Burden of Ionizing Radiation in the Diagnosis and Management of Necrotizing Pancreatitis

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INTRODUCTION: **A step-up endoscopic or percutaneous approach improves outcomes in necrotizing pancreatitis (NP). However, these require multiple radiographic studies and fluoroscopic procedures, which use low-dose ionizing radiation. The cumulative radiation exposure for treatment of NP has not been well defined.**

METHODS: **We conducted a retrospective study of consecutive patients with NP admitted to University of California San Francisco Medical Center from January 2011 to June 2019. We calculated effective doses for fluoroscopic procedures using the dose area product and used the National Cancer Institute tool for computed tomography studies. The primary outcome was the cumulative effective dose (CED). Multivariable logistic regression was used to evaluate risk factors of high exposure (CED > 500 mSv).**

RESULTS: **One hundred seventy-one patients with NP (mean follow-up 40 ± 18 months) underwent a median of 7 (interquartile range [IQR] 5–11) computed tomography scans and 7 (IQR 5–12) fluoroscopic procedures. The median CED was 274 mSv (IQR 177–245) and 30% (51) of patients received high exposure. Risk factors of high exposure include multiorgan failure (aOR 3.47, 95%-CI: 1.53–9.88, P = 0.003), infected necrosis (adjusted odds ratio [aOR] 3.89 95%-CI:1.53–9.88, P = 0.005), and step-up endoscopic approach (aOR 1.86, 95%-CI: 1.41–1.84, P = 0.001) when compared with step-up percutaneous approach.**

DISCUSSION: **Patients with NP were exposed to a substantial amount of ionizing radiation (257 mSv) as a part of their treatment, and 30% received more than 500 mSv, which corresponds with a 5% increase in lifetime cancer risk. Severity of NP and a step-up endoscopic approach were associated with CED > 500 mSv. Further studies are needed to help develop low-radiation treatment protocols for NP, particularly in patients receiving endoscopic therapy.**

BACKGROUND

Necrotizing pancreatitis (NP) occurs in up to 10% of patients with acute pancreatitis (AP) and is the primary reason for mortality in AP (1,2). Minimally invasive step-up approach including percutaneous catheter drainage (PCD) with retroperitoneal debridement and endoscopic transluminal drainage (ETD) and direct endoscopic necrosectomy (DEN) has been shown to be associated with superior patient-related outcomes compared with open necrosectomy (3–6). These approaches, however, are associated with multiple fluoroscopy-based interventions requiring frequent imaging studies (7,8).

Studies have linked exposure to low-dose ionizing radiation with the development of leukemia and solid cancers, including breast and lung (9). Although the prediction of an individual patient's risk is imprecise, the BEIR VII (Seventh Biologic Effects of Ionizing Radiation) report predicts that one radiation-induced cancer occurs for every 100 patients who receive a 100-mSv dose (10). This is primarily extrapolated from data demonstrating that a 500-mSv dose results in 5 additional cancers for every 100 patients using the linear no-threshold hypothesis (11).

Radiation exposure for patients with AP and NP is not well defined with one study finding that patients with AP received a

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median effective dose (ED) of 24 mSv and patients with severe AP received higher doses (12). In this retrospective cohort study, we determined the radiation exposure for patients with NP for imaging studies, fluoroscopic and endoscopic procedures, and identified risk factors for increased radiation exposure.

METHODS

We conducted a retrospective cohort study at the University of California San Francisco Medical Center. A total of 2942 patients admitted with AP from January 1, 2011, to July 1, 2019, were identified using the International Classification of Disease (ICD)-9 codes 577.0/577.8 and ICD-10 codes 85.0-9. The charts were reviewed manually (by N.T. and J.M.) to identify patients with NP, which was defined as patients with AP with signs of pancreatic necrosis, peripancreatic necrosis, or both, as detected on contrast-enhanced computed tomography (CT) or contrast-enhanced MRI.

A multidisciplinary team (gastroenterology/surgery/radiology) evaluated each admitted patient, and a consensus was reached on diagnosis, need for intervention, and management strategy. The initial management consisted of enteral nutritional support whenever possible, and medical management of early complications. All interventions were delayed, ideally at least 4 weeks from the onset of NP, if possible, to allow for maturation of the necrotic collection (1,13). The primary indication for intervention was suspected or confirmed infected pancreatic necrosis or symptomatic disease (1). All patients with suspected infection were initially treated with intravenous antibiotics and/or antifungals. Patients who did not undergo additional interventions were considered to have been treated using a conservative approach. If further interventions were performed, before 2016, a step-up percutaneous approach was primarily used. This involved starting with PCD and escalation to Video Assisted Retroperitoneal Debridement, minimally invasive surgical necrosectomy, or open necrosectomy (3). After 2016, step-up endoscopic approach was primarily used in all patients and involved ETD and DEN as the initial treatment modality. (See Supplementary Index 1 for details, Supplementary Digital Content 1, http://links.lww.com/CTG/A600). The timing of subsequent interventions was determined by the clinical course and amount of necrosis visualized on imaging findings (CT or fluoroscopic drain study) or endoscopy (1,3).

