (NHPs)

Non-human primates (NHPs) are considered the most suitable experimental models for biomedical research due to their close phylogenetic relationship with humans (Zhang et al., 2014). Historically, four NHP species, chimpanzees, cynomolgus monkeys, rhesus monkeys, and marmosets, have been widely used in biomedical studies with notable success (Johnsen et al., 2012). However, chimpanzees and other great apes are now banned from invasive biomedical research in many countries (Johnsen et al., 2012). NHPs are particularly valuable because their anatomy, physiology, immunology, and neurology closely resemble those of humans, facilitating the study of disease mechanisms and the evaluation of new therapeutic interventions (Cauvin et al., 2015; Zhang et al., 2014). Several primate models have been established to investigate human diseases, including infectious, cardiovascular, endocrine, reproductive, neurological, and ophthalmic disorders. Despite their scientific value, the use of NHPs is severely limited by ethical concerns, high costs, and restricted availability (Nakamura et al., 2021; Zhang et al., 2014). NHPs are occasionally used in advanced educational settings, such as comparative anatomy or neuroscience courses, to demonstrate physiological and behavioral principles that are highly translatable to humans (Takemura et al., 2019).

ALTERNATIVES TO ANIMAL MODELS

By the early twentieth century, the use of animal models had expanded considerably. Despite ongoing ethical concerns, animal experimentation became the standard approach for demonstrating biological significance. Over more than 150 years of research, science has progressed from uncovering fundamental biological principles to reproducing complex physiological and pathological events in the laboratory (Ericsson et al., 2014). Non-animal alternatives, including cell cultures, 3D tissue cultures, organs-on-chips, mathematical models, stem cells, bioprinting, in silico testing, and high-performance computer simulations, have gained increasing popularity in recent years and show great promise for the future (NIH, 2023). With improvements in alternative methods, the concept of reducing, refining, and replacing the use of animal models in research, the 3Rs increases more and more feasible. In major research countries

and territories, such as the United States, United Kingdom, China, Germany, Japan, Canada, and across the European Union, the use of animals in scientific research is strictly regulated (Conroy, 2022). These regulations aim to ensure proof of ethical practices, promote animal welfare, and encourage the development and adoption of alternative techniques wherever feasible, due to their potential to significantly reduce the number of animals used in experiments and to offer high reproducibility of results (Wysoczański et al., 2024).

Organ-on-a-chip models

Recent advances in the microfluidics-based Organ-on-a-Chip (OOC) technology, also known as microphysiological systems, have provided a promising alternative to animal testing (Ma et al., 2021). These microfluidic devices culture living cells in continuously perfused, micrometer-scale chambers, replicating the physiology and functionality of tissues and organs on a chip. The origin of OOC technology dates back over three decades, beginning with the application of microfluidic devices for cell culture and biological analysis (Bhatia and Ingber, 2014). Progress in OOC has been largely driven by advancements in microfluidics since the late twentieth century (Ma et al., 2021). OOC systems offer unique advantages over conventional *in vitro* and *in vivo* models, enabling high-resolution, real-time imaging and detailed investigation of biochemical, genetic, and metabolic processes in functional tissue and organ contexts. They have significant potential to advance understanding of tissue development, organ function, and disease pathogenesis. In drug discovery and development, OOC platforms facilitate the study of molecular mechanisms, lead compound selection, toxicity testing, and biomarker identification (Srivastava et al., 2024). Furthermore, OOC technology provides a powerful alternative in teaching laboratories, allowing students to explore organ-level physiology in a controlled, human-relevant system. For instance, a liver-on-a-chip can be used to measure hepatocyte responses to varying drug concentrations, assess cell viability, and analyze metabolite production. Such hands-on experiments enhance learning outcomes by improving understanding of organ-specific drug metabolism, experimental data interpretation, and appreciation of the ethical benefits of reducing animal use (Koyilot et al., 2022).

Genetically modified models

Rodent models, particularly mice, have long been central to biomedical research, with several hundred mouse stocks containing spontaneous or induced mutations used as models of human disease and for the study of metabolic processes. Genetically modified mouse models in which a specific gene is removed or replaced, particularly by a human gene, have proven to be invaluable tools for investigating gene function and its relationship to disease. Moreover, these models serve as powerful systems for the identification and validation of target genes, and for advancing our understanding of the molecular mechanisms underlying drug-induced toxicity through mechanistic studies. Traditionally, mutations either occurred spontaneously or were induced chemically or through radiation; however, recent advances now allow the generation of mutant strains through precise genomic engineering, with increasing specificity and efficiency. The development of knockout and humanized mouse models has therefore provided unprecedented opportunities for researchers in the field of drug metabolism and transport. From an educational perspective, genetically modified organisms such as transgenic mice, zebrafish, or *Drosophila* are also being introduced in teaching laboratories to illustrate gene expression, inheritance, and physiological regulation *in vivo*, helping students connect genotype to phenotype while promoting ethical awareness through refinement and reduction of animal use (Auer and Del Bene, 2014).

