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SURGICAL INTERVENTIONS IN KIDNEY TRAUMA: CONTEMPORARY TECHNIQUES AND CLINICAL OUTCOMES

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Abstract
Kidney trauma is a major cause of urological morbidity and it presents complicated issues in the management of patients both in the acute and long term. The development of diagnostic imaging, critical care, interventional radiology, and surgical practices have significantly changed the practice of renal trauma, where practice currently shifts towards selective intervention and renal preservation. This review gives an overall picture of modern surgical procedures in kidney trauma, focusing on the indicators of surgery, new operating methods, and related clinical and renal functional results. The current evidence is in favour of the use of standardized systems of injury grading and contrast-enhanced computed tomography in order to inform management decisions. Although non-operative management and angioembolization have become the preferred forms of treatment in a large number of full stable patients, surgery is still necessary in situations of hemodynamic instability, complicated vascular injury, or failure of non-operative therapy. Contemporary surgical practices will focus on nephron-saving methods whenever possible because there is a close relationship between nephron mass loss, acute kidney injury, and chronic kidney disease in the long run. There are special clinical situations such as paediatric trauma, solitary or transplanted kidneys and polytrauma that need specific management approaches. Perioperative renal function is closely correlated with clinical outcomes, and the acute kidney injury turns out to be a major factor of short- and long-term outcomes. This review of the existing literature indicates the best practice areas in surgical management and future research areas to focus on improving the outcomes of kidney trauma patients and their renal preservation.

KEYWORDS: Kidney trauma; renal injury; surgical management; nephron-sparing surgery; acute kidney injury; clinical outcomes

1. INTRODUCTION

Kidney trauma is an important and clinically important aspect of morbidity in the world in urology, and in trauma. The kidney is one of the most common solid organs abdominal injuries, being located retroperitoneally, having relative mobility and exposed to deceleration forces. Epidemiological evidence of large population-based surveys shows that renal trauma represents about 1-5 percent of all trauma hospitalizations and up to 10 % of abdominal traumas, most of which are patients who are young and economically active. The most common mechanism is blunt trauma that typically occurs due to road traffic accidents, falls, and sports related injuries, whereas penetrating injuries are more likely to be found in areas where interpersonal violence is higher. The trends in the management of renal trauma have changed significantly over the last several decades as a result of the development of trauma systems, diagnostic imaging, and an increased focus on organ preservation [1].

Kidney trauma is more clinically important than simply the management of haemorrhage and injuries. Acute kidney injury, renal parenchyma loss, hypertension, and development of chronic kidney disease are examples of possible short- and long-term effects of renal trauma. Such outcomes have to be viewed in the larger global context of burden of kidney disease. Chronic kidney disease is a significant health problem in the general population of any country, and there are significant differences in the occurrence, access, and outcomes of the disease among different geographical and socioeconomic areas. The lack of access to high-quality trauma care, timely imaging, and expert surgical skills can make a difference in the effects of renal trauma in most low- and middle-income countries and raise the risk of late diagnosis, inadequate treatment, and permanent renal injury. Kidney trauma, therefore, is not only an urgent operation issue but a factor in the burden of kidney disease in the world in the long-term [2].

Renal preservation has thus become one of the fundamental principles of modern kidney trauma management. In the past, the management of renal injuries was usually through compulsory surgical exploration which led to high nephrectomy and loss of renal mass. Current evidence, however, points towards the paradigm shift where kidney-preserving strategy should be used whenever possible. The results of nationwide analyses and large cohort studies have proven that nephron-sparing surgical techniques such as renal repair and partial nephrectomy have better survival and lower long-term morbidity than radical nephrectomy in patients who are properly selected. The results highlight the necessity of the personal approach to decision-making that would consider hemodynamic stability, the severity of the injury, and the possibility of renal salvage. Renal tissue preservation is needed specifically because the decline in the number of nephrons has been linked to subsequent incidence of chronic kidney disease, cardiovascular morbidities, and lower quality of life [3].

The historical development of the renal trauma care during the last century explains how deep the technological and theoretical changes in medicine can be. Initial treatment of renal trauma was defined by a few diagnostic methods and the use of exploratory surgery, which is commonly described as stabbing in the dark. The evaluation of renal injuries was revolutionized with the introduction and widespread use of contrast-enhanced computed tomography, which made it possible to accurately grade injury, determine the involvement of the vascular and collecting system and identify any associated intra-abdominal injuries. The radiographic breakthrough also enabled the establishment of selective non-operative management guidelines and the establishment of a better indication of surgery, which resulted in an astronomical decrease in unnecessary explorations and nephrectomies. Modern management practices have become combined with the use of imaging results, hemodynamic status, and patient specific to inform a treatment decision, which can be considered a more subtle and evidence-based approach [4].

The improvements notwithstanding, kidney trauma is strongly associated with the occurrence of acute kidney injury, especially among patients with high-grade injuries, haemorrhagic shock, or high comorbid conditions. Posttraumatic acute kidney injury is a complex and multifactorial disease, which is affected by hypoperfusion, inflammation, nephrotoxic exposures, and surgical stress. Even temporary cases of acute kidney injury have been linked to higher death and chronic renal failure. The acknowledgement of such a relationship has only strengthened the need to implement strategies that reduce the amount of secondary renal insults in the acute resuscitation period and later surgical care [5]. Hemodynamic stability optimization, reduction of ischemic time in renal surgery, and unjustified loss of functional renal tissue are now viewed as part and parcel of quality trauma care.

