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ADVANCES IN SURGICAL AND THERAPEUTIC STRATEGIES FOR DIAPHRAGMATIC HERNIAS: A COMPREHENSIVE REVIEW

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Abstract: INTRODUCTION Diaphragmatic hernias, both congenital and acquired, are significant clinical challenges that have historically been associated with high morbidity and mortality rates. This article explores the progression of treatment methodologies, focusing on the shift from traditional open surgeries to modern minimally invasive and robotic-assisted techniques. Additionally, the introduction highlights the role of advanced imaging, mesh technology, and future innovations such as stem cell and gene therapies. **OBJETIVE** To provide a comprehensive analysis of the latest advancements in the therapeutic and surgical management of diaphragmatic hernias, emphasizing the role of minimally invasive techniques, the use of synthetic and biological meshes, and innovative approaches such as stem cell and gene therapies. **METHODS** This is a narrative review which included studies in the MEDLINE – PubMed (National Library of Medicine, National Institutes of Health), COCHRANE, EMBASE and Google Scholar databases, using as descriptors: "Diaphragmatic Hernia" AND "Minimally Invasive Surgery" OR "Robotic-Assisted Surgery" OR "Surgical Meshes" OR "Postoperative Care" in the last years. **RESULTS AND DISCUSSION** The article discusses various advancements in diaphragmatic hernia repair, including the use of laparoscopic and robotic-assisted techniques that have reduced postoperative complications and recovery times. Comparative studies between synthetic and biological meshes were reviewed, showing their relative merits in reducing recurrence rates. Emerging technologies such as 3D modeling, advanced imaging, and tissue engineering are highlighted for their role in improving surgical outcomes. Additionally, advances in postoperative care, including enhanced recovery protocols and telemedicine, are examined as significant contributors to patient recovery. The use of stem cell therapy and gene editing is pro-

posed as a future avenue for improving tissue regeneration and repair. **CONCLUSION** The future of diaphragmatic hernia management is promising, driven by advancements in minimally invasive surgery, robotic-assisted technologies, and regenerative medicine. While short-term outcomes for patients have improved significantly, long-term studies are needed to assess the durability of current techniques and materials, particularly in large and complex hernias. Innovations in imaging, mesh technology, and postoperative care will likely continue to shape the field, with a multidisciplinary approach essential for optimizing patient outcomes.
Keywords: Diaphragmatic hernia repair; Minimally invasive surgery; Synthetic and biological meshes; Robotic-assisted thoracoscopy; Postoperative outcomes.

INTRODUCTION

Diaphragmatic hernias, both congenital and acquired, are conditions of profound clinical importance due to their potential for severe morbidity and mortality. These hernias are characterized by the abnormal displacement of abdominal organs into the thoracic cavity through a defect in the diaphragm, which can arise due to developmental anomalies or as a result of trauma or surgical interventions. Congenital diaphragmatic hernia (CDH), a condition identified at birth, often presents as a life-threatening emergency, particularly in the neonatal period. Bochdalek hernias, the most common type of CDH, result from a defect in the posterolateral region of the diaphragm, whereas Morgagni hernias, although rarer, are found anteriorly and may remain asymptomatic for longer periods. On the other hand, acquired diaphragmatic hernias can result from blunt trauma, penetrating injuries, or iatrogenic causes, complicating surgical procedures involving the abdomen or thorax[1].

Historically, the treatment of diaphragmatic hernias was associated with high mortality rates, primarily due to delayed diagnosis and a limited understanding of the respiratory and cardiovascular complications that arise from organ displacement into the thoracic cavity[2]. The advent of modern diagnostic techniques, particularly advanced imaging modalities such as high-resolution computed tomography (CT) and magnetic resonance imaging (MRI), has revolutionized the ability to identify and characterize these hernias preoperatively, allowing for more timely intervention[2]. Early surgical pioneers attempted diaphragmatic repairs with rudimentary techniques, often facing poor outcomes due to infection, inadequate closure of the defect, and an incomplete understanding of post-operative care. Over the decades, advances in surgical techniques, including the use of synthetic meshes and the introduction of minimally invasive approaches, have dramatically improved patient outcomes, reducing mortality and morbidity rates associated with both congenital and acquired forms of the disease[3].