Computer simulation models

When scientists consider alternatives to traditional animal testing, they usually speak of tissue cultures, isolated organ preparations, biochemical baths, or other *in vitro* biosystems. Only within the last few decades have computer models reached a realistic potential as alternatives to the use of animals in biomedical research. Computer-based simulations now represent an important step in the scientific method, allowing hypotheses to be tested *in silico* before being validated

experimentally, thereby reducing the number of animals used in biomedical experimentation. In educational contexts, platforms such as PhysioEx, SimBio Virtual Labs, and Virtual Physiology™ provide interactive modules where students can explore cardiovascular regulation, endocrine control, or pharmacological responses in virtual organisms. These tools offer immediate feedback, customizable experimental parameters, and reproducible results that help students grasp complex physiological mechanisms without ethical or safety concerns. However, while virtual simulations promote conceptual understanding and analytical reasoning, they cannot fully replicate the tactile, procedural, and sensory experiences of hands-on laboratory work. Therefore, integrating computer simulations as pre-laboratory or complementary learning tools, rather than complete substitutes, can significantly enhance students' preparedness for real experimental settings (De Jong et al., 2013; Rutten et al., 2012). Ongoing advances in artificial intelligence, haptic interfaces, and physically based rendering techniques are expected to increase the realism and educational value of simulation systems, paving the way for more ethical and efficient biomedical training (Malone et al., 2010).

COMPARATIVE ANALYSIS: CLASSICAL VS. EMERGING MODELS

Most research is conducted using classical model species, such as laboratory mice (*Mus musculus*), rats (*Rattus norvegicus domestica*), the fruit fly (*Drosophila melanogaster*), small fish and Non-Human Primates. These models offer clear advantages, including access to well-characterized strains and a wealth of high-quality preexisting data (Holtze et al., 2021) i.e., laboratory mouse (*Mus musculus*). Selecting an appropriate animal model is essential for advancing scientific research, evaluating therapeutic strategies, and translating preclinical findings into clinical applications. Each model has unique strengths and limitations that influence its applicability (Ferreira et al., 2025). However, classical models can introduce interpretation biases due to species-specific characteristics, which may lead to flawed or misleading generalizations. As noted by Greek and Menache (2013), traditional animal models often fail to accurately predict human responses, underscoring the need for more human-relevant and ethically responsible alternatives (Greek and Menache, 2013). While animal models remain foundational and rich in investigative potential, ethical considerations increasingly shape their use. The global adoption of the Three Rs principle (Reduction, Replacement, and Refinement) has encouraged the development of alternative methods to animal use (Kiani et al., 2022); rats, mice and purpose-bred birds comprise almost 90% of the animals that are used for research purpose. However, growing awareness of the sentience of animals and their experience of pain and suffering has led to strong opposition to animal research among many scientists and the general public. In addition, the usefulness of extrapolating animal data to humans has been questioned. This has led to Ethical Committees' adoption of the 'four Rs' principles. Emerging strategies, including integrative experimental models, in silico simulations, and artificial intelligence-driven approaches, aim to refine our understanding of biological mechanisms and accelerate the development of personalized therapies (Singh, 2022). In educational settings, simulator training in laboratory animal science has been shown to effectively support the 3Rs, particularly for inexperienced students, by reducing the need for live animal exercises (Humpenöder et al., 2021). However, current simulators cannot fully replace live animals, highlighting the need for more realistic designs and further research for broader implementation. Similarly, Andrew Knight (2007) demonstrated that non-harmful teaching alternatives - such as simulations, ethically sourced cadavers, and surgical models - can achieve equivalent or superior learning outcomes in veterinary education, while enhancing student confidence, satisfaction, and compliance with animal welfare standards.

Despite these advances, suitable alternatives are not yet available for all areas of scientific and educational research, due to prior validation requirements and substantial financial and technical investments. Consequently, classical animal models remain essential in many contexts to provide reliable and reproducible data. Table 1 summarizes the main characteristics, advantages, and limitations of both classical and emerging experimental models, emphasizing their relevance and

applications in both research and teaching contexts.