In this regard, surgical intervention of kidney trauma has taken a decisive but more and more selective position. Although the non-operative management and interventional radiology methods have grown tremendously, surgery is still a prerequisite in cases of hemodynamic unsteadiness, intricate vascular injuries, or failure of non-operative interventions. The modern methods of surgery are not focused on reducing haemorrhage and structural damage but also on the preservation of renal functioning and the better results in the long term. It is thus important to understand the signs, methods and results of surgical treatment of trauma patients to both the nephrologists and urologists participating in the treatment.

The purpose of the review is to present a detailed and recent review of surgical interventions in kidney trauma, especially with regard to the recent methods and clinical outcomes. The stress is put on preserving renal functional, perioperative issues, and long-term prognosis. This review will be able to inform multidisciplinary clinical practice by synthesizing existing evidence and bringing to light emerging trends to determine where additional research is required in order to maximize the management of kidney trauma in the modern era.

2. Classification and Initial Assessment of Kidney Trauma

The correct classification and timely first assessment are the key to the successful management of kidney trauma as they directly affect the clinical decision-making and choice of treatment. Standardized injury grading systems give a standardized language of describing a renal injury, prognosis, and operative and non-operative management. The most common scale of grading renal injury is the American Association to Surgery of Trauma (AAST) scale, which is the standard of clinical practice and study in renal trauma.

In 2018, the AAST renal injury grading scale was revised, which was a major leap forward in the classification of renal trauma. The updates incorporated current imaging discoveries and clinical experiences in order to define the severity of the injuries and enhance the risk stratification. Notably, the scale was revised and increased the predictability of the necessity of bleeding control procedures such as angioembolization and surgical exploration by better defining vascular injury, active haemorrhage, and involvement of the collecting system [6].

Computer tomography has emerged as the foundation of assessment of renal trauma in patients with stable hemodynamic. The AAST Organ Injury Scale 2018 revision highlighted the use of CT-based grading as an effective approach to injury classification to allow the accurate identification of renal parenchymal disruption, vascular compromise, and urinary extravasation. Emergency physicians, radiologists, and trauma teams should also be familiar with CT-based grading criteria so that they can diagnose in time, conduct relevant triage, and communicate with the multidisciplinary team [7].

Kidney trauma mechanisms are very significant in the initial evaluation and classification of injuries. Most renal injuries are caused by blunt trauma which is commonly caused by high energy deceleration events like motor vehicle collision or falls and less often, penetrating trauma is linked to higher grade injuries and intricate vascular pathways. Systematic review and meta-analytic evidence prove the high correlation of the injury mechanism, injury severity, need to intervene, and clinical outcomes, which support the necessity of mechanism-specific assessment in the primary evaluation [8].

In addition to the classification of anatomical injury, the initial examination should include a detailed assessment of the physiological condition of the patient. Hemodynamic stability is one of the primary factors of early management choices and is frequently used to override the grade of injuries alone. Hemodynamic instability caused by haemorrhage or shock

has the potential to largely affect renal perfusion, which adds to ischemic injury and increases the risk of acute kidney injury in traumatic patients [9]. These physiological derangements should be detected early in order to shape the resuscitation and the urgency of intervention.

The complication of acute kidney injury is frequent and severe in patients with moderate to severe renal trauma, especially in the case of hypotension, systemic inflammation, or multiple injuries. The acute kidney injury has been established to be a complicated clinical syndrome with augmented short- and long-term morbidity and mortality, despite renal dysfunction seeming to be temporary [10]. As a result, renal function evaluation and the detection of the risk factors of secondary kidney injury should be part and parcel of the initial kidney trauma assessment.

Contrast-enhanced CT imaging, which is essential to the correct diagnosis and grading, has created issues in relation to contrast-associated acute kidney injury in physiologically-weakened trauma patients. Nevertheless, the modern multicentre research that is carried out at emergency departments also indicates the risk of contrast-induced acute kidney injury to be rather minimal, provided that proper patient selection is performed, hydration is maintained, and hemodynamic optimization is achieved [11]. The findings indicate that contrast-enhanced CT should be used as a critical diagnostic tool in early evaluation of renal trauma.

The presentation state of renal perfusion also has significant prognostic value. Surgical population evidence suggests that preoperative renal malperfusion is a predictive factor of acute kidney injury and early death on its own. Despite the use of non-trauma cohorts, these results emphasize the concepts that can be directly transferred to renal trauma in which the main objectives of the primary care are to restore renal blood flow and prevent a long-term ischemia [12].

To conclude, diagnosis and early management of kidney trauma should be based on a complex method that involves standard injury grading, comprehensive imaging analysis, knowledge of injury pathophysiology, and close observation of hemodynamic and renal functional conditions. The AAST renal injury grading system is a powerful system with the assistance of CT based measurement and physiological measurements to stratify the level of injury and further diagnostic and treatment plans in patients with renal injury. Table 1 presents the summary of the American Association for the Surgery of Trauma (AAST) renal injury classification and its clinical implications.

Table 1. American Association for the Surgery of Trauma (AAST) classification and clinical characteristics of kidney trauma

AAST Grade	Injury Description	Typical Imaging Findings	Common Management Approach
I	Renal contusion or subcapsular hematoma	Normal parenchyma or small hematoma	Observation
II	Superficial cortical laceration	Non-expanding perirenal hematoma	Observation
III	Deep cortical laceration (>1 cm)	Parenchymal disruption without urinary leak	Non-operative / selective embolization
IV	Laceration involving collecting system or segmental vessels	Urinary extravasation or vascular injury	Non-operative/ intervention/surgery
V	Shattered kidney or renal pedicle avulsion	Devastating parenchymal or vascular injury	Surgery

3. Diagnostic Evaluation

Correct diagnostic assessment is the key to successful management of kidney trauma as it contributes to risk identification, decision-making therapy, and prognostication. In addition to establishing the anatomical scope of renal damage, the contemporary diagnostic methods are to determine the patients who are at risk of the secondary renal morbidity especially the acute kidney injury which is one of the factors to consider when it comes to determining the short-term and the long-term outcomes. The recent progress in imaging modalities and biomarker studies has widened the diagnostic scope of renal trauma to allow the identification of the extent of injury and physiological disturbance earlier.

