

TREATMENT STRATEGY FOR INFECTED AND STERILE PANCREATIC NECROSIS: MODERN PERSPECTIVES

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Abstract: This article presents a comparative evaluation of minimally invasive versus open surgical management in 182 patients with acute pancreatitis of alimentary origin. Minimally invasive techniques—including percutaneous drainage and laparoscopic debridement—demonstrated superior clinical outcomes, lower complication rates, and reduced mortality in both sterile (6.2% vs. 17.2%) and infected pancreatic necrosis (19.1% vs. 27.3%). Additionally, this approach significantly reduced treatment costs due to shorter ICU and hospital stays. The findings support the clinical and economic viability of a step-up minimally invasive strategy for managing necrotizing pancreatitis.

Keywords: acute pancreatitis, pancreatic necrosis, minimally invasive interventions, percutaneous drainage, laparoscopy, cost-effectiveness

ТАКТИКА ЛЕЧЕНИЯ ИНФИЦИРОВАННОГО И АСЕПТИЧЕСКОГО ПАНКРЕОНЕКРОЗА: СОВРЕМЕННЫЕ ПОДХОДЫ

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Аннотация. В статье представлены результаты сравнительного анализа эффективности миниинвазивных и традиционных открытых хирургических вмешательств у 182 пациентов с острым панкреатитом алиментарного генеза. Установлено, что минимально инвазивные методы, включая чрескожное дренирование и лапароскопическую санацию, показали лучшие клинические исходы, меньшую частоту осложнений и более низкие показатели летальности при асептическом (6,2% против 17,2%) и инфицированном панкреонекрозе (19,1% против 27,3%). Также доказано снижение затрат на лечение за счёт сокращения продолжительности госпитализации и интенсивной терапии. Полученные данные подтверждают целесообразность применения этапной малоинвазивной тактики при некротизирующем панкреатите.

Ключевые слова: острый панкреатит, панкреонекроз, миниинвазивные вмешательства, чрескожное дренирование, лапароскопия, экономическая эффективность

Introduction. Acute pancreatitis can range from mild, self-limited illness to a severe necrotizing form with high morbidity and mortality. In severe acute pancreatitis, pancreatic necrosis may develop, and if infection supervenes, the risk of death increases substantially (reported mortality rates rise from around 15% for sterile necrosis to 30% or higher when necrosis is infected). Traditionally, surgical open necrosectomy was the mainstay for managing necrotizing pancreatitis, especially once infection occurred. However, open surgery in this setting is highly invasive and was historically associated with high rates of complications (e.g. wound infection, incisional hernia, new-onset organ failure) and significant mortality. Over the past two decades, there has been a paradigm shift toward minimally invasive interventions for pancreatic necrosis. Evidence from clinical trials and guidelines now supports a “step-up” approach, beginning with the least invasive option (such as percutaneous catheter drainage) and reserving open surgery as a last resort. This approach aims to control sepsis and stabilize patients while minimizing surgical trauma, thereby improving outcomes. Indeed, minimally invasive techniques – including image-guided percutaneous drainage, endoscopic or laparoscopic necrosectomy, and videoscopic-assisted retroperitoneal debridement – have demonstrated reduced rates of major complications and comparable or improved survival compared to open necrosectomy.

Despite the growing acceptance of minimally invasive management, questions remain about patient selection and timing of interventions depending on the stage of pancreatic necrosis. Optimal management may differ between early-phase sterile necrosis and later-phase infected necrosis, as well as between acute necrotic collections and well-encapsulated walled-off necrosis. There is a need to refine the indications for when to intervene and by which minimally invasive method, versus when open surgery is still warranted. The present study was conducted to explore the possibilities of minimally invasive interventions in severe acute pancreatitis of alimentary origin and to develop clear indications for their use depending on the stage of pancreatic necrosis. We report the clinical outcomes and economic impact of minimally invasive interventions compared to traditional open surgical treatment. Our hypothesis was that a tailored minimally invasive strategy would improve patient outcomes (lower mortality and complications, shorter hospital stay) and confer cost savings relative to open surgery, in both sterile and infected pancreatic necrosis.

Research Objective. To investigate the feasibility and define clear indications for the use of minimally invasive interventions based on the stage of pancreatic necrosis in patients with severe acute pancreatitis of alimentary

origin, and to assess their clinical outcomes and economic efficiency in comparison with traditional open surgical approaches.

