Adrenal Surgery
Open, Laparoscopic, and Robotic Approaches

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KEYWORDS

• Adrenalectomy • Adrenal surgery • Robotic-assisted adrenalectomy
• Laparoscopic adrenalectomy • Open adrenalectomy • Adrenal surgical complications
• Adrenal surgery perioperative management

KEY POINTS

- It is crucial to strike a balance between avoiding overtreatment and preventing undertreatment of adrenal pathology.
- Necessitating thorough metabolic workup and accurate risk assessment for malignancy.
- Surgical intervention and approach should be tailored to the individual patient, accounting for disease characteristics, imaging findings, and patient-specific factors. Given the diversity of adrenal masses, there is no one-size-fits-all solution, and the surgeon's skill-set and experience play a critical role in selecting the most appropriate technique.
- Generally, open adrenal extirpation affords the most oncologic safety for large adrenal masses suspected to be adrenocortical carcinoma.
- Complications of adrenal surgery often can be mitigated with thoughtful perioperative planning and appropriate cross-specialty collaboration.

INTRODUCTION

The adrenal glands, small, paired organs located in the retroperitoneum cephalad to the kidneys, serve as endocrinologic powerhouses responsible for critical functions related to the stress response and hormone synthesis. Since Thornton performed the first adrenalectomy in 1889, surgical removal has been a key strategy for managing adrenal pathology.[1]

Historically, adrenal surgery necessitated large, invasive incisions to ensure safe access owing to the deep location of the adrenal glands—lying roughly equidistant from the anterior, posterior, and lateral surfaces of the body (**Fig. 1**). In turn, the advent of minimally invasive surgery has revolutionized adrenalectomy. Laparoscopic and robotic techniques—both transperitoneal and retroperitoneal approaches—now allow for the removal of adrenal tumors through small incisions, significantly reducing morbidity and recovery time. Despite these benefits, significant controversy exits regarding the use of minimally invasive surgery for suspected adrenal malignancy given reports of increased risk of tumor rupture, spillage, and worse oncologic outcomes.[2–6]

Beyond surgical technique, a deep understanding of adrenal physiology is crucial for adrenal surgeons. The gland's role in regulating blood pressure, metabolism, and stress response via

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Abbreviation	
IVC	inferior vena cava

hormone secretion is essential for determining the appropriate indications for surgery and optimizing perioperative care.

In this article, we provide a review of adrenal surgery, covering key anatomic considerations, various surgical approaches—including open, laparoscopic, and robotic techniques—along with perioperative management and potential complications.

INDICATIONS FOR ADRENAL SURGERY

In patients with adrenal mass, indications for surgery pivot on metabolic functional derangements or the risk of malignancy.

Metabolic Activity as Indication for Surgery

Metabolic evaluation is a cornerstone of adrenal mass evaluation. Depending on the hormone hypersecretion in question, symptoms may range from hypertension and electrolyte disturbances to Cushingoid body habitus.[7] However, metabolic hypersecretion occurs in over 10% of incidentally discovered adrenal masses even in patients without signs and symptoms of hormone excess.[8,9] Thus, a high index of suspicion must be maintained.

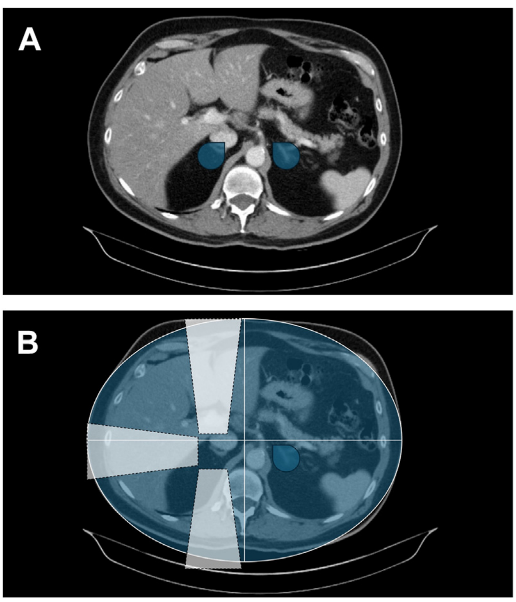

Fig. 1. Computed tomography scan depicting the anatomic location of adrenal glands along an axial plane. (*A*) Region of glands depicted by tear shaped marker. (*B*) Overlay of an ellipse with adrenal glands representing two foci abutting the major axis. Each gland lies approximately equidistant from the ipsilateral flank, anterior, and posterior body walls. As a result, open adrenalectomy typically requires large incisions for adequate exposure and access. In contrast, laparoscopic techniques allow for enhanced visualization and facilitate deep dissection with significantly smaller incisions.