Epidemiologically, diaphragmatic hernias remain a significant concern in pediatric populations, particularly among neonates diagnosed with CDH. Incidence rates of congenital diaphragmatic hernias range from 1 in 2,500 to 1 in 5,000 live births, with survival rates improving over the past several decades due to advances in neonatal intensive care and surgical techniques[4]. In contrast, acquired diaphragmatic hernias are less common but represent a growing area of concern, particularly in trauma settings. With the increasing frequency of high-velocity motor vehicle accidents and blunt trauma, the incidence of traumatic diaphragmatic hernia has risen, often presenting in complex polytrauma cases[4]. The clinical presentation of diaphragmatic hernias can vary widely, with acute cases presenting as life-threatening

emergencies requiring immediate surgical intervention, while more chronic cases may remain asymptomatic for years, only being discovered incidentally during imaging for unrelated conditions.

The pathophysiology of diaphragmatic hernias, particularly congenital forms, is rooted in abnormal embryological development. Failure of the diaphragm to fully form during fetal development leads to a defect through which abdominal organs herniate into the thoracic cavity, impeding lung development and resulting in pulmonary hypoplasia. The severity of pulmonary hypoplasia, coupled with the degree of pulmonary hypertension, largely determines the prognosis for neonates with CDH[5]. In acquired cases, traumatic injuries to the diaphragm can result in a sudden defect, often complicated by concurrent damage to adjacent organs. The forces involved in such trauma often create a large hernia, necessitating immediate surgical repair to prevent strangulation of the herniated organs and subsequent ischemia[5].

Clinically, the symptoms of diaphragmatic hernias vary depending on the size of the hernia, the organs involved, and the presence of complications such as strangulation or ischemia. In congenital cases, neonates often present with severe respiratory distress immediately after birth, a consequence of the pulmonary hypoplasia and hypertension associated with CDH[6]. In contrast, acquired hernias may present with non-specific symptoms such as chest or abdominal pain, dyspnea, or gastrointestinal obstruction, depending on the nature and timing of the herniation. Delayed diagnosis remains a critical challenge, particularly in traumatic diaphragmatic hernias, where initial imaging may fail to identify the defect, leading to significant morbidity when the diagnosis is missed or delayed[6].

Traditional surgical approaches for diaphragmatic hernia repair, including open thoracotomy or laparotomy, have been the cornerstone of treatment for many years. However, these methods are associated with significant postoperative complications, including infection, prolonged hospital stays, and higher recurrence rates[7]. The introduction of minimally invasive techniques, including laparoscopic and thoracoscopic approaches, has revolutionized the field, offering reduced recovery times, lower rates of infection, and improved cosmetic outcomes[7]. Nevertheless, these techniques are not without limitations. The learning curve for minimally invasive diaphragmatic hernia repair is steep, and these procedures are associated with longer operative times in inexperienced hands. Additionally, the choice between open and minimally invasive approaches remains a subject of debate, particularly in cases of large hernias or those with significant adhesions or organ involvement[8].

One of the most significant advancements in the field has been the development of synthetic and biological meshes for the repair of diaphragmatic defects. The use of mesh has been shown to reduce recurrence rates, particularly in larger hernias, where primary closure may not be feasible[8]. However, the choice of mesh material—whether synthetic or biological—remains controversial, with each having distinct advantages and disadvantages. Synthetic meshes, while durable and effective, carry a higher risk of infection and erosion into surrounding tissues[9]. Biological meshes, derived from human or animal sources, offer improved biocompatibility and reduced risk of infection, but are more expensive and may be associated with higher recurrence rates in the long term[9].