Open necrosectomy was considered for patients who were not candidates for minimally invasive approaches, for patients requiring laparotomy for indications other than pancreatic necrosis, e.g., bowel perforation, and for patients who failed minimally invasive strategies.

Estimate of ED

To approximate the radiation exposure for each imaging procedure, we obtained the ED for each diagnostic study and therapeutic procedure. The ED measures the detrimental effect of radiation exposure. It is calculated by weighting the concentrations of energy deposited in each organ with the use of parameters that reflect the type of radiation and the potential for radiation-related mutagenic changes in a reference subject (8). For abdominal fluoroscopic procedures (percutaneous drainage, abdominal vascular procedures, endoscopic retrograde cholangiopancreatography, and ETD), the ED was calculated by multiplying the dose area product (DAP) with the conversion coefficient 0.26 mSv/(Gy-

cm^2) (14). The Siemens Artis (Siemens Medical Solutions USA, Malvern, PA) and Phillips Allura (Phillips USA, Andover, MA) fluoroscopy systems were used for percutaneous and endoscopic interventions in this study. The ED for CT scans was calculated using a dedicated CT dosimetry software tool provided by the National Cancer Institute CT (NCI-CT) (15), which combines reference phantoms provided by the International Commission on Radiological Protection and Monte-Carlo simulations of a reference CT scanner (Somatom Sensation 16; Siemens Healthcare GmbH, Forchheim, Germany). Individual examination parameters, sex, age, height, and body weight were used as input for this mathematical phantom-based calculation. The typical EDs that have been previously reported for various diagnostic imaging studies and therapeutic procedures used in NP patients are summarized in Table 1 (16,17).

Outcomes

The primary outcome for this study was the cumulative ED (CED) received by each patient for the evaluation and treatment of NP. A high CED was defined as >500 mSv because this threshold has been associated with a 5% lifetime risk for cancer (18).

Secondary outcomes included CED calculated during 4 periods during the disease course: (i) the onset of AP to index intervention for drainage of NP (diagnostic phase), (ii) from index intervention to resolution of walled-off necrosis defined as a necrotic collection <2 cm (treatment phase), (iii) from the resolution of NP to within 6 months after the resolution of NP (early sequelae after the resolution of NP), and (iv) >6 months after the resolution of NP (late sequelae of NP). If a patient did not undergo intervention for NP, CED from the onset of AP to the resolution of NP was considered as a part of the diagnostic phase.

Statistical analysis

Patient data collected included demographics, hospitalization data, timing, and details of all CT, MRI, US, and nuclear medicine imaging studies and interventions received. Abdominal radiologists (C.K. and S.B.) reviewed all the imaging at admission, pre-intervention, and postintervention to calculate modified CT severity indices.

Table 1. Radiation dose for common imaging studies and fluoroscopy-guided procedures used in patients with NP

Study	Mean effective dose (mSv)
Chest x-ray	0.02
Abdominal x-ray	0.7
Single-phase abdominal CT	10
Triple-phase abdominal CT	31 mSv
Fluoroscopic percutaneous drainage	10 mSv
CT-guided percutaneous drainage	25 mSv
Endoscopic retrograde cholangiopancreatography	3–12 mSv
Therapeutic EUS drainage	N/A

EUS, endoscopic ultrasound; CT, computed tomography; N/A, not studied; NP, necrotizing pancreatitis.