Early detection of acute kidney injury is gradually becoming one of the most important elements of diagnostic assessment of the trauma patient. The conventional biomarkers like serum creatinine are not sensitive during the initial stages of kidney damage, which has led to the need to explore new diagnostic methods and biomarkers. New diagnostic tools such as biomarkers of tubular damage, inflammation and cell stress provide a solution to earlier and more accurate diagnosis of renal dysfunction before the changes in the traditional laboratory parameters are evident [13]. These methods can be used in the kidney trauma to detect high-risk patients who face the threat of deterioration of the kidney and inform them of the intervention and monitoring plans.

Acute kidney injury caused by trauma is pathophysiologically multifactorial. Besides the direct parenchymal injury, systemic inflammatory responses, ischemia-reperfusion injury, endothelial dysfunction, and immune activation head the list of contributing factors to renal dysfunction after trauma. There is experimental and clinical evidence of the importance of immune-mediated pathways in enhancing renal injury, the connection between local trauma and systemic inflammatory cascades that increase the severity of kidney dysfunction [14]. Identification of these mechanisms helps to emphasize the need to conduct a thorough diagnostic assessment that goes beyond structural imaging and conducts an evaluation of systemic and renal-specific physiological stress.

The basis of diagnostic assessment in renal trauma has always been imaging, especially in hemodynamically stable patients. Computed tomography with contrast enhancement gives detailed data on the subject of renal parenchyma integrity, vascular injury, collecting system destruction, and related intra-abdominal injury. The CT protocols are advanced and can be used to perform multiphasic imaging, which enhances the detection of smaller injuries that can be used to make

decisions regarding management. Of these, delayed-phase imaging has become a useful supplement to the evaluation of high-grade renal trauma.

Delayed-phase CT imaging is essential to detect urinary extravasation and gather system injuries that cannot be seen in the first phases of arteries or veins. There is some evidence that delayed imaging on admission can be of great importance to clinical management since it helps to early identify urinary leakage and make surgical repair, ureteral stenting, or conservative decisions. This practice is especially applicable in renal injuries of high-grade where the disruption of the collecting system can cause complications in the form of either a urinoma, infection, or extended stay in hospital.

Along with the description of renal injury, diagnostic examination should also consider the systematic evaluation of related traumas, which is often observed in patients with kidney injury. Renal injuries are often combined with thoracic, abdominal, pelvic, and musculoskeletal trauma, and the burden of injuries has an overall effect on the priorities and the outcomes of management. Multidisciplinary evaluation and thorough imaging regimes are thus mandatory to make sure that life endangering injuries are early detected and the renal specific treatment is included in the general trauma strategy [15].

To conclude, kidney trauma diagnostics involves a multimodal methodology, combining the progressive use of imaging methods with new knowledge of the pathophysiology of kidney injuries and the detection of kidney injuries early. New diagnostic approaches promise a faster detection of acute kidney injury, whereas the knowledge of the immunopathophysiology of trauma-induced renal dysfunction gives the background of risk stratification and preventive approaches. Delayed-phase imaging where needed and contrast-enhanced CT are essential in the definition of injury characteristics and management. These diagnostic strategies put in combination are the basis of informed clinical decision-making in the modern management of kidney trauma.

4. Indications for Surgical Intervention

Kidney trauma surgery is only applied to a few patients who cannot be treated using non-operative or minimally invasive approaches that will not result in the achievement of haemostasis, renal functional preservation and the overall survival of the patient. In modern management, the emphasis is on selective surgery, which depends on physiological status, nature of injury, and response to the initial resuscitation, as opposed to the grade of the injury. Evidence-based practice management guidelines are structured guidelines, which can help clinicians to select patients who are most likely to receive benefit because of operative intervention. Table 2 provides an overview of absolute and relative predictors of surgery in kidney trauma.

Table 2. Absolute and relative indications for surgical intervention in patients with kidney trauma

Category	Clinical Scenario	Recommended Action
Absolute	Hemodynamic instability due to renal bleeding	Immediate surgery
Absolute	Renal pedicle avulsion	Surgical exploration
Absolute	Expanding retroperitoneal hematoma	Surgery
Relative	Persistent bleeding after embolization	Surgery
Relative	Extensive devitalized renal tissue	Selective surgery
Relative	Complex collecting system injury	Surgical repair

As per the existing standards, absolute indications of surgical exploration are hemodynamic instability refractory to resuscitation due to renal haemorrhage, expanding or pulsatile retroperitoneal hematoma detected during laparotomy due to related injuries, and renal vascular pedicle avulsion. Surgical control of haemorrhage in such situations is essential because delaying exsanguination can lead to loss of consciousness in the patient. Relative clinical signs of surgery can consist of active bleeding despite angioembolization, widespread renal parenchymal damage with non-vital tissue, and complicated collecting system trauma that cannot be addressed through non-operative measures [16]. Figure 1 can be seen as a stepwise management algorithm that combines injury severity and hemodynamic stability.