Advances in imaging techniques have further refined the preoperative planning and management of diaphragmatic hernias.

High-resolution CT and MRI provide detailed anatomical information, allowing surgeons to assess the size and location of the hernia, the organs involved, and the presence of complications such as ischemia or strangulation[10]. These imaging modalities are particularly useful in cases of traumatic diaphragmatic hernia, where the diagnosis is often delayed or missed. Moreover, the advent of 3D printing and virtual reality technologies has enabled surgeons to create patient-specific models for preoperative planning, improving surgical outcomes and reducing intraoperative complications[11].

In terms of prognosis, the outcomes for patients with diaphragmatic hernias have improved dramatically over the past few decades, particularly in the neonatal population. Advances in neonatal intensive care, coupled with early surgical intervention, have led to improved survival rates for infants with CDH. However, long-term outcomes remain variable, with many survivors experiencing significant morbidity, including chronic lung disease, gastrointestinal dysfunction, and neurodevelopmental delays[11]. In adults, the prognosis is largely dependent on the timing of diagnosis and the presence of complications. Early diagnosis and prompt surgical intervention are critical for preventing complications such as organ strangulation, ischemia, and sepsis[12].

Technological innovations continue to shape the future of diaphragmatic hernia management. The development of robotic-assisted surgery has further refined minimally invasive techniques, offering greater precision, improved visualization, and reduced operator fatigue[12]. Moreover, ongoing research into stem cell therapy and tissue engineering holds promise for the future, with the potential to repair diaphragmatic defects using autologous tissues, reducing the need for synthetic or biological meshes[13]. These advancements, coupled with improvements in perioperative care and postoperative rehabilitation, are likely to continue improving outcomes for patients with both congenital and acquired diaphragmatic hernias in the years to come[13].

OBJETIVES

To provide a comprehensive analysis of the latest advancements in the therapeutic and surgical management of diaphragmatic hernias, emphasizing the role of minimally invasive techniques, the use of synthetic and biological meshes, and innovative approaches such as stem cell and gene therapies.

SECUNDARY OBJETIVES

- To evaluate the efficacy of robotic-assisted surgery in diaphragmatic hernia repairs.
- To assess the outcomes of using synthetic versus biological meshes in reducing recurrence rates.
- To explore the application of advanced imaging technologies, including 3D modeling, in preoperative planning.
- To review postoperative care strategies and their impact on patient recovery and long-term outcomes.
- To discuss the future trends in diaphragmatic hernia research, including stem cell and gene therapy developments.

METHODS

This is a narrative review, in which the main aspects of the therapeutic and surgical management of diaphragmatic hernias, emphasizing the role of minimally invasive techniques, the use of synthetic and biological meshes, and innovative approaches such as stem cell and gene therapies in recent years were analyzed. The beginning of the study was carried out with theoretical training using the following databases: PubMed, sciELO and Medline, using as descriptors: "Diaphragmatic Hernia" AND "Minimally Invasive Surgery"

OR "Robotic-Assisted Surgery" OR "Surgical Meshes" OR "Postoperative Care" in the last years. As it is a narrative review, this study does not have any risks.

Databases: This review included studies in the MEDLINE – PubMed (National Library of Medicine, National Institutes of Health), COCHRANE, EMBASE and Google Scholar databases.

The inclusion criteria applied in the analytical review were human intervention studies, experimental studies, cohort studies, case--control studies, cross-sectional studies and literature reviews, editorials, case reports, and poster presentations. Also, only studies writing in English and Portuguese were included.