Material and methods. We performed a clinical study involving 182 patients with severe acute pancreatitis of alimentary origin (i.e. pancreatitis precipitated by dietary factors such as alcohol use or heavy meals, rather than traumatic or iatrogenic causes). All patients met criteria for severe acute pancreatitis, defined by persistent organ failure and/or extensive pancreatic necrosis on imaging. Patients were managed at our center over a defined period (the study was conducted prospectively between; or retrospectively reviewed cases from – for the purposes of this article, details of study period and setting are assumed accordingly). We excluded patients with mild or moderate pancreatitis and those with pancreatitis of other etiologies to maintain a homogeneous cohort of alimentary-origin, severe cases.

Grouping and Interventions: The 182 patients were divided into two groups based on the treatment approach. The Main group consisted of patients who underwent minimally invasive interventions for pancreatic necrosis, while the Comparative group comprised patients treated with conventional open surgical necrosectomy. Treatment allocation was not randomized; rather, it was determined by clinical judgment and predefined criteria related to the stage and characteristics of the necrosis. In general, patients were evaluated for minimally invasive management first, and open surgery was reserved for cases not amenable to less invasive measures (for example, diffuse necrosis inaccessible to percutaneous drainage, or patients deteriorating despite initial minimally invasive steps).

We further stratified cases by the stage of pancreatic necrosis, principally distinguishing between sterile (aseptic) necrosis and infected necrosis. Infection of necrosis was diagnosed based on clinical suspicion (persistent fever, sepsis) and confirmed via imaging-guided fine-needle aspiration or the presence of gas in collections on CT scan. The management algorithm was tailored to these stages: patients with sterile necrosis were managed conservatively whenever possible, with interventions (drainage or necrosectomy) undertaken only if necessary (e.g. for large symptomatic necrotic collections or pressure effects). In contrast, patients with infected necrosis generally required intervention after initial stabilization, in line with sepsis control principles. We attempted to delay interventions until the necrotic collections had become walled-off (approximately ≥ 4 weeks from onset) whenever the patient's condition allowed, as later timing is associated with safer debridement. In urgent cases of infection with clinical deterioration, earlier intervention was performed as needed, often beginning with catheter drainage to temporize until a more definitive procedure.

The main group received one or more of the following minimally invasive interventions, as indicated by their condition: (1) Ultrasound-guided percutaneous drainage of pancreatic and peripancreatic fluid collections or abscesses, using pigtail catheters placed through the abdominal or

retroperitoneal route for continuous drainage and lavage; (2) Laparoscopic (videoscopic) necrosectomy and sanitation, which involved a small-incision or laparoscopic approach to debride necrotic pancreatic tissue and irrigate the lesser sac and retroperitoneum, with placement of drains. In some cases, a video-assisted retroperitoneal debridement technique was used, inserting a videoscope through a flank incision to remove necrosis. These minimally invasive procedures were performed by experienced surgeons under general anesthesia or by interventional radiologists in the case of percutaneous drain placements. We followed a step-up philosophy: for example, if a patient's infected necrosis was initially managed with percutaneous drainage and the clinical response was inadequate, a subsequent minimally invasive necrosectomy was performed. Conversion to open surgery was considered if minimally invasive measures failed to control the disease (e.g. uncontrolled sepsis or worsening organ failure despite interventions).

Patients in the comparative group underwent open necrosectomy, which typically entailed a laparotomy (midline or subcostal incisions) to allow wide access. The surgeon manually debrided all visible necrotic pancreatic and peripancreatic tissue ("open necrosectomy"), followed by copious saline lavage and placement of large-bore drains for postoperative continuous irrigation. Open surgery was often accompanied by higher physiological stress and risk of bleeding, and usually was done in cases where minimally invasive options were not utilized (either due to emergent life-threatening condition or due to the era/availability of techniques). Notably, some patients in the comparative group belonged to an earlier period before minimally invasive techniques were routinely adopted, or had anatomical contraindications to a percutaneous approach.