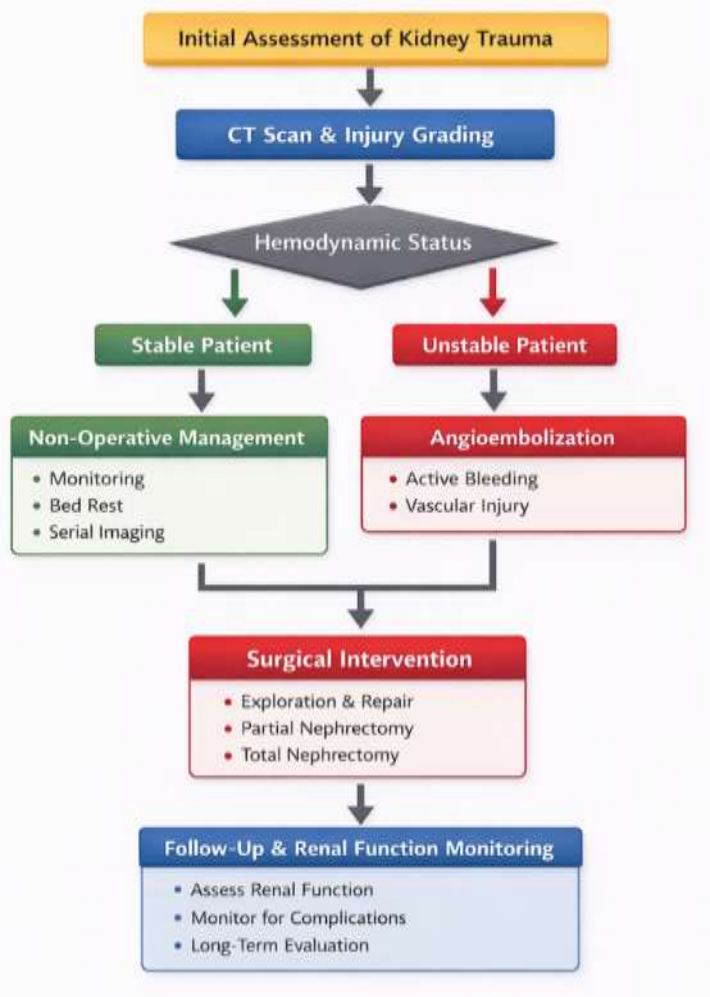

Figure 1. Management algorithm for kidney trauma based on injury grading, hemodynamic status, and stepwise therapeutic decision-making

Damage control surgery has become one of the concepts of growing importance in treatment of severe renal trauma, especially in unstable or critically injured individuals. The principles of damage control give greater emphasis to the initial haemorrhage management and temporary stabilization rather than a permanent repair to achieve the aim of reducing physiological derangement. This is used in cases of renal trauma where conservative intraoperative measures, including packing, limited debridement, or temporary vascular control, are used to save renal tissue whenever feasible. Observational studies and clinical experience indicate that the conservative approach to surgical thinking in damage control operations is related to better renal salvage and lower morbidity in the long term [17].

Renal trauma penetration is a special issue and has historically been linked with increased incidences of operative management because of the fear of vascular injury and related organ injury. Nevertheless, the current national studies show that there has been more of a move towards selective non-operative management even in penetrating injuries provided that patients are hemodynamically stable and do not have any indication of persisting haemorrhage or peritonitis. Surgical intervention is recommended in penetrating renal trauma, which is complicated by hemodynamic instability, major vascular injury, or other related intra-abdominal injuries that need exploration.

Notably, whether to continue with or not to continue with a surgery should be done with regard to the total burden of injury and the physiological reserve of the patient. Renal trauma is a common complication of polytrauma, in which time and scope of intervention may be affected by other priorities. The risks of surgery and the possible advantage of renal salvage and survival should be balanced with the help of multidisciplinary decision-making between trauma surgeons, urologists, and interventional radiologists.

To conclude, the signs of surgical intervention in kidney trauma are determined by a complex of the hemodynamic condition, the severity of the injury, the cause of injury, and the reaction to the primary treatment. Modern practice advocates a discriminatory, evidence-based policy that uses surgery in patients with life-threatening haemorrhage, unresponsive non-operative treatment, or complicated injuries not responsive to non-operative treatment. In cases of surgery, the principles of damage control and renal preservation are still the main aspects of achieving the best outcomes in patients with renal trauma [18].

5. Contemporary Surgical Techniques

Modern surgical repair of kidney trauma involves a range of procedures that are directed to haemostasis, renal function preservation and reduction of morbidity in the short and long term. The development of imaging, endovascular technology,

minimally invasive surgery and perioperative care has greatly increased the range of therapeutic choices available to clinicians. The approaches to surgery are becoming more personalized, considering the severity of injuries, hemodynamic stability, expertise at hand, and the general aim of nephron preservation. Modern surgical approaches to kidney trauma and their clinical implications are listed in Table 3.

Table 3. Contemporary surgical techniques used in kidney trauma and their clinical and renal functional outcomes

Surgical Technique	Primary Indication	Advantages	Limitations	Renal Functional Impact
Renorrhaphy	Parenchymal laceration	Renal preservation	Technical complexity	Favorable
Partial nephrectomy	Segmental destruction	Nephron-sparing	Risk of bleeding	Favorable
Total nephrectomy	Uncontrollable haemorrhage	Rapid control	Renal loss	Poor
Laparoscopic surgery	Stable patients	Reduced morbidity	Limited availability	Favorable
Robotic surgery	Complex reconstruction	Precision	Cost, expertise	Favorable

Endovascular approaches have now become a part of the current renal trauma management system, especially in patients whose bleeding is persistent and are hemodynamically stable. Angiographic embolization provides the opportunity to control haemorrhage selectively and eliminate the need to operate on the kidneys to preserve viable renal parenchyma. Embolization of the kidney has high success rates in managing renal bleeding, particularly in high grade blunt injuries and in instances of penetrating trauma that is carefully selected [19]. Consequently, endovascular embolization is currently considered as one of the first-line adjuncts or alternatives to surgery in properly chosen patients.

