

The Modern Landscape of Hernia Disease Repair: From Anatomy to Advanced Robotics – A Systematic Review of Animal-Based Clinical Outcomes and Recurrence

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Abstract:

The modern repair of hernia disease has undergone tremendous transitions in the past where open surgeries are still used to repair the hernia, to sophisticated minimally invasive and robotic assisted techniques through animal-based research being very essential in the understanding of the structure of the anatomy, biomaterials functions and the healing process. This review is a systematic analysis of the existing literature performed on animal models like rodents, rabbits, pigs, and canines to indicate the efficacy of various types of mesh, surgical methods and new technologies in enhancing clinical outcomes and recurrence. The results suggest that, biologic and composite mesh stimulates tissue integration, neovascularisation and organized collagen deposition and less inflammatory response and adhesion formation in comparison with synthetic mesh. As well, less invasive and robotic-assisted surgery methods enhance surgical accuracy, less tissue trauma, and outcome reproducibility. Nevertheless, interspecies variability, absence of standardized models, and inadequate long-term data are also limitations to direct translational applicability. The review notes the significance of the incorporation of advanced technologies including bioengineered meshes, artificial intelligence, and 3D bio printing and the necessity of standardized and long-term and interdisciplinary research to enhance the safety and efficacy of hernia repair approaches.

Keywords: Hernia Repair, Animal Models, Biologic Mesh, Composite Mesh, Robotic Surgery, Tissue Integration, Recurrence, Biomaterials.

Received: Jan. 13, 2026

Revised: Feb. 18, 2026

Accepted: March. 18, 2026

Published: April. 11, 2026

DOI: <https://doi.org/10.64063/3049-1681.vol.3.issue4.2>

<https://aktpublication.com/index.php/jprims/issue/archive>

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1. INTRODUCTION

Hernia disease has been a major issue in the field of surgical research where the internal tissues would protrude through the weakened abdominal walls and effective and long-lasting repair techniques would be required¹. The management of hernias has over the years also become innovative, as the traditional methods of surgical practice by the use of open surgical interventions has been replaced by improved methods of minimally invasive and robotic-assisted surgery, involving innovation in surgical practice and biomedical engineering. In this regard, animal research has been of critical importance in the advancement of knowledge in the study of anatomy structure, tissue recovery process, and the functionality of several biomaterials employed in reconstruction. Rodents, rabbits, pigs, and canines are also experimental models that can be used to examine mesh incorporation, inflammatory phenomenon, collagen organization, and biomechanical strength in controlled settings, which can be used to systematically assess various repair options and technologies.



Figure 1:Hernia Disease²

In this review, the current situation in hernia repair is examined based on the animal-based research, and the specific attention is paid to clinical results and recurrence rates of various methods and materials. It will strive to study the effects of mesh type and fixation techniques, surgical accuracy as well as emerging technologies such as robotic-assisted systems, and their role on the healing and long-term success. The significance of this subject is in that it may help to connect the results of experiments with the realistic progress and make the repair more effective, less invasive, and sustainable. This review demonstrates the importance of interdisciplinary methods in enhancing the outcome of hernia repair and proposing the future of surgical research.

1.1 Background Information and Context

Hernia disease is one of the major complications in surgical studies where internal tissues stick out through the loose muscles or the fascia of the body. The art of hernia repair has experienced significant change over the years and it is now no longer performed in the same manner as in the ancient times of open surgery but has now evolved through the use of more complicated methods of minimally invasive surgery and robotic-assisted surgery³. Animal models like rodents, rabbits, pigs and canines have been instrumental in cause and effect studies of the anatomical, physiological, and biomechanical mechanisms of hernia formation and repair in experimental environments. Those models offer the possibility to test mesh materials, tissue integration, inflammatory reactions, and the accuracy of a surgery, which helps the creation of a better repair strategy.

1.2 Objectives of the Review

The main purpose of the review is:

- To assess the efficacy of different mesh types (synthetic, biologic, and composite) to improve tissue healing, integration and inflammatory response in hernia models using animals.
- To examine the effects of various surgical methods, such as minimally invasive surgeries and robot-assisted surgery, on accuracy, tissue trauma, and general outcomes of the repair.
- To study the most significant factors that determine a hernia recurrence like mesh fixation techniques, surgical precision and host tissue reaction.
- To determine the application and applicability of different animal models in investigating anatomical, physiological and biomechanical factors of hernia repair.
- To investigate the possibilities of new technologies, such as bioengineered nets, artificial intelligence, and 3D bioprinting, to improve the outcomes of hernia repair and future directions of research.