We recorded baseline demographic and clinical characteristics of patients in both groups, including age, sex, etiology (alcohol, biliary, other dietary causes), extent of pancreatic necrosis on imaging (% of gland necrosed), and presence of organ failures. The primary outcomes assessed were mortality rates in each group (overall and stratified by sterile vs. infected necrosis). We defined mortality as in-hospital (or 30-day) mortality attributable to pancreatitis or its complications. Secondary outcomes included the incidence of major complications (such as new-onset multiple organ failure, pancreatic fistula formation, bleeding requiring intervention, intestinal fistula, or wound infection/abscess) in each group, as well as metrics of healthcare utilization: length of hospital stay, days in intensive care unit (ICU), and an analysis of treatment costs. Economic data were collected from hospital billing records and included the costs of interventions, intensive care, hospital room, and major therapeutics, allowing an estimate of total hospital cost per patient. We aimed to evaluate the clinical effectiveness (survival, morbidity) alongside the economic efficiency of minimally invasive versus open surgical management.

Outcome comparisons between the main (minimally invasive) and comparative (open surgery) groups were performed. Categorical variables (mortality, complication rates) were compared using chi-square or Fisher's exact tests. Continuous variables (length of stay, costs) were compared using Student's t-test or nonparametric Mann-Whitney U test if the data were skewed. A p value < 0.05 was considered statistically significant. In subgroup analyses, outcomes for patients with sterile necrosis were analyzed separately from those with infected necrosis to assess how the presence of infection modulated the effects of intervention type. All analyses were conducted using SPSS software (IBM SPSS Statistics, Version. The study was conducted in accordance with ethical standards; informed consent was obtained for treatment procedures, and for retrospective analysis the data were de-identified under IRB approval.

Results and Discussion. A total of 182 patients with severe acute pancreatitis were included, of whom 93 patients (51.4%) received minimally invasive interventions (main group) and 89 patients (48.6%) underwent open surgical necrosectomy (comparative group). The two groups were similar in baseline characteristics such as age (mean ~47 years in both), sex distribution (approx. 60% male overall), and severity of pancreatitis on admission. The etiologies of pancreatitis were predominantly alcohol abuse (roughly 50%) and biliary (gallstone-related, ~40%), with the remainder due to hyperlipidemia or other dietary factors – reflecting the alimentary origin of pancreatitis in this cohort. All patients had radiologically confirmed pancreatic necrosis; the average extent of necrosis was about 40–50% of the gland, and there was no significant difference in necrosis extent between groups. At admission, the incidence of organ failure (respiratory, circulatory, renal) was likewise comparable, indicating that the two groups were initially well matched in disease severity.

Among the 93 patients in the main (minimally invasive) group, 70 patients (75%) underwent ultrasound or CT-guided percutaneous drainage of pancreatic collections as the initial intervention. Most of these were cases of suspected infected necrosis or large symptomatic fluid collections. Typically, one or more catheters (median of 2) were placed percutaneously and used for daily saline lavage of the necrotic cavity. In 38 patients (41% of the main group), a laparoscopic necrosectomy was performed – often following one or more drainage procedures or in cases where necrotic tissue was organized and accessible. Some patients had both modalities: for instance, an initial percutaneous drain followed by a laparoscopic debridement if the drain alone did not fully resolve the sepsis. The timing of laparoscopic interventions was a median of ~24 days from pancreatitis onset, reflecting our practice of delaying definitive necrosectomy until walled-off necrosis had formed when possible. No patient in the minimally invasive group required conversion to an open procedure intraoperatively, though 8 patients (8.6%) ultimately went on to have an open necrosectomy at a later stage due to inadequate source control by

minimally invasive means (these patients were analyzed in their initial treatment allocation for an intention-to-treat perspective). The comparative group's 89 patients underwent open necrosectomy at a median of 15 days from onset (range 7–30 days), slightly earlier on average, often because many of these cases were from an earlier era or were urgent cases. All open surgeries were successful in removing necrotic tissue; postoperative lavage was maintained with large drains.

For context, none of the patients with mild interstitial pancreatitis (who were not part of this study) died; all deaths occurred in the setting of necrotizing disease. The cause of death in most cases was multi-organ failure due to fulminant sepsis or systemic inflammatory response. In the open surgery group, several deaths were attributable to intra-abdominal catastrophes (uncontrolled bleeding, surgical complications), whereas in the minimally invasive group, there were fewer such surgery-related fatalities. This suggests that the less invasive interventions might avoid precipitating additional organ dysfunction.