Meticulous perioperative management is also essential in delivering optimal outcomes in surgery in renal trauma, especially in terms of renal protection. Even though most of the evidence of perioperative acute kidney injury is based on non-trauma surgical patients, the concepts of the optimization of hemodynamic, prevention of nephrotoxic insults, and cautious fluid management can be directly applied to renal trauma surgery. Clinical practice changes have focused on the idea that renal ischemia and systemic inflammation perioperative measures are critical in the prevention of postoperative renal dysfunction [20]. These factors are particularly important when long operation time or control of the vascularity is needed during renal repair.

The relevance of open surgical procedures in treatment of severe renal injuries has been emphasized in experience of major trauma centres. Institutional series prove that surgical exploration is still necessary in patients that have hemodynamic instability, complicated vascular trauma, or related intra-abdominal trauma necessitating laparotomy. These reports can also be used to demonstrate variability in surgical treatment, which can be renal repair or nephrectomy, based on an intraoperative diagnosis and patient status [21]. These practical statistics emphasize the importance of a flexible approach to surgery and reasonable judgment of the intraoperative conditions.

The nephron-sparing surgery is one of the foundations of modern renal trauma surgery. Renorrhaphy, which is a direct repair of renal parenchymal lacerations and the collection system injuries, is one of the major methods of preserving renal tissue in high-grade injuries. Minimal evidence is provided on how even serious unilateral renal injuries can be managed successfully with renorrhaphy in selected patients, with haemostasis and preservation of functional renal mass [22]. These methods indicate the increased focus on preservation of kidneys as long as it is technically possible.

The decision of partial versus total nephrectomy in renal trauma surgery is considered as one of the most crucial ones. Whereas a lot of comparison literature is designed under an oncological background, literature evidence is always in favour of the long-term renal functional advantages of a nephron-sparing surgery compared to radical nephrectomy. Comparative systematic reviews of partial and radical nephrectomy reveal the higher level of renal function saving with the nephron-sparing methods, which substantiate their applicability in trauma under the conditions of anatomical and physiological possibilities [23]. These values have been more translated into trauma practice.

Extensive database studies have also revealed the negative effects of nephrectomy in the trauma environment. At the population level, there is evidence that nephrectomy that occurs after renal trauma is linked to higher mortality than renal-preserving measures, despite taking into account the severity of the injuries and patient factors [24]. These results have reinforced the argument of forceful efforts of renal salvage and due precaution prior to radical nephrectomy.

Surgical methods involving minimal invasive procedures have also started to be used in the treatment of the operation of the kidney trauma. The laparoscopic nephrectomy and repair have been reported to be possible with highly selected and stable patients with some benefits associated with this approach like fewer postoperative pain, shorter hospitalization and quick recovery. There is new evidence that with skilled hands, minimally invasive interventions can be as effective as open surgery and have less morbidity to surgery [25]. They are however, only used in special centres and in cases that have been selected carefully.

Robotic assisted surgery is another development of minimally invasive surgery of the kidneys, and its application in the trauma care can be considered. Even though the existing evidence is mostly based on the elective urological surgeries, the research indicates that robot-assisted surgeries can be linked to acute kidney injury, which is why special attention should be paid to patient selection and renal protection measures [26]. These lessons can be applied because robotic methods are being considered to do complex renal reconstruction in trauma cases.

Overall, modern surgery on kidney trauma involves a wide spectrum of open surgery, endovascular surgery, and minimally invasive surgery. Surgical decision-making has been altered by the dominant focus on nephron sparing, which has been facilitated by technological progress and perioperative care. The choice of the best method must consider the close

combination of patient physiology, nature of injury, and expertise available to fulfill the two objectives of survival and long-term preservation of renal functions. Figure 2 shows the progressive range of surgical procedures applied in kidney trauma that include renal repair and nephrectomy.

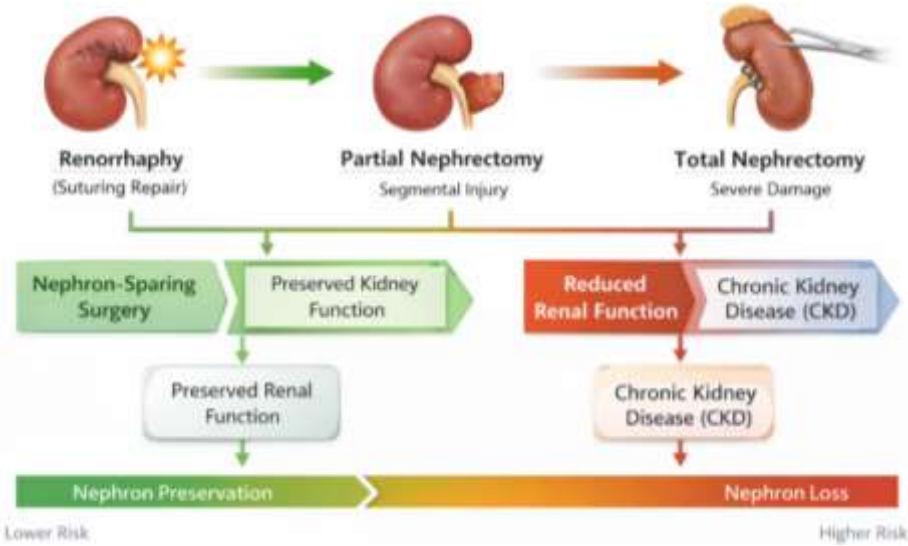

Figure 2. Spectrum of surgical interventions in kidney trauma highlighting progressive nephron loss from renal repair to nephrectomy

6. Surgical Management in Special Clinical Situations

Kidney trauma cannot be managed surgically without special attention in particular groups of patients where anatomic, physiological and psychosocial factors play important roles in affecting the decision-making process and the result. Paediatric patients, solitary or transplanted kidney patients and polytrauma patients are three unique clinical conditions whereby the usual management regimens will have to be optimally adjusted so as to maximize renal preservation and general patient recovery.