Table 2. Baseline characteristics

Factor, n(%) or median (IQR)		Overall (N = 171)
Clinical characteristics		
Age		52 (36, 62)
Sex	Women	68 (39.8%)
	Men	103 (60.2%)
Race	Caucasian	88 (51.4%)
	Black	19 (11.1%)
	Hispanic	43 (25.1%)
	Asian	19 (11.0%)
	Other	2 (1.2%)
Etiology	ETOH	48 (28.1%)
	Biliary	62 (36.3%)
	Idiopathic	33 (19.3%)
	Post-ERCP	12 (7.0%)
	Other	16 (9.4%)
ASA class at admission	1	4 (2.3%)
	2	88 (51.5%)
	3	79 (46.2%)
Charlson comorbidity index		3 (1, 4)
Characteristics of necrosis		
Location of necrosis	Head	8 (4.7%)
	Head/body	55 (32.2%)
	Body	27 (15.8%)
	Body/tail	65 (38.0%)
	Tail	16 (9.4%)
Necrotic collection size AP (cm)		10 (6.8, 14.8)
Necrotic collection size transverse (cm)		8 (5.5, 11)
Necrotic collection extends into pelvis		102 (60.0%)
Presentation		
Uninfected necrosis		47 (27.5%)
Confirmed infected necrosis		124 (72.5%)
Admission severity scores		
SAPS II		24 (16, 33)
APACHE II score		9 (5, 14)
Modified MODS score		1 (0, 2)
Modified CTSI		8 (6, 10)
Organ failure on admission		
SOF On admission		64 (37.4%)
MOF on admission		30 (17.5%)
Types of on admission		
Respiratory		64 (37.2%)

Table 2. (*continued*)

Factor, n(%) or median (IQR)	Overall (N = 171)
Cardiovascular	57 (33.3%)
Renal	109 (63.4%)
Required ICU during hospital stay	127 (74.2%)
Intervention characteristics	
Treatment strategy	
Conservative management	29 (17.0%)
Percutaneous drainage only	27 (15.8%)
ETN/ETD	28 (16.4%)
ETN/ETD + percutaneous drainage	20 (11.7%)
Percutaneous drainage + surgical debridement	40 (23.4%)
MIS alone	7 (4.1%)
Open surgery	20 (11.7%)

AP, acute pancreatitis; CTSI, computed tomography severity indices; ETD, endoscopic transluminal drainage; ERCP, endoscopic retrograde cholangiopancreatography; ; ETN, endoscopic transluminal drainage; ICU, intensive care unit; IQR, interquartile range; MIS, minimally invasive surgery; MODS, Modified Organ Dysfunction Score; MOF, multiorgan failure; SAPS, Simply Acute Physiology Score; SOF, single organ failure.

After the ED was calculated for each diagnostic imaging study and fluoroscopic and CT-guided procedure performed for NP, a CED was calculated for each patient by adding the ED for each imaging study and procedure. We then calculated CEDs for the 3 aforementioned periods.

Subsequently, multivariable logistic regression analysis, consisting of selected clinically relevant variables (age, sex, and etiology) and those with $P < 0.1$ on univariate analysis, was conducted to identify factors independently associated with a high CED (>500 mSv). All statistical analyses were performed with STATA 15 statistical package (StataCorp LP, College Station, TX). The Bonferroni correction was used to adjust for multiple hypothesis testing; a P value < 0.003 was considered statistically significant.

RESULTS

One hundred seventy-one patients with NP were identified (Table 2 for baseline characteristics). The mean follow-up was 44 ± 18 months. Thirty-one (18.1%) patients were managed using a conservative approach, consisting of enteral nutritional support and antibiotics as needed, whereas 140 (81.9%) patients underwent intervention for necrosis (i.e., drainage and/or necrosectomy procedures). Eighteen patients (10.5%) died during the study period.

Use of diagnostic imaging and therapeutic procedures using fluoroscopy

On average, patients underwent a median of 6 chest radiographs (interquartile range [IQR] 2–16), 3 abdominal radiographs (IQR 1–7), 7 CT scans (IQR 5–11), and 1 MRI (IQR 1-3) scan during
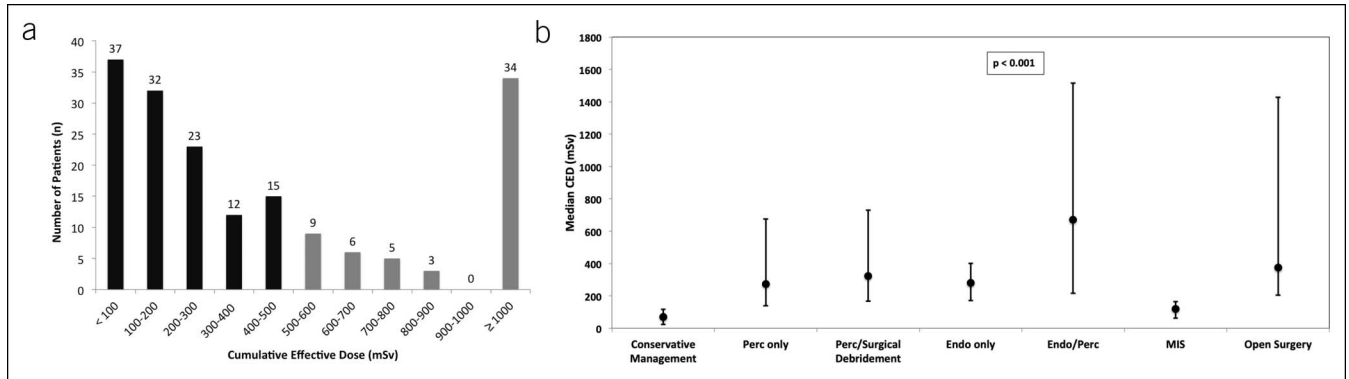
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Figure 1. (**a**) CED range of patients with NP. (**b**) Comparison of median CED by treatment approach. CED, cumulative effective dose.