1.3 Importance of the Topic

This subject matters significantly because an increased number of effective, stronger, and less invasive approaches to the repair of hernias are required⁴. The research on animals is an important source of innovation since it allows studying the process of tissue healing in detail, the behavior of biomaterials, and the progress of surgery. These aspects need to be understood in order to maximize the effectiveness of repairs and reduce the rate of complications and recurrences. Moreover, the incorporation of the new technologies like bioengineered meshes, artificial intelligence, and robots describes the future of hernia research, so this review is very timely to develop the experimental and translational surgical science.

1. ANIMAL-BASED HERNIA REPAIR: TECHNIQUES, MESH, AND OUTCOMES

The studies on hernias in animals prove that the type of mesh and the methods used in surgery have a great impact on recovery, where lightweight and biologic mesh decrease the inflammatory rates, but robotic surgeries are more precise and effective⁵. Nevertheless,

controlled and reproducible conditions notwithstanding, direct clinical applicability is limited due to variations between animal and animal physiology and lack of long-term data.

2.1 Overview of Key Animal-Based Studies

Experimental studies have been done extensively using rat and mouse models to determine the mesh biocompatibility, inflammatory reactions, and tissue remodeling after having hernia repair. Such small animal models prove useful especially in the investigation of cellular-level responses and early healing responses. The findings of these studies have always shown that when polypropylene meshes are lightweight, the meshes are related with lower levels of fibrosis, inflammatory response in the long term and better flexibility than the heavyweight polypropylene meshes which are known to cause excessive scar tissue formation.

Porcine models because of their close anatomical and physiological similarity to the abdominal wall of animals have been widely used to study sophisticated surgical procedures like laparoscopic and robotic assisted hernia repair⁶. These reports have shown that less invasive techniques, especially robotic-assisted operations, allow more accurate positioning of the mesh, better ergonomics of the surgeon, and less collateral tissue damage.

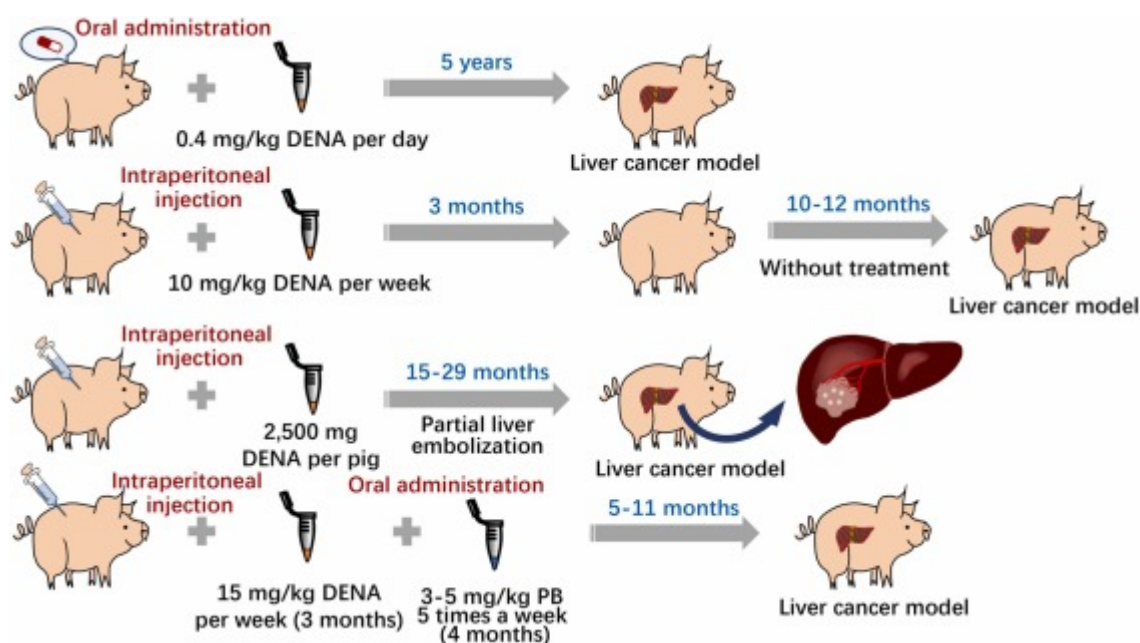


Figure 2: Porcine Models⁷

Also, the performance of collagen-based and biologic meshes has been extensively investigated on rabbit models. These experiments have indicated that such meshes enhance the process of tissue integration, neovascularization, and foreign body reaction⁸.