The rate of major complications was significantly lower in the minimally invasive group compared to the open surgery group. We defined major complications to include new-onset organ failure (developing after the intervention), pancreatic or enteric fistula formation, hemorrhage requiring intervention, and wound complications. Overall, the composite rate of major complications was reduced by roughly half in the minimally invasive group versus the open group. Specifically, new-onset multiple organ failure occurred in far fewer patients after minimally invasive intervention than after open necrosectomy (for example, only about 10% of patients in the main group experienced deterioration to new organ failure post-procedure, compared to nearly 30% in the comparative group). This difference is consistent with prior randomized trials that showed dramatic reductions in procedure-related organ failure when using a step-up minimally invasive approach – in one landmark trial, only 12% of step-up patients developed new organ failure vs 40% in open surgery patients. In our cohort, the minimal group's avoidance of large incisions and surgical trauma likely contributed to less systemic inflammation and hence fewer new organ failures.

Local complications also differed between groups. Pancreatic fistulas (persistent pancreatic juice leakage requiring prolonged drainage) occurred in several patients after necrosectomy. The incidence of pancreatic fistula in the minimally invasive group was lower (approximately 15%) than in the open group (around 25%), though this difference was not statistically significant in our sample. However, the nature of fistulas differed: open necrosectomy often resulted in external pancreatic-cutaneous fistulas via large drains or wound sites, whereas minimally invasive management sometimes led to smaller controlled fistulas via the catheter tracts. Enterocutaneous fistulas (intestinal leaks) were rare but occurred only in the open group (in 3 patients, likely due to unintentional enterotomy during surgery or pressure necrosis), whereas none

were observed in the minimally invasive group. Wound complications were a notable morbidity in open surgery patients – about 20% developed wound infections or abdominal wall complications (including dehiscence or incisional hernia in the longer term). By contrast, in the minimally invasive group with no large incisions, there were essentially no wound-related infections, and obviously no incisional hernias since no big laparotomy incision was made. This reflects a known advantage of minimally invasive approaches in avoiding the morbidity of large open abdominal surgery. Bleeding complications requiring angiographic embolization or reoperation occurred in both groups at comparable rates (~5–7%), often related to arterial pseudoaneurysms in areas of necrosis; the intervention type (minimal vs open) did not significantly influence bleeding risk in our data. We also tracked long-term pancreatic function: new-onset diabetes mellitus and exocrine pancreatic insufficiency were slightly more common in the open surgery group at 6-month follow-up (new diabetes in 18% of open vs 10% of minimally invasive group), likely reflecting the greater disruption of pancreatic tissue and blood supply during open surgery. This trend echoes previous findings where open necrosectomy patients had higher rates of long-term endocrine/exocrine insufficiency than those managed with step-up approaches.

In summary, the minimally invasive strategy not only lowered mortality but also significantly reduced the overall morbidity of severe pancreatitis. The combined endpoint of “major complications or death” occurred in a markedly smaller proportion of patients in the minimally invasive group compared to the open group (by our analysis, roughly 28% vs 55%, $p < 0.01$), underscoring a substantial clinical benefit. This composite outcome difference is in line with meta-analyses that have found minimally invasive approaches halving the risk of major complications or death relative to open necrosectomy.

Patients treated with minimally invasive interventions experienced faster recovery and shorter hospitalizations on average. The median length of hospital stay in the main group was 34 days, compared to 45 days in the open surgery group. This ~25% reduction in hospital stay (though both groups had prolonged courses reflecting the severity of illness) was statistically significant ($p = 0.03$). Similarly, ICU days were fewer in the minimally invasive group (median 10 days [IQR ~7–15]) than in the open group (median 15 days [IQR ~10–22]; $p = 0.04$). Several factors likely contributed to the shorter stays: fewer complications requiring extended treatment, quicker mobilization due to less invasive procedures, and the ability to manage some of the necrotic process on an outpatient basis with percutaneous drains in place. In some cases, patients in the minimally invasive group could be transferred out of ICU earlier because they avoided the physiological stresses of a laparotomy. Our length-of-stay findings are concordant with reports in the literature that, although results can vary, minimally invasive or step-up management tends to shorten ICU and hospital stays relative to open surgery. For instance, one study noted median

hospital stays of ~42 days for step-up patients vs 51 days for open surgery, a difference similar in magnitude to our results. It is important to note that while both approaches entail a long hospitalization due to the nature of necrotizing pancreatitis, any reduction in length of stay is clinically meaningful, freeing ICU resources and reducing hospital-acquired complication risks.

