Arrive guidelines

ITEM			Page#
Title	1	Safety and feasibility of irreversible electroporation for the pancreatic head in a porcine model	1
Abstract	2	BACKGROUND Irreversible electroporation (IRE) is a local non-thermal ablative technique which has been suggested as a potential cancer therapy. However, the specific anatomic characteristics of the pancreatic head make it challenging to perform any local ablation. Therefore, the safety and feasibility of IRE in the pancreatic head region should be further explored. AIM To evaluate the safety of IRE in pancreatic head region including its effects on pancreatic ducts, vessels and adjacent gastrointestinal organs. METHOD Eight landrace miniature pigs underwent IRE of the pancreatic head tissue successfully with a total of 16 lesions created. Laboratory testing including white blood cell (WBC) count and serum amylase before IRE with follow-up laboratory analysis and pathological examination in 1, 7, 14 and 28 days postablation were performed. RESULTS All pigs tolerated the ablation procedure without serious perioperative complications. Transient elevated WBC and amylase were oberseved at 24 hours post-IRE, suggesting an acute pancreatic tissue damage which was confirmed by pathological observations. Vascular endothelial cells and pancreatic duct epithelial cells in ablation zone were also	2

		positive in Terminal deoxynucleotidyl transferase dUTP nick end labeling (TUNEL) staining. There was extensive duodenum mucosa damage with local hemorrhage 24 hours after ablation, while renegeration of new villi structures were observed at 7 and 28 days post-IRE. Masson's trichromatic stain showed that the extracellular matrix was still intact in vessels, pancreatic duct and even in duodenum. CONCLUSION IRE-ablation to the pancreatic head may be safe and feasible without long-term damage to the surrounding vital structures. However, risks of stress injuries in acute phase should be taken into consideration to prevent severe perioperative complications. Key words:Irreversible electroporation; Pancreatic head; Duodenum; Safety; Feasibility; Stress injury.	
Introduction			
Background	3	Irreversible electroporation (IRE) is a novel local ablation technique based on the principle of nonthermal-induced damage, mainly causing irreversible perforation of the cell membrane by applying transient, high-frequency, and repeated high-voltage pulses to cells, which leads to the loss of intracellular homeostasis and induces apoptosis to achieve tumor ablation[1-3]. The characteristics of non-thermal effect make this novel technique significantly reduce the risk of thermal damage, and no thermal deposition effect affects the effectiveness of tumor ablation. Therefore, compared with local physical ablations based on the thermal effect such as radiofrequency ablation (RFA), IRE is more suitable for the treatment of locally advanced malignant tumors that cannot	4

		be radically resected owing to the invasion of vital blood vessels and thus has good application prospects[4,5]. Although the theory of IRE ablation of tumors has been widely accepted, it remains controversial in terms of whether there would be potential damage to tissues and organs adjacent to tumors that develop at special anatomical positions such as pancreatic head cancer[6,7]. Even though the safety of IRE ablation in the pancreas and upper gastrointestinal(GI) tract has been preliminarily validated[8-10], Large-scale animal studies on the local and systemic effects of ablation in this specific region of pancreatic head remain limited. Elucidating the short- and long-term effects of IRE on pancreatic head will be an essential step in demonstrating its safety and feasibility before further implementation in clinical patients..	
Objective	4	To investigate the immediate and late complications of IRE on the pancreatic head and evaluate its safety in pancreatic head region including its effects on pancreatic ducts, vessels and adjacent gastrointestinal organs.	4
Methods		Eight pigs were randomly divided into four groups (A, B, C, and D), with two pigs per group, corresponding to different observation time points (1 h, Day 1, Day 7, and Day 28 after IRE surgery). The pigs were used to evaluate the effect of IRE(Nanoknife, AngioDynamics, Queensbury, New York, USA) on the pancreatic head tissue and adjacent duodenum to observe the acute and chronic response to IRE ablation of the pancreatic head region. The IRE parameters were set as follows: fixed pulsed-field intensity of 1500 V/cm, pulse width of 100 μm, frequency of 1 Hz, needle exposure depth of 1 cm, and a	4

		preset pulse number of 120. The pancreatic head tissue adjacent to the medial duodenal wall was selected as the target area for ablation.	
Ethical statement	5	The operational procedures for the animal experiments were approved by the Institutional Animal Care and Use Committee (IACUC) of PLA General Hospital.	5
Study design	6	Eight Landrace miniature pigs weighing approximately 30 kg were selected with no gender restrictions and randomly divided into four groups (A, B, C, and D), with two pigs per group, corresponding to different observation time points (1 h, Day 1, Day 7, and Day 28 after IRE surgery). General condition of animals was observed and recorded including activity, feeding, bowel movements and weight changes. The white blood cell count and serum amylase level were measured before surgery and 1 h, 1 day, 3 days, 7 days, 14 days, and 28 days after surgery. Tissue specimens were harvested from pigs in the corresponding groups after 1 h and on Day 1, 7, and 28 after IRE. The pigs were euthanized via intravenous injection of 3% nembutal (100 mg/kg), and pathological examinations were conducted on the ablation and non-ablation zones, including hematoxylin and eosin (H-E) staining, TUNEL staining, and Masson trichrome staining and transmission electron microscopy observation.	4
Experimental procedure	7	All animals were fasted for 12h before the operation. Sedazine II (xylazine hydrochloride injection) + midazolam injection (volume ratio: 1:1) was used for anesthesia induction by 0.3 mL/kg intramuscular injection. After the induction was successful, the animals were intubated with a video laryngoscope, and isoflurane (0.8%)	5-6