All adrenal masses necessitate functional interrogation for cortisol and catecholamine hypersecretion along with hyperaldosteronemia screening in patients with history of hypertension.[10,11] This is accomplished through a variety of testing strategies, but experts promote low-dose dexamethasone suppression test or salivary cortisol testing owing to the ease of performance and interpretation of these tests in detection of cortisol excess and adrenal hypersecretion.[3,6,10,12] More specifically, the low-dose dexamethasone suppression test can be used to identify autonomous adrenal cortisol secretion with high sensitivity and specificity.[6,8] Catecholamine excess and pheochromocytoma screening via testing of plasma-free metanephrine testing is also preferred owing to ease when compared to 24-h urine testing.[4]

In patients with a history of hypertension or unexplained hypokalemia, screening for primary aldosteronism via aldosterone and renin testing is advised.[6] In patients with hyperaldosteronism, adrenal vein sampling is generally indicated to evaluate for contralateral aldosterone hypersecretion as these patients may not be helped with unilateral adrenalectomy.[13–15]

Evaluation for adrenal androgen hypersecretion is typically reserved for tumors suspicious for adrenocortical carcinoma.[6,8] Although not a prerequisite for surgical intervention, significant increases in sex steroids may further delineate suspected adrenocortical carcinoma diagnosis from benign etiologies.[6,8]

A thorough medical screening should be performed before the aforementioned evaluations, as metabolic screening for adrenal masses may be impacted by several common medications.[8] The mechanism by which testing is altered is quite variable. Highlighting this point, cortisol screening may be impacted via several mechanisms with common medications. Medications such as antidepressants, anticonvulsants, or other pharmaceuticals with cytochrome-modulating effects may impact dexamethasone metabolism for low-dose dexamethasone suppression testing.[6,8] Metanephrine and catecholamine measurements may be impacted by recent illness or medications such as tricyclic antidepressants, which can be associated with catecholamine production increases.[6] Lastly, acetaminophen and caffeine may impact the performance of the drug assays used for metanephrine testing.[16]

Risk of Malignancy as an Indication for Surgery

Primary adrenal gland malignancy is typically inferred rather than confirmed before resection, as biopsy cannot reliably distinguish between adenoma and carcinoma, except in cases of metastatic disease to the adrenal. Indeed, biopsy is generally omitted given a theoretic risk of tumor rupture or needle-track seeding.[17] Instead malignancy risk is inferred from radiographic findings, tumor size, and rate of growth.[18] Among imaging signatures, lipid poor lesions (Hounsfield unit measurements >10) or those that do not exhibit washout on adrenal washout computed tomography (CT) imaging are less likely to be benign adenoma.[10,18] There is also a well-documented association between the size of adrenal lesions and malignancy. Lesions greater than 6 cm in size have an estimated 25% rate of malignancy and are typically managed surgically.[19] For adrenal masses that measure between 4 to 6 cm, there is approximately a 6% malignancy rate.[19] As such, decision to proceed with surgery is calibrated based on patient's age and competing risk status.[19] In lesions monitored with imaging, rapid growth kinetics may also inform the decision to proceed with resection.[11] A notable exception to these size criteria are myelolipomas, which exhibit abundant macroscopic fat on imaging and are benign.[11]

Adrenal glands may also harbor metastatic cancer from other sites—with lung and kidney metastases being most common. Although this is a rapidly changing landscape with advent of better systemic therapies, adrenalectomy is often indicated in patients in whom adrenal oligometastatic disease is suspected.[20] In these cases, once catecholamine secreting pheochromocytoma has been excluded, adrenal biopsy may be warranted, particularly in patients with a history of nonadrenal malignancy.[21]

Contraindications to Adrenal Surgery

Adrenal surgery is not without risks. Indeed over 10% of patients who undergo adrenalectomy may experience a complication as suggested by administrative claims data.[22–25] As with any surgery, inability to tolerate anesthesia due to cardiopulmonary status or risk of severe bleeding in the setting of coagulopathy warrant nonsurgical strategies. Obesity, previous surgery, especially in the retroperitoneum, very large tumor size, or concern for extensive invasion into locoregional structures may make adrenal resection challenging or unfeasible.[25] These factors also inform surgical approach.

Current guidelines recommend that large adrenal tumors (generally >6 cm in size) merit an open surgical approach, owing to risk of tumor rupture and spillage during minimally invasive surgery, resulting in higher rates of recurrence and carcinomatosis.[2,26,27] Nevertheless, adrenocortical carcinoma (ACC) is a rare disease and data derived from institutional case series and administrative datasets make it difficult to detect differences in outcomes by surgical approach.[28]

Although beyond the scope of this article, there are several procedural alternatives to adrenal surgery in the case of metabolically active and small tumors. In patients who may have a contraindication to surgical management, percutaneous ablative therapy may be performed for small adrenal masses. The primary available therapies involve either radiofrequency ablation, cryoablation, or microwave ablation.[29] Lastly, these percutaneous approaches may also serve a role in management of residual or recurrent disease after surgical management.[29,30] Additionally, for larger tumors and those suspected to harbor malignancy, these approaches are unproven.