their treatment for NP; 158 patients (92%) underwent at least one fluoroscopic procedure with a median of 7 (IQR 5–12) fluoroscopic procedures. Forty-six patients underwent a median of 4 (IQR 2–7) endoscopic procedures using fluoroscopy. Ninety-five patients underwent a median of 8 (IQR 4–12) PCD procedures. Eighty patients underwent a median of 1 (IQR 1–3) fluoroscopic nasojejunal tube placements with interventional radiology. Twenty patients underwent a median of 1 (IQR 1–2) vascular procedure, and 13 patients underwent a median of 2 (1–3) percutaneous biliary drainage procedures. When we compared rates of diagnostic image utilization or therapeutic fluoroscopic procedure utilization by year, there was no statistical difference in the median number of studies or CED per patient over time (see Supplementary Figure 1, http://links.lww.com/CTG/A599).

Cumulative effective dose received

A total of 6391 diagnostic and therapeutic studies using ionizing radiation were performed for a total of 102,723 mSv (Figure 1A). The median CED per patient was 274 mSv (IQR 177–245). Patients received a median of 106 mSv (IQR 51–201) from CT imaging and 149 mSv (IQR 4–52) from fluoroscopic procedures. The median CED stratified by treatment approach is displayed in Figure 1B.

Forty-eight patients underwent 244 endoscopic drainage or ERCP procedures, with a median ED of 18 (IQR 9–47) mSv for combined ETD/ERCP, 15 (IQR 5–34) mSv for ETD/DEN, and 10 (IQR 3–18) mSv for ERCP alone. Eighty-seven patients underwent 684 percutaneous drainage procedures with a median ED of 13 mSv (IQR 3.6–36). One hundred twelve fluoroscopic-guided nasojejunal tubes were placed with a median ED of 31 (IQR 13–87) mSv. Thirty-eight vascular procedures were performed with a median ED of 127 mSv (IQR 38–438). Twenty-seven percutaneous biliary drainage procedures were performed with a median ED of 24 mSv (IQR 5–88).

The patients, on average, received a median CED of 46 mSv (IQR 17–88) mSv in the diagnostic phase, 204 (IQR 96–369) mSv from index intervention to the resolution of NP, 65 (IQR 30–119) mSv from the resolution of NP to 6 months after the resolution of NP, and 22 (IQR 9–49) mSv > 6 months after the resolution of NP.

Patients with high exposure (>500 mSv)

Total CED exceeded 500 mSv in 51 (30%) patients. On multivariable analysis, age, sex, and etiology of pancreatitis were not found to be associated with high exposure (Table 3). Importantly, disease severity

is strongly correlated with high exposure. Indeed, on admission, APACHE II score (adjusted odds ratio [aOR] 1.10, 95% CI 1.04–1.16, $P = 0.001$), ICU (aOR 5.64, 95% CI 1.90–16.82, $P = 0.002$), and multiorgan failure (aOR 3.46 95% CI 1.56–7.80, $P < 0.001$) were associated with an increased odds of high exposure (Figure 2). Infected necrosis was also associated with significantly increased odds of high exposure (OR 3.89 95% CI 1.53–5.18, $P < 0.001$).

Examining characteristics of the necrotic collection, the size of the collection, extent of the necrosis to the pelvis, and the presence of disconnected pancreatic duct syndrome were not associated with high overall exposure. However, disconnected pancreatic duct syndrome was associated with increased median CED at >6 months after the resolution of NP (Figure 3A).