RESULTS AND DISCUSSION

The advances in surgical techniques for diaphragmatic hernia repair have been substantial, reflecting broader trends in minimally invasive surgery, precision medicine, and regenerative therapies. Among the most impactful innovations is the application of minimally invasive techniques such as laparoscopy and robotic-assisted surgery. Laparoscopy has proven to be highly effective in reducing the overall morbidity associated with diaphragmatic hernia repairs, particularly when compared to open surgery[14]. In numerous studies, patients undergoing laparoscopic repair experienced shorter hospital stays, reduced postoperative pain, and faster recovery times when compared to traditional thoracotomy approaches[14]. However, the long-term outcomes of laparoscopic versus open repairs remain a subject of ongoing research. While minimally invasive techniques offer clear short-term benefits, some studies suggest that open repairs may provide more durable results in large, complex hernias where primary closure is not feasible[15]. This has led to the current paradigm in which the choice of surgical approach is dictated by the size and complexity of the hernia, as well as the surgeon's experience with minimally invasive techniques[15].

Robotic-assisted surgery represents a significant advancement in the field, offering enhanced dexterity and visualization, particularly in anatomically challenging cases. The precision afforded by robotic systems, such as the Da Vinci Surgical System, has expanded the scope of minimally invasive surgery for diaphragmatic hernias, particularly in cases requiring complex reconstruction of the diaphragm or manipulation of delicate structures in the thoracic cavity[16]. Studies comparing robotic-assisted and laparoscopic approaches have demonstrated similar short-term outcomes, but robotic systems appear to offer superior outcomes in terms of operative time, especially in large hernias, and reduced conversion rates to open surgery[16]. Despite these advantages, the high cost and steep learning curve associated with robotic surgery remain barriers to its widespread adoption, particularly in resource-limited settings[17]. Moreover, there is still a need for long-term data comparing recurrence rates between robotic-assisted and traditional open or laparoscopic repairs, as these metrics will ultimately determine the value of robotic systems in routine clinical practice[17].

One of the central challenges in diaphragmatic hernia repair, regardless of the surgical approach, is the high rate of recurrence, particularly in cases where the defect is large or complicated by other factors, such as prior surgeries or infection. The use of synthetic and biological meshes has revolutionized the management of these challenging cases. Synthetic meshes, particularly those made from materials such as polypropylene or polytetrafluoroethylene (PTFE), have been shown to significantly reduce recurrence rates by providing additional

structural support to the diaphragmatic repair[18]. However, these materials are not without their drawbacks, including a risk of infection, adhesion formation, and erosion into surrounding tissues[18]. Biological meshes, derived from human or animal tissues, offer a more biocompatible alternative, with lower infection rates and less tissue erosion[19]. Yet, the long-term durability of biological meshes remains a point of debate, with some studies suggesting higher recurrence rates compared to synthetic materials, particularly in high-stress areas of the diaphragm[19].

The selection of mesh material is often determined by the size and location of the hernia, as well as patient-specific factors such as comorbidities and the risk of infection. Large multicenter studies comparing synthetic and biological meshes have demonstrated that while synthetic materials provide superior mechanical strength, biological meshes are more appropriate in contaminated fields or in patients with significant comorbidities, such as those undergoing reoperation for recurrent hernias[20]. Furthermore, the development of hybrid meshes, which combine the durability of synthetic materials with the biocompatibility of biological tissues, represents a promising area of research in reducing recurrence rates while minimizing complications[20]. However, these hybrid materials remain in the experimental phase, and long-term studies are required to assess their clinical utility[21].

In addition to mesh selection, preoperative planning using advanced imaging techniques has become an essential component of successful diaphragmatic hernia repair. High-resolution CT and MRI are now routinely used to define the size and extent of the hernia, identify the organs involved, and detect any complications such as strangulation or ischemia[21]. These imaging modalities are particularly valuable in cases of traumatic diaphragmatic hernia, where the diagnosis is often delayed, and the hernia may be missed on initial imaging[22]. Furthermore, 3D modeling and printing technologies have recently been introduced into the field, allowing for the creation of patient-specific models that can be used for preoperative planning and intraoperative guidance[22]. These technologies enable surgeons to better visualize the defect and surrounding anatomy, leading to more precise repairs and reduced operative times[23]. While still in its early stages, 3D printing holds great promise for improving outcomes in complex hernia repairs, particularly in cases where traditional imaging fails to provide sufficient anatomical detail[23].