ADRENAL ANATOMY AND SURGICAL ANATOMIC LANDMARKS

Adrenal Gland Surgical Anatomy

The adrenal glands are paired retroperitoneal endocrine organs. In the average adult, each gland weighs approximately 4 to 6 g and is composed of 2 distinct regions: the cortex and the medulla.[31] Each of these 2 regions, have different embryologic origins and, therefore, physiologic functions. The cortex is responsible for producing steroid hormones such as cortisol, aldosterone, and adrenal androgens, while medulla synthesizes and secretes catecholamines (epinephrine and norepinephrine).[32] The adrenal gland is characterized by a fine, granular surface and firm consistency, differentiating the gland from the surrounding retroperitoneal fat.[32]

Briefly, the right adrenal gland is pyramidal in shape and lies superior to the right kidney, posterior to the liver, adjacent to the inferior vena cava (IVC), and anterior to the diaphragm.[32] The left adrenal gland is crescent-shaped, positioned superior and posterior to the left kidney, anterior to the diaphragm, and lies near the aorta, spleen, and pancreas.[32]

Ectopic adrenal tissue, known as adrenal rest tissue, may remain as a remnant of embryologic development.[33] Typically, this tissue will be found adjacent to the renal pelvis; however, it may also be associated with gonadal structures, given the embryologic descent of the testis.[33]

Vascular Supply

The adrenal glands receive a substantial blood supply, including from small unnamed vessels. Understanding the anatomic relationship between the adrenal gland and its blood supply is critical during surgery, as inadvertent injury to these vessels can lead to significant bleeding.

While the arterial blood supply stems from 3 primary sources, each source rapidly branches before penetrating the adrenal capsule.[32,34] Dozens of these perforating vessels may be present and must be ligated during dissection—though often not discretely visible at the level of the adrenal.

Named vessels presented in anatomic studies include:

- Superior adrenal artery: a branch of the inferior phrenic artery carrying the majority of the blood supply to the adrenal gland.
- Middle adrenal artery: a direct branch from the abdominal aorta. An anatomic study has indicated this artery may be unilaterally absent in up to half of patients.[34]
- Inferior adrenal artery: a branch of the renal artery.

Venous drainage differs between the glands and may be further complicated by the presence of accessory or aberrant veins. With hormonally active adrenal glands or lesions, it is preferable that adrenal veins are ligated before gland manipulation to avoid untoward catecholamine release.

Venous anatomy on either side of the midline is typically presented as follows:

- Right adrenal vein: drains directly into the inferior vena cava (IVC). Also known as the "vein of death" - the course of the right adrenal vein into the IVC is notably short (on average 9 mm),[35] making it considerably difficult to control bleeding if inadvertently torn, especially before adequate dissection and vena caval exposure has been performed.
- Left adrenal vein: drains into the left renal vein. At 2 to 3 cm the left adrenal vein is longer than the right adrenal vein.[35] Typically joins with the inferior phrenic vein.

Lymphatic Drainage

Lymphatic drainage from the adrenal glands primarily follows the venous drainage, with lymph nodes located alongside the renal hilum, para-aortic, and paracaval regions.[32] In cases of adrenal cortical carcinoma, appropriate lymph node dissection may impact disease-free survival and cancer-specific mortality.[36]

Innervation

The adrenal medulla is innervated by cholinergic preganglionic sympathetic fibers, primarily from the thoracic splanchnic nerves, which facilitate the release of catecholamines (epinephrine, norepinephrine, and dopamine).[32] Collectively, these innervating fibers typically run alongside vasculature and are ligated during dissection.

Comparatively, the adrenal cortex is mediated by hormonal stimulation arising from the hypothalamic-pituitary axis, underscoring the importance of the extensive adrenal vasculature for modulating its function.[32]

Adjacent Structures and Surgical Landmarks

Understanding the proximity of the adrenal glands to vital structures such as the IVC, aorta, pancreas, liver, spleen, and kidneys is essential for safe surgical dissection. Key surgical landmarks include the renal vessels, the crura of the diaphragm, and the lateral border of the psoas muscle.[37] Identification of these landmarks is crucial for orienting the surgeon during adrenalectomy and avoiding injury to adjacent organs.