Looking at intervention characteristics, any procedure for NP significantly increased the odds of high exposure (18.67, 95%-CI 2.50–140 $P = 0.005$). Sixty-five patients were treated with a percutaneous step-up approach (PCD ± escalation to surgical necrosectomy), whereas 46 patients were treated with an endoscopic step-up approach (ETD ± PCD with escalation to DEN). A step-up endoscopic approach was associated with a significantly higher median CED than a step-up percutaneous approach (398 mSv (IQR 198–658) vs 237 (IQR 98–518), $P < 0.001$, Figure 3B). After adjustment for infected necrosis and MOF on admission, a step-up endoscopic approach was associated with significantly increased odds of high exposure (aOR 1.86, 95% CI 1.41–1.84, $P = 0.001$).

DISCUSSION

In this cohort of consecutive patients with NP, we found that patients received a substantial CED of ionizing radiation with a median of 274 mSv, with 30% of patients receiving a dose of more than 500 mSv. Disease severity (need for ICU admission, increased APACHE II score, and multiorgan failure) and the development of infected necrosis were associated with a CED of >500 mSv. Overall, 40% of the cumulative radiation dose was from diagnostic CT imaging, with 54% of the total radiation dose from therapeutic fluoroscopic procedures. Although an endoscopic step-up approach was associated with significantly higher median CED (398 mSv vs 237 mSv, $P < 0.001$) when compared with the percutaneous step-up approach, 42% of patients in the endoscopic approach group needed percutaneous drainage as well.

Our study is the first to comprehensively assess the radiation exposure in patients with NP over their entire disease course in the era of minimally invasive approaches. In our review of the

Table 3. Association between patient factors and CED >500 mSv

	Number of patients	Median (IQR)
Frequency of therapeutic procedures using fluoroscopy		
PCD	95	8 (4–12)
Endoscopy	72	4 (2–7)
NJ tube	80	1 (1–3)
Vascular procedure	20	1 (1–2)
PTBD	13	2 (1–3)

	No. of procedures	Mean CED, (IQR)
Cumulative effective dose by fluoroscopic intervention		
PCD	684	13 mSv (3.6–36)
Endoscopy	244	16 mSv (5–35)
ETD/DEN + ERCP	84	18 mSv (I9-47)
ETD/DEN	114	15 mSv (5–34)
ERCP alone	86	10 mSv (3–18)
Nasojejunal feeding tube	112	31 mSv (I13-87)
Vascular procedure	38	127 mSv (38–438)
PTBD	27	24 mSv (I5-88)

Baseline characteristic	Odds ratio (95% CI)	P-value
Age	1.01 (0.99–1.03)	0.18
Male sex	1.67 (0.84–3.34)	0.15
History of pancreatitis	0.71 (0.34–1.48)	0.36
Etiology (compared with alcoholic)		
Biliary pancreatitis	0.82 (0.22–3.06)	0.77
Post-ERCP	0.67 (0.17–2.61)	0.56
Idiopathic	1.0 (0.25–4.06)	1.00
Other	1.2 (0.25–5.78)	0.82
Charlson comorbidity index	1.10 (0.98–1.25)	0.15
Severity on admission		
APACHEII	**1.10 (1.04–1.16)**	**0.001**
Modified CTSI	0.89 (0.77–1.04)	0.15
ICU On admission	**5.64 (1.90–16.82)**	**0.002**
SOF On admission	**2.24 (1.14–4.38)**	**0.02**
MOF on admission	**3.46 (1.54–7.80)**	**0.003**
Necrosis characteristics		
Size of necrosis in AP (cm)	1.10 (0.91–1.15)	0.21
Size of necrosis in transverse (cm)	1.04 (0.97–1.12)	0.27
Infected necrosis	**3.89 (1.53–5.18)**	**0.004**
Presence of disconnected pancreatic duct	0.95 (0.46–1.99)	0.91
Collection extends into pelvis	1.5 (0.90–1.78)	0.12

Table 3. (*continued*)

Baseline characteristic	Odds ratio (95% CI)	P-value
Intervention characteristics		
Intervention performed for NP	**18.67 (2.50–140)**	**0.005**
Percutaneous drainage performed	**6.60 (2.12–20.52)**	**0.001**
Step-up percutaneous approach	—	—
Step-up endoscopic (± percutaneous) approach	**1.86 (1.41–1.84)**	**0.001**

Bolded values represent values that are statistically significant.
AP, acute pancreatitis; CED, cumulative effective dose; ETD, endoscopic transluminal drainage; NP, necrotizing pancreatitis; PCD, percutaneous catheter drainage.