2.2 Methodologies Used in Animal Studies

The experimental methodologies used in animal-based studies on hernias embrace a variety of the existing, time-tested approaches to achieve uniformity and credibility of the outcomes⁹. Hernia defects induced by means of surgery are usually created to enable standardization of the

experimental model and enable comparison of various methods and materials of repair in a controlled way.

The histopathological examination is a key factor in assessing tissue response where the parameters are inflammation, fibrosis, collagen deposition, and angiogenesis¹⁰. This is usually accompanied by biomechanical tests, especially tensile strength tests, to determine the durability and mechanical strength of the tissue repaired.

Processes such as ultrasound scans and computer tomography (CT) scans have advanced to be used in a non-invasive manner to monitor the healing progression, mesh integration and complications such as seroma or recurrence¹¹.

Moreover, surgical animal trials that are performed with robots have advanced precision-controlled systems, which increase the accuracy of the surgery, reduce error of the animals and enable consistent reproducibility between the experimental conditions and hence the reliability of the results¹².

2.3 Findings from Experimental Models

There are a number of valuable lessons that have been learned as a result of experimental animal studies on hernia repair strategies¹³. Composite and biologic mesh was indicated to have a significant improvement in vascularization and the ordered deposition of collagen which are essential to tissue strength and healing in the long term. However, synthetic meshes have high tensile strength and structural support, which is compared to increased inflammatory reactions and possible adhesion development.

Robotic aided surgical repair has been shown to have greater mesh position consistency, less surgical performance variability and less frequency of technical failures than traditional methods¹⁴. These benefits help in the improved overall success of surgery in the controlled environment.

As well, it has been reported that the recurrence rate is greatly minimal when reinforced mesh fixation methods are utilized, which shows the reinforced and stable mesh fixation is essential in the prevention of postoperative failure¹⁵.

2.4 Critical Evaluation

Strengths

Animal models allow a high level of control of the variables of the experiment, that is, particular factors that affect the outcome of hernia repair are investigated¹⁶. They also provide the opportunity of such detailed invasive analyses as histological and molecular assessments that are not possible with animals. In addition, reproducibility of these models makes finding validation and comparison of results across studies.

Weaknesses

Animal models have limitations that are inherent in spite of their benefits¹⁷. The irrelevance of the findings to clinical practice might be limited by the difference in animal structure and

immune response and healing processes between animals and animal. Also, most of the studies have a relatively brief follow-up period, which might be insufficient in terms of long-term effects, including chronic pain or late recurrence. The interpretation and generalization of the results is further complicated by variability in design of the experiments and insufficient standardization between experiments¹⁸.

2. DETERMINANTS OF HERNIA REPAIR IN ANIMAL MODELS

In hernia research, animal models (including pigs, dogs and rodents) are critical in the study of anatomical compatibility, biomaterials and surgical techniques of the future, but animal differences in healing rates may have an impact on clinical translation. Research shows that mesh type, fixation procedure, surgical accuracy, and host tissue reaction are critical to healing and recurrence and that biologic and composite mesh and minimal procedures can have better tissue unification and better results in the long term¹⁹.

3.1 Anatomical Considerations in Animal Models

Pigs and dogs are other animal models that have structures of the abdominal walls that closely resemble the animal structure in terms of muscle layering, fascial structure, and tensile strength thus being highly useful in the translation of hernia research to animals²¹. Specifically, porcine models are much more popular because of their similar intra-abdominal pressure dynamics and tissue thickening. On the contrary, rodent (rat and mouse) models are very common in initial studies due to their affordability and handling. Nevertheless, rodents have a faster wound healing rate, stable high metabolism, and different collagen deposition patterns, which can cause the over-estimation of success of repair and restriction of the prediction of long-term clinical outcomes to animals²².

3.2 Biomaterials and Mesh Innovation

The area of hernia repair has greatly been researched on with the use of three main types of mesh materials having different biomechanical and biological characteristics:

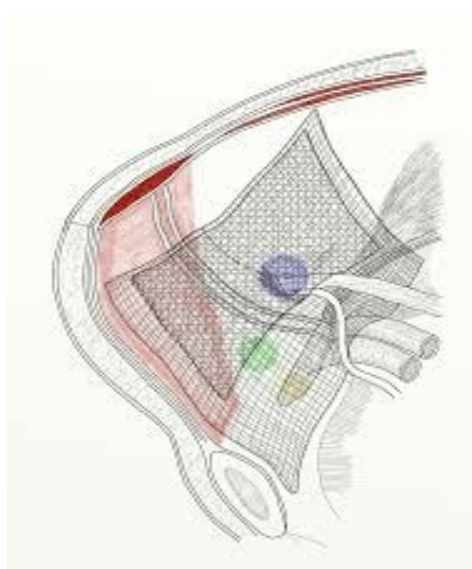


Figure 3: Biomesh²³

- **Synthetic Meshes:** These are usually made of polypropylene or polyester which are of high tensile strength and long lasting. Nevertheless, they can cause chronic inflammation and fibrosis as well as such complications as mesh shrinkage or infection.
- **Biologic Meshes:** It is a type of mesh based on decellularized human or animal tissues, which allows the infiltration of cells, neovascularization, and tissue regeneration. They are linked with the decreased formation of adhesion and also decreased inflammatory reaction which makes them acceptable to contaminated surgical fields.
- **Composite Meshes:** Composite meshes are designed to provide biocompatibility of biologic components with the mechanical strength of synthetic materials and may have anti-adhesive coatings which reduce visceral adhesions with preservation of structural integrity.

The series of animal research also show that biologic and composite meshes enhance tissue remodeling, collagen organization, and adhesion formation reduction as opposed to traditional synthetic meshes, thus leading to improved integration and functional results²⁴.

3.3 Robotic and Minimally Invasive Techniques

Minimally invasive surgical techniques and robot-assisted surgical procedures have received much concern in research on hernia in animals because these methods may enhance the accuracy of surgery and patient outcomes²⁵. These approaches enable:

- The improved accuracy of mesh positioning with the help of articulated instruments and 3D visualization.
- Lessening of surgical trauma caused by the smaller incisions and minimum tissue manipulation.
- Better reproducibility, standardization of procedures across the experimental studies.

Porcine models have been used especially as a model to test these techniques due to their anatomical relevance with humans in simulation of laparoscopic and robotic surgeries. Research has shown that robotic platforms can be used to perform complicated suturing, maximize mesh fixation, and minimize variation in operation, as well as a good intermediary between experimental studies and clinical implementation²⁶.

3.4 Recurrence and Healing Outcomes

Animal experiments are important in availing crucial information in understanding the factors affecting hernia recurrence and biological mechanisms that determine tissue healing²⁷. The repeat rates have been found to be highly influenced by:

- The nature and characteristics of the used mesh.
- The technique of fixation of the mesh (e.g., sutures, tacks, adhesives, etc.)
- The accuracy of the surgical procedure and repair of the defects.

- Immune response of the host and remodeling of the tissues.

Investigations in canine and porcine models over a longer period of time, as well as those employing reinforcement of repair methods, especially the use of appropriate mesh and its fixation, have all shown a significant decrease in the incidence of recurrence. Also, it is mentioned in the literature that balanced collagen incorporation (I/III ratio), sufficient vascularization, and controlled inflammatory reaction play a crucial role in the realization of long-term and functional healing outcomes²⁸.

3. EMERGING TECHNOLOGIES AND FUTURE DIRECTIONS IN ANIMAL-BASED HERNIA REPAIR RESEARCH

The combination of modern technologies has dramatically increased the area of study of hernias of animals, allowing more specific and biological repair options. There have been encouraging results in preclinical models like rodents and pigs with bioengineered meshes especially those engineered with nanotechnology²⁹. These meshes replicate natural extracellular matrices and can be loaded with antimicrobial agents or growth factors to control drug delivery which in turn promotes tissue regeneration with little infection and inflammatory responses. Animal models have shown that angiogenesis, collagen alignment and decreases in adhesion formation are elevated in comparison to traditional synthetic meshes. Moreover, 3D bioprinting has been considered as a revolutionary strategy whereby the shape of customized grafts can be made to suit particular defective size and anatomical designs in animal models. These constructs are more integrative, and they are more mechanically compatible, which provides a possible way to find personalized solutions to hernia repair.

Table 1: Literature Review on AI and Robotic Advancements in Hernia Surgery³⁰

Author(s) & Year	Study Title	Focus Area	Methodology	Key Findings
Restrepo-Rodas et al. (2025) ³¹	The role of AI in modern hernia surgery: a review and practical insights	Application of AI in hernia surgery	Review-based study	AI improved diagnostic accuracy, surgical planning, and intraoperative decision-making; enhanced prediction of outcomes and reduced complications, though ethical and data challenges persisted.
Rivero-Moreno et al. (2023) ³²	Robotic surgery: a comprehensive review of the literature and current trends	Robotic surgery advancements and trends	Comprehensive literature review	Robotic surgery provided enhanced precision, visualization, and dexterity; limitations included high cost, longer initial operative times, and