Kidney trauma in children is very different than in adults in the mechanisms of injury, anatomic susceptibility, and potential healing. The kidneys of children are relatively bigger, the perirenal fat is less, and the rib cage is more compliant, and thus more vulnerable to renal injury despite the low energy trauma. There is substantial multicentre evidence of paediatric trauma data to support the assumption that most renal injuries in children may be treated non-operatively, including many high-grade injuries, so long as the patient is hemodynamically stable [27]. Paediatric surgical intervention is thus only done in select cases of persistent haemorrhage, hemodynamic instability or related injuries, which require laparotomy. In cases where surgery is required, nephron-sparing strategies are highly preferred to maintain the renal functionality over a long period of time and to minimize the likelihood of developing chronic kidney disease in the future. The case of trauma of one of the single kidneys poses an extremely difficult situation since the rest of the functional renal unit can be lost and the person becomes dependent on renal replacement therapy throughout the life. Patients who have only one functioning kidney when injured may have had a congenital anomaly, previous nephrectomy or functional atrophy of their kidney. Evidence in cases demonstrates that even high-grade injuries in isolated kidneys may in many cases be treated in a conservative or minimally invasive way, including urinary diversion or percutaneous drainage, to prevent nephrectomy [28]. The principles of surgical decision-making in this environment focus on the renal preservation where possible and vigorous efforts to manage the bleeding and repair of system injuries without interrupting renal perfusion.

Other special clinical situations include kidney trauma in transplant patients. Whereas traumatic injury to transplanted kidneys is not very common, the aftereffects might be severe because of immunological, functional aspects, and psychological values of the graft. In addition to the immediate surgical factors, trauma of transplanted kidneys can have a psychosocial impact in the long-term, such as anxiety, post-traumatic stress, and fears of graft survival. Research investigating the psychological outcomes of post-traumatic experiences in patients undergoing kidney transplantation underscores the significance of holistic care that can be provided to patients both in terms of physical harm and psychological wellbeing throughout the recovery process [29]. Close collaboration of the trauma surgeons with the transplant surgeons and the nephrologists is necessary to manage the patients to achieve a balance between graft preservation, immunosuppression, and the risk of infection.

Patients with polytrauma and renal injury present further problems because they have competing life-threatening injuries. Renal trauma management, in those situations, should be combined with a larger damage control approach that puts an emphasis on the quick stabilization and care of the most severe injuries. Renal trauma is predisposed to orthopaedic, thoracic, abdominal, and neurological injuries, which require multidisciplinary care. Modern principles of polytrauma management focus on gradual surgical intervention, close attention to the timing of definite renal repair, and the prevention of extended operative cases among physiologically unstable patients [30]. In polytrauma conditions renal injury is thus often treated conservatively in the acute period and delayed intervention is thought about after the general state of the patient has become stable.

To conclude, there are special clinical conditions in kidney trauma that need non-standard management approaches that are not based on the general algorithm. The advantages of a non-operative and nephron-sparing treatment in paediatric

patients, as well as the need to focus more on the renal preservation and long-term functional outcomes in people with solitary or transplanted kidneys, can be seen. The management of renal injury in patients with polytrauma needs to be well balanced with competing priorities by applying multidisciplinary and damage control principles. These special considerations should be identified in order to maximize the results of complicated cases of renal trauma.

7. Clinical Outcomes of Surgical Management

Surgical management of kidney trauma depends on several factors which affect clinical outcomes such as severity of injury, physiology of the patient, time of intervention, and perioperative care. Although surgical intervention may prove to be life-saving in the isolated cases, it is also characterized by high risks that have to be weighed against the possible benefits. Knowledge about the perioperative morbidity and mortality, complication rates, and the necessity of reintervention can ensure the achievement of the best results and evidence-based decision-making.

Morbidity and mortality in perioperative patients who are subjected to renal trauma surgeries are closely related to the physiological stresses that the trauma and operative intervention exert. Surgical and anaesthesia may trigger systemic inflammatory reactions, hemodynamic instability, and renal hypoperfusion, which will lead to the onset of acute kidney injury. The topic of acute kidney injury has been brought to light in narrative reviews on the effects of surgery and anaesthesia as one of the most common and severe complications of the perioperative period, especially affecting high-risk and critically ill patients [31]. These risks are compounded in the trauma situation by haemorrhagic shock, massive transfusion, and coexistence of other related injuries.

The acute kidney injury has become one of the most important predictors of the long-term and short-term outcomes after the surgical intervention. It has been shown that patients with acute kidney injury after surgery have greater postoperative complications, delay in recovery and mortality. Notably, long-term follow-up studies indicate that despite recovery of renal functionality following an incidence of acute kidney injury, the patient still is at a higher risk of developing chronic kidney disease, cardiovascular events, and poor survival [32]. These observations highlight the relevance of preoperative measures to reduce renal trauma in the treatment of surgical kidney trauma.