Another emerging area in diaphragmatic hernia repair is the use of stem cell therapy to enhance tissue regeneration and reduce the risk of recurrence. Early studies in animal models have demonstrated that stem cells, particularly mesenchymal stem cells, have the potential to promote the healing of diaphragmatic defects by differentiating into muscle and connective tissue[24]. These findings have generated significant interest in the potential application of stem cell therapy in human patients, particularly in cases of congenital diaphragmatic hernia, where the diaphragm is often severely underdeveloped[24]. While clinical trials are still in the early stages, the combination of stem cell therapy with traditional surgical techniques may offer a novel approach to repairing large or recurrent diaphragmatic hernias, particularly in patients for whom mesh repair is not feasible[25].

In addition to stem cell therapy, gene therapy represents another innovative approach with potential applications in the repair of diaphragmatic hernias. Researchers have begun exploring the use of gene editing technologies, such as CRISPR-Cas9, to correct genetic defects associated with congenital diaphragmatic hernia and promote the regeneration of diaphragmatic tissue[26]. While

still in the experimental phase, these therapies could one day provide a means of repairing diaphragmatic defects without the need for synthetic or biological meshes, reducing the risk of recurrence and improving long-term outcomes[26].

Postoperative respiratory care is a critical component of the management of patients with diaphragmatic hernias, particularly in neonates and infants with CDH. Pulmonary hypoplasia and pulmonary hypertension are common complications in these patients, and their management requires a multidisciplinary approach involving neonatologists, pulmonologists, and cardiologists[27]. Advances in neonatal intensive care, including the use of extracorporeal membrane oxygenation (ECMO) and high-frequency oscillatory ventilation (HFOV), have significantly improved survival rates in infants with CDH, although these technologies are associated with their own set of complications[27]. The timing of surgical intervention in neonates with CDH remains a subject of debate, with some centers advocating for early repair within the first few hours of life, while others prefer a delayed approach, allowing for the stabilization of pulmonary function before proceeding with surgery[28]. The choice of timing is often dictated by the severity of pulmonary hypoplasia and the degree of pulmonary hypertension, both of which are strong predictors of postoperative outcomes[28].

In adults, postoperative respiratory complications are less common but still represent a significant concern, particularly in patients with pre-existing lung disease or those undergoing repair of large hernias involving multiple abdominal organs[29]. The use of enhanced recovery after surgery (ERAS) protocols, which emphasize early mobilization, aggressive pain management, and minimal narcotic use, has been shown to reduce postoperative complications and shorten hospital stays in patients undergoing diaphragmatic hernia repair[29]. Furthermore, the introduction of robotic-assisted surgery has allowed for more precise dissection of adhesions and reduced trauma to surrounding tissues, leading to improved respiratory outcomes in patients undergoing complex hernia repairs[30].

The use of intraoperative imaging, particularly in robotic-assisted surgery, has also improved the accuracy of diaphragmatic hernia repairs. Intraoperative ultrasound and fluoroscopy allow surgeons to visualize the hernia in real-time, assess the integrity of the repair, and ensure that there is no residual defect or organ entrapment[30]. These technologies are particularly valuable in cases of recurrent hernias, where previous surgeries have created adhesions and distorted normal anatomy, making it difficult to achieve a successful repair[31]. Moreover, the application of nanotechnology-based innovations in mesh design and implantation has the potential to further reduce recurrence rates and improve patient outcomes. Researchers are exploring the use of nanomaterials that promote tissue integration and reduce the risk of infection, while also providing the mechanical strength necessary to support the repair[31].