CONCLUSION

This review has described and contextualized classical experimental models and their evolution. Although alternative approaches are continually developing, animal research remains essential, and the relevance of animals for advancing both veterinary and human health is undeniable. Over time, the continued use of various animal models has been crucial in academic and research activities. Researchers employing animals must justify their use and ensure that their work adheres to ethical principles and high standards of laboratory practice.

Given increasing concerns over animal welfare, the development of innovative technologies offers promising alternatives, including genetically engineered organisms, organs-on-chips, and in silico simulations. Animal ethics is as important as human welfare, and the introduction of alternatives requires reexamining the use of sentient animals in both research and teaching, with a focus on reduction, refinement, and, ultimately, replacement. Nevertheless, these alternatives cannot yet fully replace classical models.

In the meantime, animal models continue to provide a solid foundation and remain a key component of vital research. Innovation in tools and models is crucial for advancing experimental teaching and scientific research. While these technologies cannot completely eliminate the need for animal use, they aim to complement or partially replace classical approaches. Moreover, despite their advantages, these technologies are often limited by high costs and the sophisticated equipment required, which partly explains why their widespread adoption remains constrained. Future research should focus on enhancing the realism and applicability of alternatives, such as organ-on-a-chip systems, 3D tissue cultures, and in silico models. While promising for research and teaching, classical animal models remain essential where alternatives are not fully validated. Broader adoption will require training, funding, and supportive policies to ensure ethical and effective implementation.

REFERENCES

Adner M., Canning B.J., Meurs H., Ford W., Ramos Ramírez P., Van Den Berg M.P.M., Birrell M.A., Stoffels E., Lundblad L.K. A., Nilsson G.P., Olsson H.K., Belvisi M.G., Dahlén S.-E. (2020). Back to the future: Re-establishing guinea pig in vivo asthma models. *Clinical Science*, 134: 1219-1242.

Andersen M.L., Winter L.M. (2017). Animal models in biological and biomedical research-experimental and ethical concerns. *Anais da Academia Brasileira de Ciências*, 91(suppl 1): e20170238.

Auer T.O., Del Bene F. (2014). CRISPR/Cas9 and TALEN-mediated knock-in approaches in zebrafish. *Methods*, 69: 142-150.

Bauer B., Mally A., Liedtke D. (2021). Zebrafish Embryos and Larvae as Alternative Animal Models for Toxicity Testing. *International Journal of Molecular Sciences*, 22: 13417.

Bédard P., Gauvin S., Ferland K., Caneparo C., Pellerin È., Chabaud S., Bolduc S. (2020). Innovative Human Three-Dimensional Tissue-Engineered Models as an Alternative to Animal Testing. *Bioengineering (Basel, Switzerland)*, 7: 115.

Benditha D., B., Rich Milton R., D., Reign Arwen S., C., Maricris A., D., Mary Grace M., M., Andrea R., M., Neil Zhyra L., Z. (2021). In-vitro activity of ethanolic extract of *Lentinus strigosus* mycelia in N2 wild strain *Caenorhabditis elegans* - An animal model for obesity and its chemical composition. *Journal of Applied Biology and Biotechnology*: 41-46.

Bhatia S.N., Ingber D.E. (2014). Microfluidic organs-on-chips. *Nature Biotechnology*, 32: 760-772.

Burggren W.W., Warburton S. (2007). Amphibians as Animal Models for Laboratory Research in Physiology. *ILAR Journal*, 48: 260-269.

Carnovale F., Jin X., Arney D., Descovich K., Guo W., Shi B., Phillips C.J.C. (2021). Chinese Public Attitudes towards, and Knowledge of, Animal Welfare. *Animals*, 11: 855.

Cauvin A.J., Peters C., Brennan F. (2015). Chapter 19—Advantages and Limitations of Commonly Used Nonhuman Primate Species in Research and Development of Biopharmaceuticals. In J. Bluemel S. Korte, E. Schenck G.F. Weinbauer (Éds.), *The Nonhuman Primate in Nonclinical Drug Development and Safety Assessment* (p. 379-395). Academic Press.

Claudia Janeth Juárez-Portilla (2019). The use of animals in research and teaching: Guidelines and directives for their treatment.

Conroy G. (2022). Top 10 Countries Powering Life Sciences Research (www.nature.com).

De Jong T., Linn M.C., Zacharia Z.C. (2013). Physical and Virtual Laboratories in Science and Engineering Education. *Science*, 340: 305-308.

Domínguez-Oliva A., Hernández-Ávalos I., Martínez-Burnes J., Olmos-Hernández A., Verduzco-Mendoza A., Mota-Rojas D. (2023). The Importance of Animal Models in Biomedical Research: Current Insights and Applications. *Animals*, 13: 1223.