Right Adrenal Gland

The right adrenal gland is bordered by the liver (superiorly and anteriorly), the inferior vena cava (medially), and the diaphragm (posteriorly).[37] The right adrenal gland is anterior to the 12th rib.[32]

Left Adrenal Gland

The left adrenal gland is bordered by the spleen (superiorly and laterally), the splenic artery and vein (superiorly), body of the pancreas (anteriorly), the abdominal aorta (medially), and the diaphragm (posteriorly).[32] The left adrenal gland is anterior to the 11th and 12th ribs.[32]

ADRENAL SURGICAL TECHNIQUE

Open Adrenalectomy

Open adrenalectomy is the traditional approach for adrenal gland removal, particularly for large or malignant tumors, or when there is suspicion of local invasion.[38] The open approach provides excellent exposure and allows for meticulous dissection and minimizes the risk of spillage in cases of malignant tumor excision.[39] Morbid obesity is known to further complicate open adrenalectomy due to limited exposure.[25]

Flank Retroperitoneal Approach

The first documented flank approach for adrenalectomy was performed in 1927 by Mayo.[40] In this approach, the patient is positioned in a lateral decubitus position with the surgical table flexed to maximize the space between the costal margin and the iliac crest.[37] The initial dissection involves exposing the 11th rib until the periosteum is stripped off the rib from the tip back toward the paraspinal muscles.[37] Rib resection was historically performed to facilitate the operation.[37]

Once the rib is adequately resected or mobilized, the transversus abdominis muscle is divided, and the retroperitoneal space is entered.[37] Careful blunt dissection is performed to identify and mobilize the adrenal gland, while major structures such as the kidney and diaphragm are carefully avoided.[37] The adrenal vein is identified early and controlled either with sutures or vascular clips, given its short length and proximity to the inferior vena cava (on the right) or renal vein (on the left).[37] Once the adrenal gland is fully mobilized and hemostasis is ensured, the gland is removed through the retroperitoneal space.[37] This approach provides a direct route to the adrenal gland while minimizing intra-abdominal dissection, which can be advantageous in certain patients, particularly those with a history of extensive abdominal surgery or other contraindications to transabdominal approaches.[37]

Posterior Lumbodorsal Approach

This approach offers the benefit of access to bilateral adrenal glands; however, limited visualization may make dissection and control of bleeding more challenging.[37] There are several variations to this procedure, which may or may not include rib resection or diaphragmatic dissection.[37] The patient is positioned prone and the initial dissection is performed similar to that of the flank retroperitoneal approach.[37] On the right, hepatic attachments must be dissected to visualize the adrenal gland.

This approach is generally reserved for smaller tumors or non-invasive adrenal pathology, as large or invasive tumors are typically not amenable to this approach due to the constrained visualization and difficulty in achieving vascular control, particularly of the adrenal vein.[36] Given these limitations, careful preoperative planning and patient selection are critical when considering the posterior lumbodorsal approach for adrenalectomy, typically reviewed for historical consideration as its use has diminished in modern adrenalectomy.

Anterior Transabdominal Approach

Various surgical incisions have been described for the transabdominal approach to adrenal surgery. Depending on the incision, this approach potentially offers exposure along the midline, allowing access to bilateral lesions and visualization of major vessels for simultaneous tumor thrombus dissection or lymphadenectomy.[37,41] Incisions such as the midline, subcostal, chevron, or modified Makuuchi incision provide extensive exposure to the adrenal glands and surrounding anatomy (**Fig. 2**).[37] With this anterior approach, there is improved access to vital structures, which is especially useful in cases of larger tumors, those involving vascular invasion, or when bilateral adrenalectomy is required.[37,41]

However, wide exposure comes with risks of injury to surrounding organs, including the bowel, pancreas, spleen, and diaphragm.[41] Meticulous surgical technique and careful handling of these structures are essential to minimize complications, particularly in cases of complex or invasive adrenal pathology. Preoperative imaging and planning play a crucial role in selecting this approach to ensure optimal outcomes while balancing the risks of extensive intra-abdominal dissection.

Thoracoabdominal Approach

The thoracoabdominal approach provides access to both the thoracic and abdominal cavities, making it particularly useful for large or locally advanced tumors that invade adjacent structures. However, the invasiveness of this technique

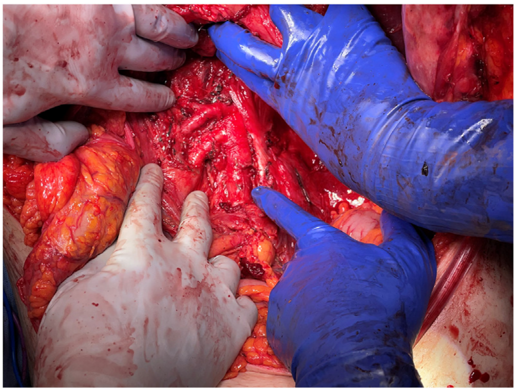

Fig. 2. The modified Makuuchi incision provides excellent exposure to the upper abdomen. In this case, a 20 cm left adrenocortical carcinoma and the left kidney have been resected, revealing the left crus of the diaphragm, the aorta, the celiac artery, and the superior mesenteric artery, all of which are clearly visible. The surgeon's blue-gloved right hand is retracting the pancreas superiorly.