literature, we identified only 2 studies that have looked at radiation exposure in severe or necrotizing pancreatitis (NP). One study reviewed CED from diagnostic CT from the era of primary open necrosectomy and found a CED of 63 mSv, whereas the other found a CED of 55 mSv from diagnostic CT imaging in patients with severe AP (19,20). By contrast, our study looked at radiation exposure during different stages of NP, including the impact of therapeutic interventions and late sequelae. We found that NP patients currently receive substantially higher doses (median CED 277) of radiation than previously reported using accepted clinical pathways, suggesting that they may be at significant risk of developing subsequent radiation-associated cancer (19,20). Although it is not clear whether there is an increased radiation risk of low doses of cumulative radiation (<100 mSv), a CED > 100 mSv has been shown to be associated with the risk of cancer in a linear fashion with a 1% increased risk for every 100 mSv of radiation exposure (21). Based on this linear model, patients with NP in our study would have a median increased lifetime risk of solid and hematologic malignancies of 2.7%, and 30% of patients would have more than a 5% increased lifetime risk. It is especially concerning that a small subpopulation of our patients received more than 1,000 mSv, who have a substantial lifetime cancer risk. This represents a substantially higher cancer risk than that expected in patients with other gastrointestinal conditions, including inflammatory bowel disease (mean CED of 37 mSv) (22) and cirrhosis (mean annual ED of 51 mSv) (23).

In our cohort, CT imaging was responsible for 40% of the CED. Most CT-related radiation exposures occurred in the diagnostic (56 mSv [53%]) and therapeutic (30 mSv [28%]) phases. Indications for CT imaging included the following: initial evaluation of AP on presentation, for evaluation of the evolution of NP from an acute necrotic collection to walled-off necrosis, for planning initial and subsequent interventional strategies, and for monitoring of NP-related complications, e.g., biliary obstruction, gastric outlet obstruction, or bleeding (1,13). In an effort to reduce radiation exposure, CT imaging should be used only in patients with clinical decompensation requiring potential early intervention and should be avoided to simply follow the serial progression of necrotic collections. This would substantially reduce the CT-related CED in the diagnostic phase of treating NP. In addition, although it is not our practice to obtain a CT scan
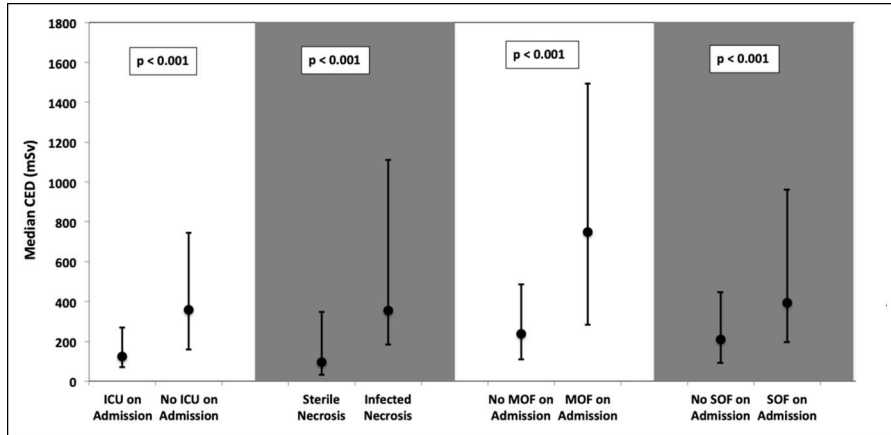
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Figure 2. Median values for CED stratified by disease severity characteristics. The *P* values given are for differences existing between subgroups. CED, cumulative effective dose.

before each percutaneous or endoscopic procedure, a significant proportion of patients underwent periprocedural diagnostic CT imaging to plan interventions, and we believe that it is important to minimize these studies. An alternative approach might be to use MRI imaging instead of CT; however, limitations of MRI include longer study duration and poorer patient tolerance, resulting in poor imaging quality difficulty for clinicians to interpret when compared with CT (24). Further studies using MRI-based protocols are warranted in the setting of NP and clinicians likely need to become more adept at interpreting MRI studies. This is particularly important in obese patients, who are at higher risk of acute NP and have increased radiation exposure with both CT imaging and fluoroscopy (25). Thus, it is important to study and validate MRI-guided protocols, especially in these patients, because rates of obesity continue to rise rapidly.