Ericsson A.C., Crim M.J., Franklin C.L. (2014). A Brief History of Animal Modeling. *Missouri medicine*, 110: 201.

Ferreira M., Gerales V., Felix A.C., Oliveira M., Laranjo S., Rocha I. (2025). Advancing Atrial Fibrillation Research: The Role of Animal Models, Emerging Technologies and Translational Challenges. *Biomedicines*, 13: 307.

Greek R., Menache A. (2013). Systematic Reviews of Animal Models : Methodology versus Epistemology. *International Journal of Medical Sciences*, 10: 206-221.

Holtze S., Gorshkova E., Braude S., Cellerino A., Dammann P., Hildebrandt T.B., Hoeflich A., Hoffmann S., Koch P., Terzibasi Tozzini E., Skulachev M., Skulachev V. P., Sahm A. (2021). Alternative Animal Models of Aging Research. *Frontiers in Molecular Biosciences*, 8: 660959.

Johnsen D.O., Johnson D.K., Whitney R.A. (2012). Chapter 1—History of the Use of Nonhuman Primates in Biomedical Research. In C. R. Abee, K. Mansfield S. Tardif, T. Morris (Éds.), *Nonhuman Primates in Biomedical Research* (Second Edition) (p. 1-33). Academic Press.

Jota Baptista C.V., Faustino-Rocha A.I., Oliveira P.A. (2021). Animal Models in Pharmacology: A Brief History Awarding the Nobel Prizes for Physiology or Medicine. *Pharmacology*, 106: 356-368.

Kang M., Long T., Chang C., Meng T., Ma H., Li Z., Li P., Chen Y. (2022). A Review of the Ethical Use of Animals in Functional Experimental Research in China Based on the “Four R” Principles of Reduction, Replacement, Refinement, and Responsibility. *Medical Science Monitor*, 29.

Kiani A.K., Pheby D., Henahan G., Brown R., Sieving P., Sykora P., Marks R., Falsini B., Capodicasa N., Miertus S., Lorusso L., Dondossola D., Tartaglia G.M., Ergoren M.C., Dundar M., Michelini S., Malacarne D., Bonetti G., Dautaj A., Bertelli M. (2022). Ethical considerations regarding animal experimentation. *Journal of Preventive Medicine and Hygiene*, 63: E255.

Knight A. (2007). The effectiveness of humane teaching methods in veterinary education. *ALTEX*, alternatives to animal experimentation, 24: 91-109.

Koyilot M.C., Natarajan P., Hunt C.R., Sivarajkumar S., Roy R., Joglekar S., Pandita S., Tong C.W., Marakkar S., Subramanian L., Yadav S.S., Cherian A.V., Pandita T.K., Shameer K., Yadav K.K. (2022). Breakthroughs and Applications of Organ-on-a-Chip Technology. *Cells*, 11: 1828.

Lasko P., Lüthy K. (2021). Investigating rare and ultrarare epilepsy syndromes with *Drosophila* models. *Faculty Reviews*, 10.

Lleras-Forero L., Winkler C., Schulte-Merker S. (2020). Zebrafish and medaka as models for biomedical research of bone diseases. *Developmental Biology*, 457: 191-205.

Lowen A.C., Bouvier N.M., Steel J. (2014). Transmission in the Guinea Pig Model. In R. W. Compans and M.B.A. Oldstone (Éds.), *Influenza Pathogenesis and Control—Volume 385*: 157-183. Springer International Publishing.

Ma C., Peng Y., Li H., Chen W. (2021). Organ-on-a-Chip: A New Paradigm for Drug Development. *Trends in Pharmacological Sciences*, 42: 119-133.

Makowska I.J., Weary D.M. (2019). A Good Life for Laboratory Rodents? *ILAR Journal*, 60: 373-388.

Malone H.R., Syed O.N., Downes M.S., D'Ambrosio A.L., Quest D. O., Kaiser M.G. (2010). Simulation in Neurosurgery: A Review of Computer-Based Simulation Environments and Their Surgical Applications. *Neurosurgery*, 67: 1105-1116.

McMurray D.N. (2001). Disease model: Pulmonary tuberculosis. *Trends in Molecular Medicine*, 7: 135-137.

Nakamura T., Fujiwara K., Saitou M., Tsukiyama T. (2021). Non-human primates as a model for human development. *Stem Cell Reports*, 16: 1093-1103.