Perioperative acute kidney injury also directly affects the overall outcomes of surgery such as length of stay and general resources usage. Recent research indicates that patients that develop perioperative renal failure have much longer hospital stays, increased intensive care unit hospitalization and postoperative complications as compared to patients with no renal dysfunction [33]. These contribute significantly to patients being morbid and burdened in the context of renal trauma surgery.

Surgical and trauma patients develop acute kidney injury pathophysiology in a complex and multifactorial manner. The contributory role is played by ischemia-reperfusion injury, systemic inflammation, endothelial dysfunction, and nephrotoxic exposures. The extensive disease primers have pointed out that acute kidney injury cannot be considered an isolated phenomenon but a systemic syndrome with long-term effects, which supports the importance of prompt detection, prevention, and follow-up in patients undergoing surgery [34]. The view is specifically pertinent in cases of renal trauma, direct parenchymal trauma exacerbates systemic insults.

The rates of complications after surgical treatment of kidney trauma involve the renal and procedure-related complications. Ongoing or repeated bleeding, leakage of urine, infection and vascular complications might require further interventions. Traumatic formation of pseudoaneurysms is increasingly being considered an important delayed outcome of renal trauma and renal surgery. Endovascular therapy has become a viable and minimally invasive treatment of such complications, and does not necessarily require repeat open surgery [35]. The presence of these methods has affected modern outcome profiles in terms of low reoperation rates and the morbidity rates.

In a more general epidemiological view, surgery-related acute kidney injury is an issue of considerable health concern on an international level. Substantial proportions of prospective multicentre studies have shown that acute kidney injury is common in surgical patients and is independently related to both higher mortality rates and longer hospitalization, independent of the type of surgery [36]. These data confirm the significance of renal-protective measures and close postoperative observation of every patient under surgery, even those who were addressed with kidney trauma by surgery.

To conclude, the interaction between the extent of injury, the factors that occur during surgery, and perioperative renal function determines the clinical outcomes after the surgical management of kidney trauma. The occurrence of acute kidney injury is a very strong predictor of perioperative morbidity and mortality, as well as an increase in the rates of complications, prolonged hospitalization, and additional intervention. The progress in perioperative treatment and endovascular procedures have enhanced the outcome profiles, and surgical treatment of renal trauma is a high-risk procedure that needs patient selection, multi-disciplinary care, and further follow-up to ensure the maximization of survival and renal health.

8. Renal Functional Outcomes

Renal functional outcomes are an important aspect of prognosis of kidney trauma patients, especially those who are surgical patients. Although the survival and haemorrhage control during an acute stage are regarded as the main priorities, the renal function preservation and the avoidance of long-term kidney disease are the core objectives of modern treatment. Rapidly growing in recognizing the interdependence of acute kidney injury, chronic kidney disease, and ultimate kidney failure as mutually reinforcing outcomes with a significant impact on morbidity and mortality in the long-term after renal trauma.

Kidney trauma is known to result in acute kidney injury (AKI), which is one of the most frequent and clinically important complications. Cases of AKI can be caused by direct parenchymal injury, renal ischemia caused by haemorrhagic shock, systemic inflammation, or perioperative insults. Systematic reviews of AKI outcomes also show that even a short or mild AKI is not a harmless process; on the contrary, it is linked to the development of higher risks of long-term renal

dysfunction, cardiovascular diseases, and mortality [37]. These risks are further increased in trauma patients by the cumulative effect of the severity of the injury, stress of surgery, and critical illness.

Trauma-associated acute kidney injury pathophysiology is a multifactorial phenomenon. In addition to mechanical destabilization of renal tissue, trauma leads to a systemic inflammatory reaction that is involved in endothelial dysfunction, microcirculatory dysfunction, and immune-mediated kidney damage. It has been illustrated through experimental and clinical research that the inflammatory mediators, leukocyte activation, and complement pathways are at the centre of enhancing the renal injury following trauma, even following localized injury [38]. This immunopathophysiological approach underlines the reasons why the renal dysfunction can be continued in cases when there is seemingly stable primary injury.

Proper measurement and observation of the renal function is the key to measuring the renal outcomes after kidney trauma. The traditional tests of renal functionality such as serum creatinine, blood urea nitrogen, and estimated glomerular filtration rate are still the primary method of clinical assessment. Nevertheless, these parameters are not without limitations especially in the acute setting where the parameters might be delayed in responding to actual renal injury. The complete knowledge of the renal function testing and its interpretation is thus needed in order to detect the early dysfunction, track recovery and provide long-term follow-up in patients recovering renal trauma [39].

The renal mass loss that results with surgical intervention has far-reaching effects on renal outcome in the long term. Partial or total nephrectomy decreases the number of nephrons and puts an extra strain on the remaining renal tissue. It has been shown that patients that have nephrectomy are particularly at high risk of developing chronic kidney disease, kidney failure, and death than patients where the kidney tissue is spared [40]. These results confirm the significance of nephron-sparing approaches in surgery on renal trauma where it is anatomically and physiologically possible.

New approaches to kidney preservation and early detection of patients with potential risks of renal degradation are getting more and more popular. The biomarker-based strategies have demonstrated potential in the detection of patients at risk of developing AKI and the opportunity to timely apply kidney-saving therapies. The possibility to decrease the severity of AKI and minimize long-term renal injury by individualized and personalized care can be explained by clinical trials that assess biomarker-directed renal protection approaches in critical illness [41]. Though these methods are yet to be embraced in trauma-specific guidelines, they are a significant future trend in enhancing renal functional outcomes in case of kidney trauma.