As expected, most of the radiation exposure in our study occurred during the treatment phase. This was primarily due to the utilization of minimally invasive fluoroscopy–based interventions, including endoscopic and percutaneous drainage, each of which contributes differently. It reflects the evolution of the management of NP toward a step-up percutaneous or endoscopic approach (3,26,27). Although a minimally invasive approach has been shown to improve patient morbidity and decrease the length and cost of hospitalization, the impact of these approaches on radiation exposure and long-term cancer risk is not well known. We demonstrated that these procedures contributed a median CED of 149 mSv. Potential ways to reduce this radiation burden include initial placement of a larger bore percutaneous drain at the time of index intervention, avoiding drain checks or replacement until there is clinical resolution of NP, and avoiding, or alternatively minimizing, fluoroscopy during endoscopic necrosectomy procedures.

Among patients treated using a minimally invasive approach, an endoscopic step-up approach was associated with significantly higher median CED when compared with a percutaneous step-up approach (398 vs 297 mSv, $P < 0.001$). In our cohort, one reason for this difference is the utilization of fluoroscopy during endoscopic procedures. There are several reasons for this. First, patients are often treated with multiple transluminal stents (also known as the multiple gateway approach), each step using fluoroscopy (26,28). Second, endoscopic necrosectomy procedures can often be long (>2 hours) and, at our institution, are

performed with fluoroscopic guidance. Third, the ED reported for a single endoscopic procedure may involve multiple complex procedures, including endoscopic necrosectomy, ERCP, and endoscopic nasojejunal feeding tube or gastrojejunal feeding tube placement, all combined into one procedure. Finally, endoscopic therapy has been shown to be associated with the need for more necrosectomy procedures compared with a step-up percutaneous approach or open surgery (2,5).

Another separate reason for the increased dose of CED in patients undergoing endoscopic therapy is the concomitant utilization of percutaneous drainage in these patients, i.e., a dual-modality approach. In our endoscopic step-up cohort, 42% of patients needed a percutaneous approach as well. The need for a dual-modality approach, a combination of endoscopic and percutaneous drainage, allows decompression of the necrotic cavity in locations that are not amenable to transluminal endoscopic access and drainage and subsequent lavage of the cavity on the patient care unit and provides access for percutaneous sinus tract necrosectomy or Video Assisted Retroperitoneal Debridement and has been reported in 27%–58% of patients with NP (26,27,29). Of note, within the endoscopic step-up approach group, CED was lower in patients who underwent endoscopic drainage and necrosectomy alone (without PCD), likely reflecting more localized necrosis, easy endoscopic access, less critically ill patients, and, therefore, a lower need for radiologic studies.