Neuhaus W., Reininger-Gutmann B., Rinner B., Plasenzotti R., Wilflingseder D., De Kock J., Vanhaecke T., Rogiers V., Jírová D., Kejlová K., Knudsen L.E., Nielsen R.N., Kleuser B., Kral V., Thöne-Reineke C., Hartung T., Pallocca G., Leist M., Hippenstiel S., Spielmann H. (2022). The Rise of Three Rs Centres and Platforms in Europe. *Alternatives to Laboratory Animals*, 50: 90-120.

NIH (2023). When Are Alternatives to Animals Used in Research?
<https://grants.nih.gov/grants/policy/air/alternatives>.

Noguchi T., Fujiwara S., Hayashi S., Sakuraba H. (1994). Is the guinea-pig (*Cavia porcellus*) a rodent? *Comparative Biochemistry and Physiology Part B: Comparative Biochemistry*, 107: 179-182.

OPARIN O.A. (1957). The origin of life on the Earth. 29.

Padilla-Carlin D.J., McMurray D.N., Hickey A.J. (2008). The Guinea Pig as a Model of Infectious Diseases. *Comparative Medicine*, 58(4).

Parichy D.M., Elizondo M.R., Mills M.G., Gordon T.N., Engeszer R.E. (2009). Normal table of postembryonic zebrafish development: Staging by externally visible anatomy of the living fish. *Developmental Dynamics*, 238: 2975-3015.

Patton E.E., Zon L.I., Langenau D.M. (2021). Zebrafish disease models in drug discovery: From preclinical modelling to clinical trials. *Nature Reviews Drug Discovery*, 20: 611-628.

Robert K.J. (1997). Unusual Laboratory Rodent Species: Research Uses, Care, and Associated Biohazards. *ILAR Journal*, 38: 13-21.

Robinson N.B., Krieger K., Khan F.M., Huffman W., Chang M., Naik A., Yongle R., Hameed I., Krieger K., Girardi L.N., Gaudino M. (2019). The current state of animal models in research: A review. *International Journal of Surgery*, 72: 9-13.

Rutten N., Van Joolingen W.R., Van Der Veen J.T. (2012). The learning effects of computer simulations in science education. *Computers and Education*, 58: 136-153.

Singh A. (2022). Alternatives to use of animal experiments in teaching and research- A review. *Journal of Laboratory Animal Science*, 4: 27-32.

Srivastava S.K., Foo G.W., Aggarwal N., Chang M.W. (2024). Organ-on-chip technology: Opportunities and challenges. *Biotechnology Notes*, 5: 8-12.

Swearengen J.R. (2018). Choosing the right animal model for infectious disease research. *Animal Models and Experimental Medicine*, 1: 100-108.

Tessadori F., Roessler H.I., Savelberg S.M.C., Chocron S., Kamel S.M., Duran K.J., Van Haelst M.M., Van Haaften G., Bakkers J. (2018). Effective CRISPR/Cas9-based nucleotide editing in zebrafish to model human genetic cardiovascular disorders. *Disease Models and Mechanisms*, 11: dmm035469.

Thomas B., Bhat K., Mapara M. (2012). Rabbit as an animal model for experimental research. *Dental Research Journal*, 9: 111.

Van Rooijen E., Fazio M., Zon L.I. (2017). From fish bowl to bedside: The power of zebrafish to unravel melanoma pathogenesis and discover new therapeutics. *Pigment cell and melanoma research*, 30: 402-412.

Vila R., Castaner R., Cole P. (2014). Emerging animals models in scientific research. *Drugs of the Future*, 39: 0557.

Wittbrodt J., Shima A., Schartl M. (2002). Medaka-A model organism from the far east. *Nature Reviews Genetics*, 3: 53-64.

Wysoczański B., Świątek M., Wójcik-Gładysz A. (2024). Organ-on-a-Chip Models-New Possibilities in Experimental Science and Disease Modeling. *Biomolecules*, 14: Article 12.

Xu X., Allen W., Miao Z., Yao J., Sha L., Chen Y. (2018). Exploration of an interactive “Virtual and Actual Combined” teaching mode in medical developmental biology. *Biochemistry and Molecular Biology Education*, 46: 585-591.

Zang L., Maddison L.A., Chen W. (2018). Zebrafish as a Model for Obesity and Diabetes. *Frontiers in Cell and Developmental Biology*, 6: 91.

Zhang X.-L., Pang W., Hu X.-T., Li J.-L., Yao Y.-G., Zheng Y.-T. (2014). Experimental primates and non-human primate (NHP) models of human diseases in China: Current status and progress. *Zoological Research*, 35: 447-464.

References