increases the complexity and risk of the procedure. Despite yielding optimal exposure, this is considered the most invasive approach as it necessitates both rib splitting and pleural cavity entry.[42] Care should be taken to avoid dividing the phrenic nerve, which enters the diaphragm at the level of the 8th thoracic vertebra via the vena caval hiatus on the right and at the level of the 10th thoracic vertebra via the esophageal hiatus on the left.[37]

Injury to the phrenic nerve can result in diaphragmatic paralysis, which can have significant respiratory consequences postoperatively.[37] Additionally, pleural entry increases the risk of postoperative complications such as pneumothorax or pleural effusion.[37] Given these risks, this approach is typically reserved for highly selected cases where less invasive options are not feasible, and the potential benefits of broad exposure outweigh the increased morbidity. With the advent of modern fixed retractors, such as the Thompson retractor, abdominal incisions now provide comparable exposure with significantly reduced morbidity, making the thoracoabdominal approach increasingly rare.

Laparoscopic Adrenalectomy

First described in 1992,[43–45] laparoscopic adrenalectomy has become the standard of care for most benign adrenal tumors due to its minimally invasive nature. This approach offers significant advantages over open surgery, including reduced postoperative pain, smaller incisions, and quicker return to normal activities.[39] However, there is a notable learning curve associated with laparoscopy, particularly in mastering the delicate dissection of adrenal tumors and avoiding potential intraoperative complications, such as vascular injury and tumor spillage.[46]

While open adrenalectomy remains the standard of care for adrenal lesions greater than 6 cm suspected of being adrenocortical carcinoma, due to concerns about incomplete tumor resection and capsular rupture, emerging evidence suggests that laparoscopic approaches may yield comparable oncologic outcomes in carefully selected patients.[28] In particular, for tumors without extensive local invasion and with no evidence of distant metastasis, laparoscopic adrenalectomy can offer a safe and effective alternative with appropriate preoperative planning and expertise in advanced laparoscopic techniques.[28]

Nonetheless, patient selection is critical, and larger or more invasive adrenal tumors may still necessitate an open approach to ensure adequate tumor resection and minimize the risk of recurrence.[28]

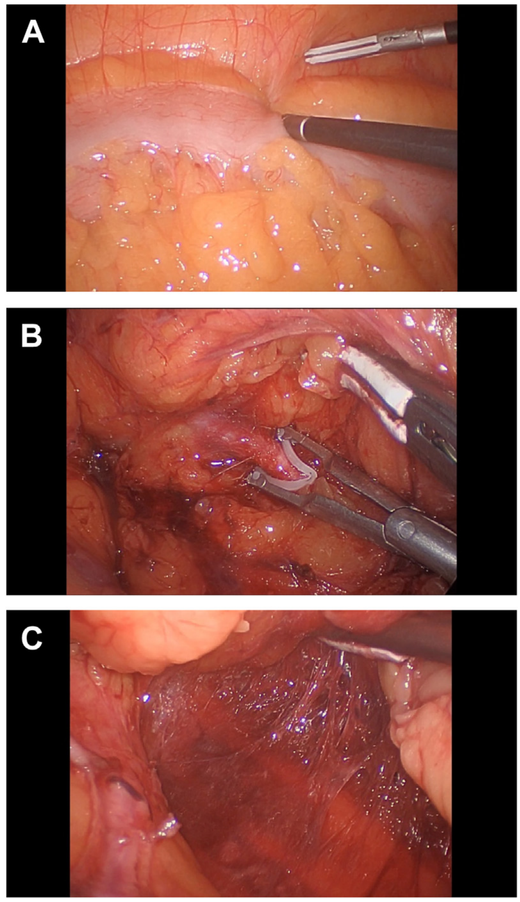

Fig. 3. Transperitoneal left laparoscopic adrenalectomy. (*A*) Mobilization of left colon along white line of Toldt. (*B*) Heme-o-lok clip is applied to the left adrenal vein before significant adrenal gland manipulation. Perforating arterial vessels are secured with an energy device. (*C*) The adrenal gland is carefully lifted off the underlying psoas muscle to facilitate further dissection and complete gland removal.

Transperitoneal Approach

In the first documented laparoscopic adrenalectomy, a transperitoneal approach was used.[44] Similar to the open anterior approach, this technique provides excellent visualization of the adrenal gland and surrounding structures (Fig. 3) but carries an increased risk of injury to intra-abdominal organs, such as the bowel, liver, spleen, or pancreas, due to the necessary mobilization of these structures during dissection. This approach is favored for its wide access to the adrenal region, making it suitable for most benign adrenal lesions and cases requiring extensive adrenal exposure.