To conclude, the severity of acute injury, the systemic inflammatory response, surgical decision-making, and postoperative care are the factors that influence renal functional outcomes after kidney trauma. Acute kidney injury is a central point between trauma and long-term kidney dysfunction and high mortality rates. Renal mass preservation, close attention to the renal functioning, and implementation of new kidney-protective measures are the key to reducing the risk of chronic kidney disease and kidney failure. An objective emphasis on renal functional outcomes is thus a key to the maximization of both short- and long-term prognosis in kidney trauma patients.

9. Comparison with Non-Surgical Approaches

Kidney trauma management has evolved over time towards non-surgical approaches due to the developments in imaging, critical care, and interventional radiology. Modern studies are showing an increased support of conservative and minimally invasive treatment of a broad spectrum of renal injury including selected high-grade cases as long as patients are not hemodynamically unstable. The comparison of the surgical and non-surgical methods thus takes centre stage in the selection of treatment based on outcomes.

The use of non-operative management has emerged as a popular choice in most patients having kidney trauma, despite the existence of high-grade isolated injuries. Paediatric case series show that well-identified patients with high grade renal trauma could be treated successfully, without surgery, with favorable outcomes and without nephrectomy and renal dysfunction in the long run [42]. Such results emphasize the need to select patients, monitor them closely, and provide supportive care when implementing conservative measures. Table 4 shows a comparison between surgical and non-surgical management strategies of kidney trauma.

Table 4. Comparison of surgical and non-surgical management approaches in patients with kidney trauma

Parameter	Surgical Management	Non-Surgical Management
Indication	Instability, failed NOM	Hemodynamic stability
Renal salvage	Variable	High
Complication rate	Higher	Lower
Risk of AKI	Higher	Lower
Long-term CKD risk	Increased	Reduced

The growing amount of evidence behind the conservative management is also supported by systematic reviews and meta-analyses. Extensive studies on high-grade renal trauma reveal that non-operative renal management is related to high renal salvage and tolerable complication in stable patients. Notably, these studies show that there is no significant mortality increase when conservative methods are used when suitable and this makes a challenge to the use of operative intervention on severe injuries which has been the historical reliance [43]. This type of data has helped to create a paradigm shift in the treatment of trauma, as it has focused on selective and not on routine surgical exploration.

Angioembolization has become one of the most important minimally invasive treatment methods to substitute surgery in the treatment of actively bleeding kidney diseases in patients with hemodynamic stability. Systematic reviews in support of angioembolization of blunt renal injuries provide high technical success and good haemorrhage control with the added

advantage of preserving parenchymal renal preservation [44]. Angioembolization is less morbid and requires fewer nephrectomies than open surgery, which is why it is a necessary part of the modern renal trauma algorithm.

Paediatric trauma populations also shed more light on the relative efficacy of non-surgical strategies. Institutional experience over a long period has shown that the majority of children with high-grade renal trauma may be treated conservatively or by using adjunctive minimally invasive treatment, and surgery is used only in cases of hemodynamic instability or in those whose non-operative treatment has failed [45]. The results highlight the strength of paediatric renal tissue and support the generalizability of conservative interventions in the elderly.

Not only immediate survival and haemorrhage control are being used in outcome-based treatment selection, but also long-term renal health. Translational and experimental studies indicate that renal injury triggers molecular mechanisms that culminate in fibrosis and progression of chronic kidney disease even without apparent surgical intervention. The new findings of ferroptosis as the cause of renal damage and fibrosis point to the possibility of specific treatment to prevent irreversible damage to the kidneys [46]. Although these measures are still experimental, there is a biological justification of reducing surgical renal mass loss where possible.

To conclude, the review of surgical and non-surgical methods of intervention shows a definite shift towards the conservative treatment and minimal invasive procedures in kidney trauma. Non-operative management and angioembolization can effectively be used as alternatives to surgery in the right choice of patients and they have the benefit of not damaging renal functioning and lower morbidity in the long term. The selection of treatment by outcomes must hence be based on the stability of the patient, the nature of the injury and long-term renal retention with surgical intervention being the final resort in the treatment of cases where non-surgical measures are unlikely to be effective.

10. CONCLUSIONS AND FUTURE DIRECTIONS

The surgical treatment of kidney trauma has been significantly transformed due to the development of imaging, perioperative care, and increased focus on kidney preservation. Modern data favours a highly selective attitude to surgery, and only in patients with hemodynamic instability, complicated vascular trauma, or in those in whom non-operative and interventional methods have failed, operative intervention is used. In cases where surgery is necessary, the nephron-sparing methods need to be considered whenever anatomically and physiologically possible because the preservation of the renal mass is closely linked with better survival and long-term renal outcomes. Clinically, renal trauma can only be managed best when there is close coordination between trauma surgeons, urologists, nephrologists, interventional radiologists, and the critical care team. Timely diagnosis and intervention of acute kidney injury, careful perioperative care, and organized follow-up of the kidney in the long term are key elements of quality care. Specific populations, such as paediatric patients, patients with isolated or transplanted kidneys, and polytrauma patients, should be considered with separate approaches to management that would consider the immediate need to save the life of patients and long-term renal health. The future studies are aimed at the improvement of the risk stratification instruments, the validation of kidney-specific biomarkers to detect the renal injury early, and the determination of the standard follow-up procedures to assess the long-term renal performance after the trauma. New understanding of the molecular mechanisms of renal injury and fibrosis can provide new therapeutic opportunities that would help to restrain the development of chronic kidney disease. The further combination of evidence-based surgical practice with the development of the renal protection strategies will be essential in the context of improving the outcomes of patients with kidney trauma in the contemporary era.

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