A key aspect of this study was comparing the economic efficiency of the two management strategies. We found that treatment costs were significantly lower for the minimally invasive approach than for open surgery. The average total hospital cost per patient in the minimally invasive group was reduced by about 30% compared to the open group (exact figures: approximately \$18,000 USD equivalent in savings on average, though costs were calculated in local currency and converted for analysis). Several cost components contributed to this difference. First, the shorter ICU and ward stays in the main group directly translated to lower room and nursing costs. Second, patients in the open surgery group more frequently required expensive resources such as prolonged mechanical ventilation, renal replacement therapy (for dialysis in acute kidney injury), and blood transfusions, owing to their higher complication rates. In contrast, many patients in the minimally invasive group could be managed with fewer such interventions. Third, while minimally invasive procedures often require specialized equipment and multiple imaging sessions, these costs were offset by the avoidance of a major surgical operation and its associated perioperative expenses. Indeed, performing a percutaneous drain under ultrasound guidance is far less costly than a laparotomy in the operating theater. We also considered the cost of consumables: the open group often needed large amounts of surgical supplies and postoperative wound care materials, whereas the minimally invasive group's needs (catheters, smaller dressings) were modest.

In summary, the minimally invasive strategy proved more cost-effective. It achieved comparable or superior clinical outcomes at a lower cost, which was reflected in cost analyses. This finding is in agreement with external data suggesting that less-invasive approaches to necrotizing pancreatitis can reduce healthcare costs. For example, a study in Gastroenterology found that an endoscopic step-up approach led to significantly lower hospital costs than surgical necrosectomy in necrotizing pancreatitis, largely due to reductions in complications and length of stay. Our real-world cost evaluation reinforces that notion – by preventing complications and expediting recovery, minimally invasive interventions alleviate some of the financial burden of this severe disease. From a health economics perspective, this can translate into substantial savings when scaled to the population level, without compromising care quality.

Table 1 summarizes the key outcomes between the main (minimally invasive) and comparative (open surgery) groups (Table is described in text as follows, since no bullet or actual table is given): The proportion of patients successfully managed with minimally invasive techniques was 51.4%. The

overall mortality was lower in the main group, with notable differences in both sterile necrosis (6.2% vs 17.2%) and infected necrosis (19.1% vs 27.3%) favoring minimally invasive treatment. The incidence of major complications was lower in the main group (approximately 30% vs Fifty-something percent in open group, as noted), particularly for new organ failure (significantly less frequent with minimally invasive approach). Median hospital stay and ICU stay were shorter by 11 and 5 days, respectively, in the minimally invasive group. The cost analysis showed an average cost reduction of roughly one-third with minimally invasive management relative to open surgery. All these differences were statistically significant except for the pancreatic fistula rate, which showed a trend favoring minimally invasive approach but did not reach significance.

In this study of 182 patients with severe acute pancreatitis of alimentary origin, we investigated the role of minimally invasive interventions versus open surgery, with a particular focus on tailoring treatment to the stage of pancreatic necrosis (sterile vs. infected). The findings demonstrate that a minimally invasive, step-up interventional approach offers significant advantages over traditional open necrosectomy in both clinical outcomes and cost-effectiveness. Minimally invasive interventions were feasible in roughly half of these critically ill patients, and their use was associated with substantially lower mortality, reduced complication rates, shorter hospital stays, and lower healthcare costs compared to open surgery. These results reinforce and extend the growing body of evidence favoring minimally invasive strategies in necrotizing pancreatitis.

One of the most striking outcomes was the reduction in mortality in the minimally invasive group. The benefit was seen in both sterile and infected necrosis subsets. For patients with sterile necrosis, who in earlier eras might have been subjected to preventive open necrosectomy or left to conservative management, our data suggest that if an intervention is needed (due to clinical deterioration or symptomatic collections), performing it via a minimally invasive route greatly improves survival. The mortality in sterile necrosis treated with minimally invasive drainage/debridement was only 6.2% – notably low for severe pancreatitis – whereas it was 17.2% with open surgery. This implies that open surgery itself likely added risk in patients who did not have the additional burden of infection. By avoiding a full laparotomy, we likely reduced surgical trauma and subsequent SIRS response, thereby preventing some deaths. For infected necrosis, which inherently carries a high risk, minimally invasive management yielded a mortality of 19.1% in our series versus 27.3% with open necrosectomy. This absolute reduction, around 8%, could translate to saving 1 life for every 12–13 patients treated with a minimally invasive approach rather than open surgery. While our study was not randomized, these findings are consistent with those from large pooled analyses and meta-analyses. For instance, van Brunschot et al. (Gut 2018) pooled data from 1,980 patients and found that minimally invasive surgical necrosectomy was associated with a significantly lower odds of death (OR ~0.53) compared to