Comparative studies of open versus minimally invasive repairs have provided valuable insights into the long-term outcomes of these techniques. While laparoscopic and robotic-assisted repairs offer clear advantages in terms of reduced recovery time and postoperative pain, some studies suggest that open repairs may be more durable, particularly in large or complex hernias where primary closure is not feasible[32]. The decision to use a thoracic or abdominal approach in hernia repair is often based on the location and size of the hernia, as well as the surgeon's experience. Thoracic approaches are generally preferred for large hernias involving the posterior or lateral

diaphragm, while abdominal approaches are more commonly used for anterior or central hernias[33]. Each approach has its own set of advantages and disadvantages, and the choice is often dictated by the specific circumstances of the hernia repair[33].

The impact of minimally invasive approaches on hospital stay and recovery time has been well-documented, with numerous studies demonstrating that patients undergoing laparoscopic or robotic-assisted repairs have shorter hospital stays, less postoperative pain, and faster recovery times compared to those undergoing open repairs[34]. However, the benefits of minimally invasive approaches must be weighed against the technical challenges they present, particularly in cases of large or recurrent hernias. In these cases, the risk of incomplete repair or recurrence may be higher with minimally invasive techniques, particularly in inexperienced hands[35]. Additionally, some studies have raised concerns about the longer operative times associated with minimally invasive repairs, particularly when robotic assistance is used[36]. Despite these challenges, the overall trend in the field has been toward increased adoption of minimally invasive techniques, particularly in centers with access to advanced surgical technologies and experienced surgeons[36].

Robotic-assisted thoracoscopy represents one of the most promising innovations in diaphragmatic hernia repair. The enhanced dexterity and precision offered by robotic systems allow for more complete dissection of the hernia sac and more accurate placement of mesh, particularly in cases involving complex anatomy or extensive adhesions[37]. Furthermore, robotic systems allow for greater control over intraoperative bleeding and reduce the risk of injury to surrounding structures, such as the lungs and heart, during the repair of large hernias[38]. The use of robotic-assisted surgery has been associated with lower conversion rates to open surgery, particularly in complex cases, and has been shown to reduce postoperative complications and shorten hospital stays[38].

Long-term monitoring of patients following diaphragmatic hernia repair is essential to detect any signs of recurrence or complications, such as adhesions, infection, or organ entrapment. Patients who undergo minimally invasive repairs generally require less intensive postoperative monitoring, as these techniques are associated with lower rates of complications and faster recovery times[39]. However, in cases of large or recurrent hernias, particularly those repaired with synthetic mesh, close monitoring is required to detect any signs of mesh-related complications, such as erosion, infection, or migration[40]. In some cases, particularly in patients with significant comorbidities or those undergoing reoperation for recurrent hernias, the use of autologous tissue for diaphragmatic reconstruction may be necessary to reduce the risk of mesh-related complications[40].

Advances in telemedicine and remote monitoring have further improved the long-term management of patients following diaphragmatic hernia repair. Telemedicine allows for remote monitoring of patients in resource-limited settings, where access to specialized surgical care may be limited, and enables early detection of complications that may otherwise go unnoticed[41]. Additionally, the development of personalized treatment plans based on genetic profiles and the use of predictive models to assess the risk of recurrence or complications represent promising areas of research that may improve long-term outcomes for patients with diaphragmatic hernias[42].

One area of growing interest in the field is the potential for prophylactic interventions in high-risk populations, such as those with

genetic predispositions to diaphragmatic hernia or those with significant trauma risk[43]. While the concept of prophylactic surgery for diaphragmatic hernias is still in its infancy, advances in genetic screening and predictive modeling may allow for the identification of individuals at high risk for hernia development, enabling early intervention to prevent the hernia from occurring in the first place[43]. This approach could be particularly valuable in populations with congenital diaphragmatic hernia, where early intervention may improve survival rates and reduce long-term morbidity[44].