Several variations of the transperitoneal approach have been described in the literature. One such variation involves a gasless technique, where a specialized apparatus is used to lift the abdominal wall, creating a working space without the need for insufflation.[47] This method can be advantageous in certain clinical situations, particularly for patients who are poor candidates for pneumoperitoneum due to respiratory or cardiovascular issues.[47]

Retroperitoneoscopic Approach

A posterior retroperitoneoscopic approach was first described in 1995 by Walz and colleagues[48,49] This approach is beneficial for smaller tumors and offers direct access to the adrenal glands without the need to mobilize intraperitoneal organs, reducing the risk of related complications.[48,50]

The choice between a transperitoneal and retroperitoneoscopic approach is typically determined by surgeon preference and experience, as both approaches offer distinct advantages.[5] However, some evidence suggests that the retroperitoneoscopic approach may be safer and more efficient in patients with a history of prior intra-abdominal surgery, as it avoids scar tissue and adhesions within the peritoneal cavity, which can complicate dissection.[47] In such cases, the retroperitoneal approach minimizes the risk of injury to previously operated organs and provides a more direct pathway to the adrenal glands.

Robotic-Assisted Laparoscopic

Robotic adrenalectomy, an extension of laparoscopic surgery, offers enhanced dexterity, three-dimensional visualization, and greater precision through the use of robotic instruments.[51] The first reported robotic adrenalectomy was performed in 1999 and the procedure has since gained popularity, particularly in major academic centers.[45] This approach is especially advantageous in complex cases requiring delicate dissection, such as tumors near major vessels or in anatomically challenging cases.

While robotic technology provides superior ergonomics and control compared to traditional laparoscopy,[52] the evidence on whether robotic adrenalectomy yields improved operative outcomes, morbidity, or disease control remains mixed.[53,54] Some studies suggest advantages in surgeon comfort and technical ease, particularly in complex or larger tumors, but the differences in patient outcomes compared to standard laparoscopic adrenalectomy are less clear.[51]

Robotic adrenalectomy is typically approached similarly to the standard laparoscopic technique, with ports placed for robotic instrument access.[38] In some cases, a 5th port may be added for bedside assistance, offering flexibility in managing larger or more complex tumors.[37] The decision to use robotic assistance is often based on surgeon experience, institutional resources, and the complexity of the case.[52] While laparoscopic adrenalectomy remains the primary approach for adrenal extirpation,[52] robotic adrenalectomy continues to gain traction as a feasible and effective option in the surgical management of adrenal tumors.[52,53]

Partial Adrenalectomy

Partial adrenalectomy, using any of the above-mentioned surgical approaches, may be performed to preserve as much adrenal tissue as possible, maximizing the likelihood of adrenal function recovery postoperatively. This approach is particularly useful for small adrenal masses, especially in patients with a solitary adrenal gland or bilateral adrenal disease, where complete adrenalectomy could result in lifelong steroid dependence and other significant endocrinological complications.[55]

Compared to total adrenalectomy, partial adrenalectomy has been associated with a lower risk of postoperative hemodynamic complications, such as adrenal insufficiency, while maintaining comparable overall morbidity and oncologic outcomes.[55,56] This makes it a valuable option in specific clinical scenarios, particularly for benign tumors such as pheochromocytomas or hereditary syndromes where future adrenal tumors may develop.[55]

Intraoperative ultrasound may be used to differentiate adrenal tumors from normal adrenal tissue, ensuring adequate tumor resection while sparing as much healthy adrenal tissue as possible.[57] This tool is especially helpful in localizing small, less palpable tumors and guiding precise dissection, further reducing the risk of damage to the remaining adrenal tissue.[57]

COMPARISON OF MODALITIES

Choosing the appropriate surgical modality depends on multiple factors, including tumor size, suspicion of malignancy, patient comorbidities, and surgeon experience. While laparoscopic and robotic approaches are preferred for most benign tumors due to their minimally invasive nature, open surgery remains crucial for large, invasive, or malignant tumors. Robotic surgery, though more expensive upfront, may offer advantages in precision and ergonomics, particularly in complex cases.[52,58]

Open Versus Laparoscopic Adrenalectomy

In contemporary surgical practice, laparoscopic adrenalectomy has been shown to provide improved postoperative pain control, shorter hospital stays, and decreased morbidity compared to open surgery.[52] Although some studies have yielded contradictory results, the overall trend across multiple studies, including meta-analyses, supports these benefits for laparoscopy in adrenalectomy.[59–62] In addition to these advantages, laparoscopic surgery has demonstrated reduced blood loss, quicker bowel recovery, and better pain outcomes in obese patients.[63]

Oncologic outcomes are particularly relevant when determining the best surgical approach for adrenocortical carcinoma. Early retrospective studies comparing open and minimally invasive adrenalectomy showed higher rates of positive surgical margins, tumor spillage, local recurrence, and worse cancer-specific and overall survival in minimally invasive approaches,[26,27,38,64] However, more recent systematic reviews and meta-analyses from high-volume centers have called these findings into question, showing no significant differences in these outcomes between open and minimally invasive techniques.[58–61]

Despite these findings, open adrenalectomy remains the standard of care for suspected or confirmed ACC due to its more reliable outcomes in achieving complete resection.[26,27] Ongoing research is needed to better define the optimal surgical approach for ACC.