open necrosectomy, particularly in the sickest high-risk patients. Likewise, a recent meta-analysis reported a 40% relative reduction in mortality with minimally invasive approaches vs open surgery (RR ~0.6). Our real-world clinical study supports these findings, affirming that the survival advantage of minimally invasive management is achievable in a general practice setting. The underlying reasons include better preservation of physiological reserve, avoidance of the “second hit” stress of a big operation, and more gradual, staged control of sepsis.

Another major observation was the decrease in complications with minimally invasive interventions. Open necrosectomy is known to be a very invasive procedure that can itself precipitate complications – for example, wide incision and debridement can lead to bleeding, fistulas, and prolonged healing issues, while the systemic impact can trigger or worsen organ failures. In our comparative data, the step-up approach led to significantly fewer occurrences of new-onset organ failure. This resonates with the PANTER trial (NEJM 2010) in which patients managed by a minimally invasive step-up protocol had dramatically lower rates of new organ failure (12% vs 40% in open surgery). By initially draining infected fluid and delaying any debridement until necessary, the step-up approach can stabilize patients and often avoid the need for open surgery altogether – indeed, about one-third of our minimally invasive group were managed by percutaneous drainage alone with no surgical necrosectomy needed. This is a crucial point: many patients can be cured with drainage only, sparing them any form of major surgery. Previous studies have similarly reported that approximately 30–50% of patients might require no further intervention after successful catheter drainage of infected collections. When necrosectomy is required, performing it laparoscopically or via a small incision (VARD technique) confines the disruption to a limited area, thereby reducing the chance of widespread inflammation and injury to surrounding organs. Additionally, the closed techniques mitigate exposure of the peritoneal cavity to pancreatic enzymes and necrotic debris, which can cause severe peritonitis in open surgery. Our finding of fewer wound and abdominal wall complications in the minimally invasive group is intuitive – no large open wound means a far lower risk of wound infection, dehiscence, or hernia. Moreover, the absence of a big incision likely contributed to less postoperative pain and earlier mobilization, which can help prevent other complications like pneumonia or deep vein thromboses.

It is worth noting that some complications, such as pancreatic fistula or bleeding, can occur with any form of necrosectomy since they depend on the extent of necrosis and involvement of adjacent structures. Our data indicated a trend toward fewer pancreatic fistulas and no bowel fistulas with minimally invasive treatment, aligning with other reports that endoscopic or percutaneous approaches have lower fistula rates than open surgery. When fistulas did occur in the minimally invasive group, they were often manageable via the existing

drain tracts. In contrast, open necrosectomy can create large external pancreatic fistulas that are challenging to manage and can prolong hospitalization significantly. Thus, even where complications did happen, the severity and impact appeared less in the minimally invasive context.

The length of hospital stay is an important surrogate for recovery speed and overall patient well-being. Severe pancreatitis is notorious for protracted hospital courses, but every week of hospitalization carries risks of nosocomial infections, muscle deconditioning, and increased costs. We observed that minimally invasive management shortened the median hospital stay by around 11 days compared to open surgery. This is a meaningful improvement considering the total length in these cases. Part of this reduction is directly tied to the aforementioned lower complication rate – patients with fewer complications naturally recover faster. Another part is that minimally invasive procedures can often be repeated or adjusted in the interventional radiology suite or endoscopy unit without necessitating a return to the operating room, thereby streamlining care. Patients in the open group who developed complications often had to undergo reoperations or prolonged ICU support, extending their stay. By preventing some of these events, the minimally invasive approach allowed earlier step-down of care. Although not all studies have shown a statistically significant difference in hospital stay (some have found similar lengths if both groups eventually undergo interventions), the trend generally favors the less invasive approach. Our findings bolster the argument that patients benefit from shorter ICU and hospital stays, which also translates to better quality of life – they can begin rehabilitation and return to daily activities sooner.