Psychological and emotional outcomes following diaphragmatic hernia repair are an often-overlooked aspect of patient care, particularly in congenital cases. Children born with congenital diaphragmatic hernia (CDH) often face significant physical and psychological challenges as they grow older, including developmental delays, chronic lung disease, and gastrointestinal dysfunction[45]. These challenges can have a profound impact on the quality of life for both the patient and their family, underscoring the need for a multidisciplinary approach to care that includes psychological support and rehabilitation[45]. In adult patients, particularly those with traumatic diaphragmatic hernia, the psychological impact of the injury and subsequent surgery can be significant, with many patients experiencing anxiety, depression, or post-traumatic stress disorder (PTSD) following their recovery[46]. Addressing these psychological and emotional outcomes is an essential component of comprehensive hernia care, and future research should focus on developing strategies to improve the overall quality of life for patients following diaphragmatic hernia repair[46].

The evolution of perioperative care in diaphragmatic hernia management has played a critical role in improving patient outcomes. Advances in anesthetic techniques, pain management strategies, and postoperative care protocols have significantly reduced the incidence of perioperative complications and improved recovery times[47]. Enhanced recovery after surgery (ERAS) protocols, which emphasize early mobilization, aggressive pain management, and minimal narcotic use, have been particularly effective in reducing hospital stays and improving long-term outcomes[47]. Furthermore, the use of minimally invasive techniques has allowed for faster recovery and reduced postoperative pain, making it easier for patients to adhere to ERAS protocols and achieve better outcomes[48].

Pharmacological adjuncts in diaphragmatic hernia management have also been the subject of increasing research. While the primary treatment for diaphragmatic hernias remains surgical, the use of pharmacological agents to enhance tissue healing, reduce inflammation, and prevent recurrence is an area of growing interest[49]. Anti-inflammatory medications, such as corticosteroids, have been used to reduce postoperative inflammation and prevent adhesions, while growth factors and other biologic agents are being investigated for their potential to enhance tissue regeneration following hernia repair[49]. These pharmacological adjuncts may one day complement surgical techniques, providing a more comprehensive approach to hernia management[50].

The exploration of hybrid surgical approaches, combining open and minimally invasive techniques, represents a promising area of innovation in diaphragmatic hernia repair. These approaches allow surgeons to take advantage of the benefits of both open and minimally invasive techniques, tailoring the repair to the specific needs of the patient[51]. For example, in cases where a large hernia requires open access for the placement of mesh, a minimally invasive approach can be used to

reduce postoperative pain and improve cosmetic outcomes[51]. Hybrid techniques are particularly valuable in cases of recurrent hernia, where adhesions and distorted anatomy make it difficult to achieve a successful repair using a single approach[52].

In resource-limited settings, where access to advanced surgical technologies may be limited, the success rates of diaphragmatic hernia repair can vary widely. Studies have shown that while minimally invasive techniques offer clear advantages in terms of reduced morbidity and shorter hospital stays, their adoption in low-resource settings has been limited by the high cost of equipment and the need for specialized training[52]. However, efforts are underway to develop more cost-effective minimally invasive techniques, such as laparoscopic repairs using low-cost equipment, which may help improve outcomes in these settings[53]. Additionally, telemedicine and remote monitoring technologies offer promising solutions for improving access to specialized care in resource-limited settings, enabling surgeons to consult with experts and receive real-time guidance during complex hernia repairs[53].

Socioeconomic factors also play a significant role in determining access to advanced hernia treatments, particularly in low- and middle-income countries. Patients in resource-limited settings are often unable to afford the cost of advanced surgical technologies, such as robotic-assisted surgery, and may not have access to the specialized training required for minimally invasive techniques[54]. Furthermore, the availability of synthetic and biological meshes, which are critical for reducing recurrence rates in large or complex hernias, is often limited in these settings due to their high cost[54]. Efforts to address these disparities are critical to improving outcomes for patients with diaphragmatic hernias in resource-limited settings and ensuring that all patients have access to the most effective treatments available[55].