Laparoscopic Versus Robotic-Assisted Adrenalectomy

Mixed data exist regarding the comparative outcomes between laparoscopic and robotic adrenalectomy. Recent large meta-analyses demonstrate similar complication rates between both approaches, particularly when evaluating conversion rates and blood loss or transfusion rates.[54,65] This similarity in complication rates has also been found to hold true in cases of large masses greater than 5 cm.[66]

The literature also suggests that there is no significant difference in oncologic outcomes between these minimally invasive modalities as it relates positive margins.[53] A systematic review and pooled analysis comparing retroperitoneal laparoscopic versus robotic adrenalectomy, it was demonstrated that patients who underwent robotic adrenalectomy had a small but statistically significant shorter hospital stay with a weighted mean difference of 0.78 days.[65] Interestingly, within this same study, subgroup analysis demonstrated no significant difference in length of stay for patients with tumors less than 5 cm.[65] The authors suppose the shorter length of stay for robotic adrenalectomy may be associated with diminished blood loss for the robotic approach in patients with larger tumors ($\geq$5 cm)—there was no statistically significant difference in blood loss noted between the modalities for patients with tumors less than 5 cm.[65]

Although robotic adrenalectomy is more costly compared to laparoscopic or open approaches, evidence suggests that these cost differences become insignificant in high-volume surgical centers.[58,67] To this effect, mixed evidence exists regarding differences in operative time between these modalities.[54,65]

Both laparoscopic and robotic adrenalectomies are associated with significant learning curves, with laparoscopic adrenalectomy requiring 20 to 40 cases for proficiency and robotic adrenalectomy requiring approximately one-half that number in reported series.[46,68] However, as adrenalectomies are increasingly performed in high-volume centers, the impact of the learning curve may become less pronounced in practice, leading to more uniform outcomes across different surgical modalities.[22] Over time, 1 modality may become favored by surgeons, as they will have mastered the learning curve for this modality during their training.[22]

PERIOPERATIVE MANAGEMENT

In this section, several perioperative considerations are discussed. Optimized perioperative management is essential to yielding the best possible surgical and disease-related outcomes as well as minimizing the risk of complications.

A thorough preoperative evaluation is essential for successful adrenal surgery. This is covered in detail in the respective section of this special issue. This workup is paramount before surgical resection and may include imaging, hormonal evaluation, adrenal vein sampling, and consideration of risk factors.[10]

Before the routine use of catecholamine blockade, perioperative mortality for adrenal surgery, particularly pheochromocytoma resection, was as high as 50%.[69]

Patients with hormone-secreting tumors require specific preoperative management, which are outlined in their respective sections below.

Pheochromocytoma

Preoperative alpha-blockade with drugs like phenoxybenzamine or doxazosin is highly recommended in order to control blood pressure and prevent intraoperative hypertensive crises.[70] Beta-blockers may be added if tachycardia develops.

Alpha-adrenergic blockers (eg, phenoxybenzamine) are typically administered up to 14 days preoperatively to control hypertension.[70] Dosing is classically titrated to achieve a normotensive blood pressure; however, limited data support particular treatment goals.[70]

Beta-blockers are introduced to counteract alpha-blocker tachycardia and arrhythmias only after adequate alpha-blockade to prevent unopposed alpha-adrenergic stimulation.[70]

Hypercortisolemia

Patients may need preoperative steroid supplementation to manage adrenal insufficiency postoperatively.[41] In cases where cortisol hypersecretion has led to contralateral adrenal gland suppression, perioperative steroid replacement is essential.[71] A typical regimen includes stress dose hydrocortisone on the day of surgery, followed by maintenance dosing. A tapering regimen is necessary to wean patients off steroids while monitoring for signs of adrenal insufficiency.[71] It is worth noting that steroid administration, especially high dose and prolonged, may negatively impact wound healing as well as incur untoward metabolic complications—as such, steroids should only be used when indicated.[71] Endocrinology consultation is recommended for long-term management.[71]

The median time for recovery of adrenal function varies, with mild autonomous cortisol secretion typically resolving in about 6.5 months, while full recovery in cases of Cushing syndrome can take up to 11 months as defined by time to withdrawal of hydrocortisone therapy.[72] A small percentage of patients may never achieve complete recovery.[71] As such, steroid replacement may be necessary until full normalization of hypothalamic-pituitary-adrenal axis.