Our study has several limitations. The main limitation is its retrospective design; there may be unmeasured confounders that could affect our evaluation of risk factors. There was a significant variation in the types of interventions used in our patient population. This partly reflects the heterogeneous nature of NP that necessitates individualized treatment strategies and partly our institutional evolution to a more minimally invasive endoscopic approach. This could limit the external validity of our results because centers with a specific-protocol using one primary modality could have differences in radiation exposure. However, there is generally a trend toward endoscopic therapy, and in our study, a step-up endoscopic approach was associated with a higher CED compared with other approaches. After discharge, patients may have had diagnostic or therapeutic radiologic studies at other facilities, which we may not have captured. Finally, our calculations for ED are an indirect estimate, given that the NCI-CT dose calculation uses standardized phantoms based on a Siemens scanner, such that actual patient body habitus and
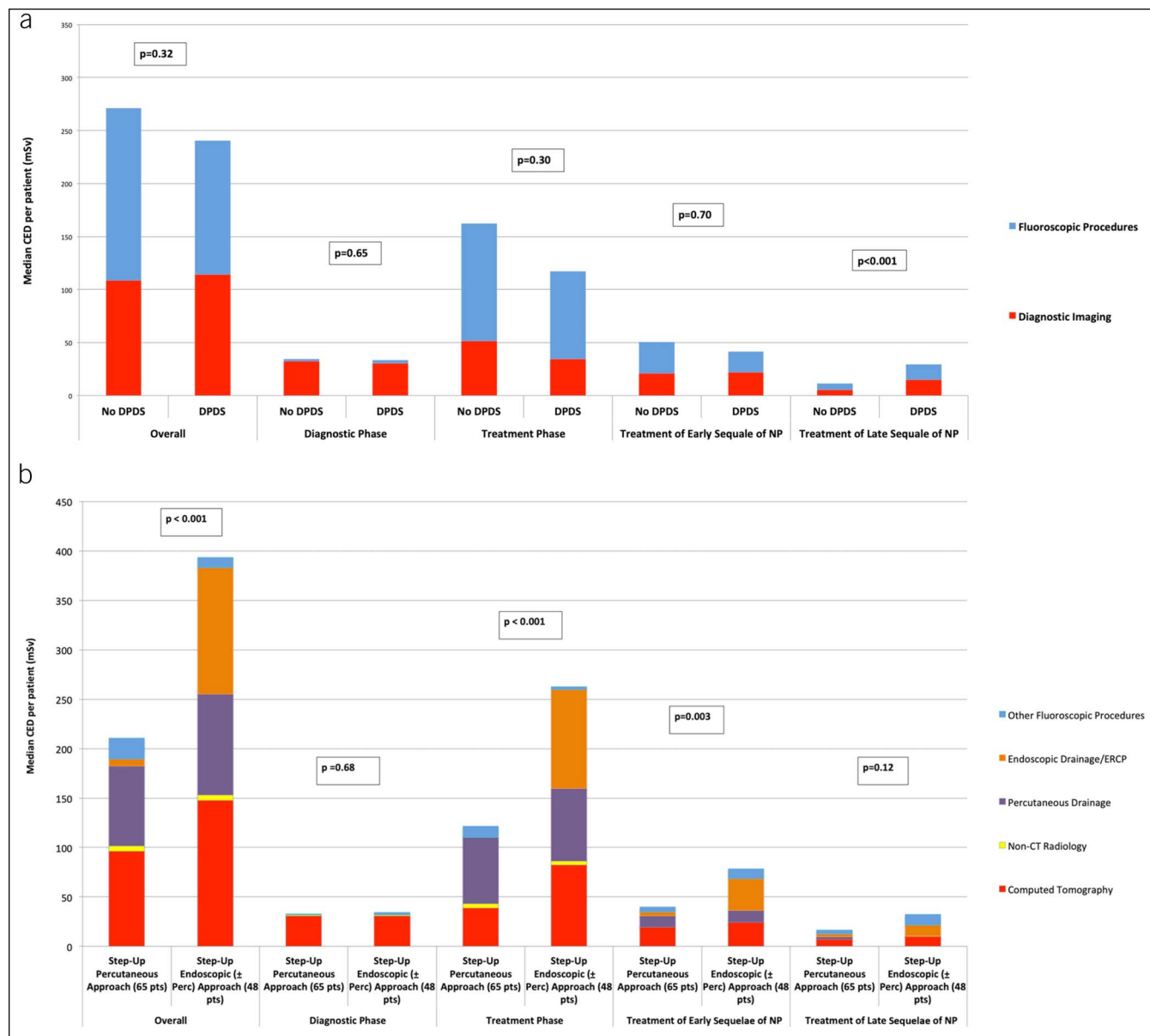
Figure 3. (**a**) Median CED stratified by the presence of a disconnected duct. (**b**) Median CED compared between step-up percutaneous and step-up endoscopic approaches. CED, cumulative effective dose.

organ doses may differ. Despite this, NCI-CT has been found to be the most accurate tool for estimating ED for CT examinations (15).

In conclusion, patients with NP were exposed to a substantial amount of radiation (a median of 257 mSv) from both diagnostic imaging and therapeutic procedures. Most of this radiation exposure was from diagnostic CT imaging and fluoroscopy-guided endoscopic and percutaneous procedures. Utilization of a step-up endoscopic approach, especially when combined with a percutaneous approach, was associated with a substantially higher CED when compared with a step-up percutaneous approach. This highlights that although minimally invasive therapies reduce morbidity related to NP, they can be associated with a significant amount of ionizing radiation. This is particularly important in NP because these patients often tend to be young,

may have additional risk factors for malignancy such as smoking and alcohol, and can develop chronic pancreatitis, which increases the risk of pancreatic cancer (30–32). Our study highlights the need to further investigate protocols to minimize radiation in the evaluation and treatment of NP to prevent future radiation-associated neoplasia.

CONFLICTS OF INTEREST

manuscript. All authors reviewed the data and the analytic methods and contributed to the manuscript.

Study Highlights

WHAT IS KNOWN

✓ Minimally invasive approaches, including endoscopic therapy, improve outcomes in NP. They require multiple percutaneous and/or endoscopic procedures using fluoroscopy.

WHAT IS NEW HERE

✓ Patients with necrotizing pancreatitis were exposed to a median of 272 mSv and 30% received more than 500 mSv.

✓ Severity of disease and the use of an endoscopic step-up approach were associated with radiation exposure >500 mSv.

TRANSLATIONAL IMPACT

✓ Our studies indicate the need for the development of clinical protocols to minimize radiation exposure for both diagnostic imaging and therapeutic procedures.

✓ Further research is needed to understand the impact of this radiation on pancreatic acinar cells and neoplasia risk.

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