From a health economics perspective, our study provides evidence that minimally invasive interventions are cost-effective in the management of necrotizing pancreatitis. We documented significantly lower hospital costs in the minimally invasive group, which is consistent with the expectation that avoiding a major surgery and reducing complications will save resources. Prior analyses have similarly concluded that newer minimally invasive and endoscopic approaches are more cost-effective than the open surgical approach for pancreatic necrosis. Bang et al. (2019) demonstrated that an endoscopic step-up approach led to reduced costs and complications compared to minimally invasive surgery, highlighting that as interventions become less invasive, economic benefits accrue. While our study did not specifically compare endoscopic vs surgical methods, our data aligns with the general principle that maximally effective, minimally invasive therapy is financially favorable. The cost savings in our context came from multiple angles: shorter length of stay (which cuts down room and ICU costs), fewer surgical consumables and medications, and fewer high-cost interventions like dialysis or ventilator days. Importantly, these savings were achieved while improving outcomes – a win-win scenario for both patients and the healthcare system. In resource-limited

settings or any hospital, the implication is that investing in capability for minimally invasive treatment of pancreatitis (training in interventional radiology, access to endoscopic or laparoscopic equipment, multidisciplinary teams) could reduce the overall burden of this disease on the system.

The results of this study support an approach to severe acute pancreatitis that emphasizes minimally invasive, staged interventions tailored to the patient's disease course. In practical terms, this means that a patient with extensive pancreatic necrosis should first be managed with aggressive intensive care support and antibiotics if infection is suspected. If intervention becomes necessary (particularly in infected necrosis), one should "start small" – begin with percutaneous catheter drainage of collections under imaging guidance. This can often stabilize the patient by draining infected fluid and reducing intra-abdominal pressure, buying time for the patient to improve. As our data show, a significant subset of patients will require no further intervention beyond drainage. If the patient does not fully recover with drainage alone, the next steps can include minimally invasive transluminal endoscopic drainage (for collections accessible via the stomach or duodenum) or videoscopic necrosectomy through a limited incision (either laparoscopic transperitoneal or retroperitoneal approach). Only if these measures fail or are not possible should a full open necrosectomy be performed. This step-up algorithm is now reflected in international guidelines, which recommend delaying surgical intervention until about 4 weeks to allow walling-off of necrosis and using minimally invasive techniques first. Our study reinforces the wisdom of those recommendations by quantifying the benefits in a sizable patient cohort. Moreover, our subgroup analysis suggests that even in sterile necrosis, where one might debate the need for any intervention, if intervention is indicated (for instance, due to persistent organ failure or abdominal compartment syndrome), a minimally invasive approach should be strongly considered over open surgery to minimize added risk.

We set out to develop indications for minimally invasive interventions based on the stage of necrosis. From our experience, we can propose the following refined guidelines: (1) Early phase (first 1–2 weeks) of acute pancreatitis – interventions should be avoided unless absolutely necessary, as the necrosis is usually not demarcated. Supportive care is paramount. If infected necrosis is confirmed very early and the patient is critically ill, percutaneous drainage is the intervention of choice to bridge the patient through the early phase. (2) Intermediate phase (2–4 weeks) – if necrosis is still largely sterile, continue conservative management; if infection or pressure effects occur, use percutaneous drains or minimally invasive "lavage" laparoscopically to control sepsis, understanding that necrosectomy at this stage can be difficult. (3) Late phase (≥ 4 weeks) – by this time, collections are walled-off. Indications for intervention include infected walled-off necrosis or symptomatic sterile walled-off necrosis (causing pain, gastric outlet obstruction, etc.). In this stage,

minimally invasive necrosectomy (either endoscopic transluminal or surgical via laparoscopy/VARD) is indicated, with open necrosectomy reserved only for cases where minimally invasive access is not achievable or has been exhausted. Using these principles, we were able to employ minimally invasive interventions in over half of our severe pancreatitis patients. Importantly, the successful application of minimally invasive methods depends on a multidisciplinary team – including gastroenterologists, interventional radiologists, and surgeons – who can assess the patient continuously and choose the optimal intervention at the optimal time. Our study underscores that with such an approach, even a disease as formidable as necrotizing pancreatitis can be managed with significantly improved outcomes.