Hyperaldosteronism

Potassium supplementation and blood pressure control are essential before and after surgery.[37] Standard potassium repletion strategies may be employed to correct hypokalemia.[37]

COMPLICATIONS

The overall complication rate for adrenal surgery ranges from 1.7% to 30.7%,[73,74] depending on factors such as tumor size, surgical approach, and patient comorbidities.[24] Specific surgical complications will also vary depending upon laterality.[74] An estimated 40% of patients will experience a complication post discharge.[75] Evidence has suggested that undergoing an adrenalectomy at high-volume centers may decrease the risk of experiencing complications.[22]

Bleeding

Hemorrhage poses a significant risk due to the adrenal gland's rich vascularization and its proximity to major vascular structures such as the inferior vena cava, aorta, adrenal veins, and hepatic veins. Yet, reported blood transfusion rates are well below 5%.[75]

Injury to Neighboring Structures

While not exhaustive, the list below includes some of the more commonly reported injuries. Surgeons should remain aware of these risks and take steps to mitigate them whenever possible.

- Renal injury from direct injury or infarction from inadvertent ligation of renal vasculature.[74]
- Gastrointestinal perforation – stomach, duodenum, colon (depending upon approach) from direct injury or infarct from inadvertent ligation. Injury to the superior mesenteric artery is devastating as it is nearly uniformly lethal.[37]
- Splenic injury required bleeding control. In cases where splenic hemorrhage cannot be controlled, splenectomy may be indicated—appropriate postoperative vaccination (ie, meningococcal, pneumococcal, Haemophilus influenzae type b) should be ensured.[37,74]
- Hepatic lacerations are managed with prioritization of bleeding control.[37]
- Pancreatic injury may be managed differently depending on the laterality of dissection and timing of injury identification. On the left, pancreatic tail injury may be managed with resection, whereas right-sided injury to the pancreas or pancreatic duct may warrant leaving a surgical drain and ensuring optimization of medical management postoperatively.[74]
- Diaphragm perforation and associated pneumothorax.[74]

Tumor Spillage and Surgical Margins

Careful handling of the adrenal gland is essential to prevent spillage of tumor cells, which could lead to local recurrence or metastasis. In cases where there is concern that appropriate margins may not be attainable via a laparoscopic approach, an open approach is preferred—especially with adrenal cortical carcinoma.[26,27,75] In one study of adrenocortical carcinoma, positive margins or intraoperative tumor spillage was noted in up to 30% of laparoscopic adrenalectomy as compared to 16% with open adrenalectomy.[75] However, as discussed previously, recent data from high-volume surgical centers have demonstrated no significant difference between the modalities in select patients.[2,28]

Medical Complications

Most medical complications include hypotensive and hypertensive crises. These are serious concerns, particularly in patients with pheochromocytoma.[25,69] Intraoperative management includes careful hemodynamic monitoring and readiness to administer vasoactive drugs.[25] Delayed intervention may increase risk for cardiac arrest or cerebrovascular accidents.[25,74]

SUMMARY

Adrenal surgery has evolved significantly over the years, with advancements in surgical techniques and perioperative management enhancing patient outcomes. Understanding the intricate anatomy and surgical landmarks of the adrenal glands is essential for safe and effective surgery, particularly in avoiding complications. The choice between open, laparoscopic, and robotic adrenalectomy depends on various factors, including tumor characteristics, patient comorbidities, and surgeon expertise. Each modality offers distinct advantages, while open approaches are preferred for large tumors suspected to be ACC and minimally invasive approaches remain the standard for most other adrenal lesions.[3]

Perioperative management, particularly in patients with hormone-secreting tumors, is critical to minimizing complications and ensuring rapid recovery.[3] Proper preoperative optimization, intraoperative vigilance, and postoperative care are key components in achieving favorable outcomes.[75] Despite the advancements in surgical technology, complications such as bleeding, injury to adjacent organs, and adrenal insufficiency must remain top of mind and require careful management.[23,75] Shifts in adrenalectomy toward high-volume surgical centers have been associated with improved perioperative morbidity and mortality; however, they may also have opened the door for inequities in access to care.[22]

As the field evolves, future advancements may include the refinement of techniques such as single-site adrenalectomy, improved imaging and diagnostic tools, and more personalized approaches to adrenal surgery. The ongoing development of less invasive procedures and optimized perioperative protocols offers great potential for further enhancing outcomes in adrenal pathologies. A multidisciplinary approach, involving collaboration among urologists, endocrinologists, anesthesiologists, and other specialists, is essential for achieving the best results in adrenal surgery. By continuing to innovate and adhere to best practices, adrenal surgery will continue to offer life-saving benefits to patients with adrenal gland disorders.

CLINICS CARE POINTS

- All adrenal masses warrant hormonal workup, which should be tailored based on clinical characteristics such as the presence of hypertension.
- Surgical approach and technique for adrenal extirpation should be determined based on adrenal mass characteristics, anatomic complexity, hormonal evaluation, patient clinical history, and surgeon experience.
- Hormonally active adrenal masses may warrant specific preoperstive, intraoperative, and postoperative medication planning, which should be coordinated in collaboration with endocrinology and anesthesiology.
- Open adrenalectomy is currently considered the preferred approach for large adrenal masses suspected to be adrenocortical carcinoma.

DISCLOSURES

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