				need for specialized training.
Santosa & Azizah (2025)³³	Surgical Treatment and Management of the Hernia Umbilical Review and Update	Umbilical hernia management	Review study	Mesh-based repairs reduced recurrence rates compared to suture repair; minimally invasive techniques improved recovery; treatment depended on patient-specific factors.
Schiano di Visconte (2025)³⁴	Robotic inguinal and umbilical hernia repair: clinical outcomes, costs, and future perspectives	Robotic hernia repair outcomes and cost analysis	Narrative review	Robotic surgery improved precision, reduced pain, and enhanced recovery, but higher costs raised concerns about cost-effectiveness.
Shafik (2025)³⁵	Remote Surgery and Robotic-Assisted Procedures: Technologies, Benefits and Limitations	Remote and robotic surgical technologies	Book chapter / review	5G-enabled remote surgery improved access and outcomes; challenges included infrastructure, legal regulations, and cybersecurity issues.

Simultaneously, procedures are being redefined through the implementation of artificial intelligence and robotic-assisted surgery systems that are transforming the definition of accuracy and reproducibility of the procedure in the laboratory. A series of animal research, especially in porcine, demonstrated that AI assisted robotics can improve intraoperative decision-making, optimization of mesh placement and variability in results as compared to manual methods. These systems allow real time integration of imaging and having control over the surgical procedures, which has resulted in better surgical outcomes and decreased recurrence rate when applied in controlled settings³⁶. Although these improvements have been made, there are still a number of challenges such as high implementation cost, technical complexity and uncertainties on long-term biocompatibility and performance. Also, differences in animal models still restrain the direct applicability of the translation. The interdisciplinary work on building scalable, cost-effective, and clinically relevant hernia repair solutions can be the focus of future research based on innovations in material science and computational modeling and state-of-the-art surgical technologies.

4. DISCUSSION

Animal experimental results indicate that the success of hernia repair is determined by the type of mesh used, surgical procedures, and the anatomical structures; biologic meshes and robotics enhance recovery and accuracy³⁷. Nevertheless, constraints including variability and variability

of the models, short term information, interspecies disparity become a reason to build the standard, long-term and technology incorporating research.

5.1 Interpretation and Analysis of Findings

The computing of animal based research has shown that the result of hernia repair is highly determined by the interaction of anatomy compatibility, mesh type and the method used in surgical procedures³⁸. Biologic and composite meshes have an unanimously high level of tissue integration, vascularization, and decreased tissue inflammatory reactions in comparison to synthetic meshes. Also, robots and minimally invasive robots enhance accuracy in mesh positioning and decrease the variance of surgery. But because of the variation in healing processes, collagen deposition and immune response among animal models, the results might vary and interpret the findings differently.

5.2 Implications and Significance

The research has significant implications to the development of hernia repair strategies. Animal models give a controlled environment upon which to test novel biomaterials and surgery technologies prior to wider use. The better results related to high meshes and robotic procedures indicate that they will help decrease recurrence rates and increase the durability of long-term repairs. Moreover, such studies would lead to more effective and standardized surgical procedures, which would enhance the translational process of the experimental studies into the practice³⁹.

5.3 Research Gaps and Future Directions

Although there is great improvement, animal-based hernia research is still limited in a number of ways. It lacks standardized experimental models, thereby making the results of the studies to be varied. Most studies have a limited follow-up time which limits the information on the recurrence and complications in the long term. Also, interspecies variations are problematic in extrapolation of results. The future studies ought to concentrate on the long-term longitudinal research, standardization of animal models and comparative analysis of new technologies including bioengineered meshes, AI-assisted robotics and 3D bioprinting. Material science and computational models will be essential in order to enhance the validity and usability of results by incorporation of interdisciplinary approaches⁴⁰.

5. CONCLUSION

In summary, this review points out that the animal-based studies have immensely helped in advancing the knowledge on the topic of hernia repair by offering important information on the compatibility of anatomy, performance of biomaterials, and surgical innovation. The results indicate that biologic and composite mesh is better in terms of tissue integration, vascularization, and decreased inflammatory reactions than traditional synthetic materials, and minimally invasive and robotic-assisted methods will promote surgical accuracy, less tissue injury, and overall repair results. Also mesh choice, fixation and response of the host tissue are also

significant in predicting success of recurrence and long term healing. In spite of these developments, a shortage of availability of interspecies variability, incomplete experimental designs, and unavailable long-term results limit their direct application to human subjects. Thus, future studies must target standardization, protracted assessment and incorporation of upcoming technologies like bioengineered meshes, artificial intelligence, and 3D bioprinting to enhance the dependability, performance and translational usefulness of hernia repair plans.

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