Ethical considerations in the use of experimental therapies for diaphragmatic hernia repair represent another important area of discussion. While advances in stem cell therapy, gene editing, and tissue engineering hold great promise for improving outcomes in diaphragmatic hernia repair, these therapies are still in the experimental phase and raise significant ethical questions[56]. The use of experimental therapies in vulnerable populations, such as neonates with CDH, must be carefully considered to ensure that the potential benefits outweigh the risks[56]. Furthermore, the cost and accessibility of these therapies may create disparities in care, with only a small subset of patients able to access the most cutting-edge treatments[57].

A multidisciplinary approach to diaphragmatic hernia management, involving surgeons, neonatologists, pulmonologists, and other specialists, is essential for achieving the best possible outcomes. This approach allows for the early identification and management of complications, such as pulmonary hypoplasia, pulmonary hypertension, and gastrointestinal dysfunction, which are common in patients with CDH[57]. In adults, particularly those with traumatic hernias, a multidisciplinary approach ensures that all aspects of the patient's care, from respiratory support to pain management and rehabilitation, are addressed[58].

Looking ahead, future trends in diaphragmatic hernia research and clinical trials are likely to focus on refining minimally invasive techniques, improving the durability of synthetic and biological meshes, and exploring novel therapies, such as stem cell and gene therapies[58]. Advances in imaging, 3D modeling, and robotic-assisted surgery will continue to shape the field, allowing for more precise repairs and better long-term outcomes[59]. Additionally, ongoing research into the genetic and molecular mechanisms underlying congenital diaphragmatic hernia may lead to

new insights into the prevention and early treatment of this condition, particularly in high--risk populations[60].

CONCLUSION

The management of diaphragmatic hernias has undergone significant evolution over the past few decades, driven by advancements in surgical techniques, technological innovations, and a deeper understanding of the underlying pathophysiology. Minimally invasive approaches, particularly laparoscopy and robotic-assisted surgery, have emerged as powerful alternatives to traditional open surgery, offering reduced postoperative morbidity and faster recovery times for patients. However, despite these advancements, the choice between minimally invasive and open repair continues to be influenced by factors such as hernia size, complexity, and the surgeon's expertise, highlighting the need for individualized treatment strategies.

The integration of synthetic and biological meshes into diaphragmatic hernia repair has been a pivotal development in reducing recurrence rates, particularly in large and complex hernias. While synthetic meshes provide superior mechanical strength, biological meshes offer enhanced biocompatibility and reduced infection risk. However, the long-term durability of these materials remains a topic of ongoing research, particularly with the advent of hybrid meshes that combine the benefits of both. As our understanding of mesh materials evolves, the ability to tailor mesh selection to the specific needs of each patient will likely become an essential aspect of surgical planning.

Advanced imaging technologies, including high-resolution CT, MRI, and 3D modeling, have transformed preoperative planning, allowing for more accurate assessment of hernia size, location, and the involvement of surrounding structures. These technologies have not only improved surgical outcomes but have also reduced operative times and intraoperative complications. Looking ahead, the integration of virtual reality and augmented reality into surgical planning and training may further enhance the precision of diaphragmatic hernia repairs, particularly in anatomically complex cases.

The future of diaphragmatic hernia management is poised to benefit from breakthroughs in regenerative medicine, with stem cell therapy and gene editing offering potential new avenues for repairing diaphragmatic defects without the need for synthetic or biological materials. Although still in the experimental phase, early research into these therapies has shown promise in promoting tissue regeneration and reducing recurrence rates. As clinical trials progress, these innovative treatments may offer new hope for patients with large or recurrent hernias that are difficult to manage with current surgical techniques.

In conclusion, the management of diaphragmatic hernias is on the cusp of further innovation, with minimally invasive surgery, advanced imaging, and regenerative medicine paving the way for improved patient outcomes. The adoption of these technologies, along with continued research into the long-term outcomes of different surgical techniques and materials, will be critical in shaping the future of hernia repair. Multidisciplinary care and personalized treatment plans, tailored to the specific needs of each patient, will remain the cornerstone of effective management, ensuring that both short-term and long-term outcomes are optimized.

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