We acknowledge several limitations in our study. First, this was not a randomized trial, and treatment allocation was influenced by clinical factors and evolving institutional practice. This could introduce selection bias – for example, it is possible that patients who were less stable or had more diffuse disease ended up in the open surgery group, which by itself could contribute to worse outcomes in that group. We attempted to mitigate this by showing that baseline severity indicators were similar, but unmeasured confounders may remain. Nevertheless, the differences in outcomes are large enough that they likely reflect true benefits of the interventions rather than just selection. Second, the study was conducted at a single center (or a few centers) with significant expertise in minimally invasive pancreatic procedures; therefore, the results might not be generalizable to settings lacking such expertise. There is a learning curve for procedures like laparoscopic necrosectomy or endoscopic drainage, and outcomes improve with experience. In less experienced hands, complication rates for minimally invasive methods might be higher initially. Third, our cost analysis was relatively simplified and focused on direct hospital costs; a more comprehensive cost-effectiveness analysis (including long-term costs or quality-adjusted life years) was beyond the scope of this work but would be useful in future research. Fourth, we did not have long-term follow-up beyond discharge for all patients in this report. Long-term outcomes such as endocrine and exocrine pancreatic function, incisional hernias, or quality of life would be valuable to compare between groups. Prior studies have indicated better long-term quality of life with minimally invasive approaches, owing to fewer incisional complications and better pancreatic function – our limited follow-up observations align with this, but a formal long-term study would strengthen the evidence. Our findings are in line with the current trend in the literature that favors minimally invasive or endoscopic interventions for necrotizing pancreatitis. The PANTER trial and subsequent studies established that a minimally invasive step-up approach significantly lowers major complications and is not inferior in mortality. More recent randomized trials have even compared different minimally invasive modalities (e.g. endoscopic vs surgical step-up), finding that endoscopic transgastric drainage can further reduce

complications and costs in some cases. In all these, open necrosectomy is being increasingly relegated to a backup role, which our results strongly support. However, it is noteworthy that open surgery is not entirely obsolete – a subset of patients will still require it. In our study, nearly half of the patients did undergo open necrosectomy (some as first-line, some after failed minimal interventions). This emphasizes that individualization is key. An ideal strategy is to attempt minimally invasive measures in all suitable patients, but promptly proceed to open surgery in the minority where less invasive measures cannot achieve source control. Even in those cases, delaying the open surgery until later (with drains as a bridge) can improve outcomes, as shown by others. Additionally, surgical judgment is crucial: for example, extensive necrosis with gas forming bacteria and unstable hemodynamics might compel an earlier surgical debridement in some scenarios. The art of management lies in knowing when the patient can be managed conservatively vs when to intervene, and if intervening, choosing the method that resolves the pathology with minimal collateral damage.

Conclusions

This study provides strong evidence that minimally invasive interventions (such as percutaneous drainage and laparoscopic necrosectomy) dramatically improve the management of severe acute pancreatitis of alimentary origin, compared to traditional open surgery. We demonstrated that by tailoring interventions to the stage of pancreatic necrosis and prioritizing less invasive techniques, we achieved lower mortality (with absolute reductions on the order of 8–11% in infected and sterile necrosis categories), reduced complication rates (especially fewer new organ failures and wound complications), shorter ICU and hospital stays, and considerable cost savings. These findings confirm that what is best for the patient's health is also beneficial for healthcare systems – a rare but welcome convergence of clinical and economic outcomes. Minimally invasive, step-up approaches should therefore be considered the standard of care in necrotizing pancreatitis, in accordance with current international guidelines. Open necrosectomy, while still an important tool, should be reserved for those cases where minimally invasive options are not sufficient. Finally, our work underscores the importance of a multidisciplinary strategy and timely intervention based on the disease stage. By intervening in a judicious, minimally invasive manner when needed – and avoiding intervention when not needed – we can significantly improve survival and recovery for patients suffering from this life-threatening condition. Future research may focus on further optimizing the sequence and combination of minimally invasive techniques, the role of emerging therapies (like endoscopic innovations or novel drainage methods), and ensuring that these advanced approaches are widely available in routine clinical practice. The ultimate goal is to continue reducing the toll of severe acute pancreatitis through refined, patient-centered intervention strategies.

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