		inhalation at a flow rate of 0.7 L/min combined with intravenous injection of 3-5 mg/kg fentanyl citrate through the ear vein was used for anesthesia maintenance. Rocuronium bromide was administered intravenously at a dose of 1-1.5 mg/kg as a muscle relaxant to prevent severe muscle contraction during electrical pulse generation. Vital signs including blood pressure, heart rate, and temperature were monitored during the operation. Two 19G IRE probes(AngioDynamics) were used to puncture parallelly into the target area with a distance of 1 cm and a puncture depth of 1.5 cm. After completing the probe deployment, 20 trial pulses were applied based on the preset parameters, and the remaining 100 pulses were administered after confirming that there was no voltage overload. Then, the pigs' response and changes in pancreatic head tissue and duodenum in the ablation zone were observed and recorded during IRE ablation. After the ablation was completed, the probes were removed and the abdomen was suctured closed layer by layer after observing no abnormality in the pig's vital signs, and bunarizine hydrochloride injection was used for anesthesia induction by intramuscular injection (3-5mg/kg, 1/day) for postoperative analgesia.	
Experimental animals	8	Eight Landrace miniature pigs weighing approximately 30 kg were selected with no gender restrictions and randomly divided into four groups (A, B, C, and D), with two pigs per group, corresponding to different observation time points (1 h, Day 1, Day 7, and Day 28 after IRE surgery). The pigs were provided by the Experimental Animal Center of Chinese PLA General Hospital.	4

Housing and husbandry	9	All animals were provided by the Experimental Animal Center of the PLA General Hospital, where they were reared under clean experimental and single-cage standard conditions (22 °C, 12 h/12 h light/dark, 60% humidity, ad libitum access to food and water).	4-5
Sample size	10	Eight pigs were randomly divided into four groups (A, B, C, and D), with two pigs per group, corresponding to different observation time points (1 h, Day 1, Day 7, and Day 28 after IRE surgery).	5
Allocating animals to experimental groups	11	Eight Landrace miniature pigs weighing approximately 30 kg were selected with no gender restrictions and randomly divided into four groups (A, B, C, and D), with two pigs per group, corresponding to different observation time points (1 h, Day 1, Day 7, and Day 28 after IRE surgery). General condition of animals was observed and recorded including activity, feeding, bowel movements and weight changes. The white blood cell count and serum amylase level were measured before surgery and 1 h, 1 day, 3 days, 7 days, 14 days, and 28 days after surgery. Tissue specimens were harvested from pigs in the corresponding groups after 1 h and on Day 1, 7, and 28 after IRE. The pigs were euthanized via intravenous injection of 3% nembutal (100 mg/kg), and pathological examinations were conducted on the ablation and non-ablation zones, including hematoxylin and eosin (H-E) staining, TUNEL staining, and Masson trichrome staining and transmission electron microscopy observation.	4
Experimental outcomes	12	General condition of animals was observed and recorded including activity, feeding, bowel movements and weight changes. The white blood cell count and serum amylase level were measured before surgery and 1 h, 1 day, 3 days, 7	6

		days, 14 days, and 28 days after surgery. Tissue specimens were harvested from pigs in the corresponding groups after 1 h and on Day 1, 7, and 28 after IRE. The pigs were euthanized via intravenous injection of 3% nembutal (100 mg/kg), and pathological examinations were conducted on the ablation and non-ablation zones, including hematoxylin and eosin (H-E) staining, TUNEL staining, and Masson trichrome staining and transmission electron microscopy observation.	
Statistics methods	13	SPSS version 22.0 statistical software was used to analyze the experimental results, and the measurement data were expressed as mean ± standard error. The experimental data were subjected to multiple comparisons among groups and the pairwise t-test, and the difference was considered statistically significant at $P < 0.05$ for the test criteria.	6
Results			
Baseline date	14	All animals were subjected to IRE ablation and survived to the respective experimental endpoints. The animals started to be active 6 h after surgery, but their activity was reduced and they did not consume food. Within 24 h after surgery, the animals gradually increased their activity and had a small amount of food and defecation. Then, at 2 days after surgery, the animals' activity, food intake, and defecation essentially returned to normal. No significant change in body weight was observed at the preoperative and postoperative time points in each group.	6
Numbers analyzed	15	The results of the laboratory testing showed that the white blood cell count in the postoperative acute phase of IRE gradually elevated from the preoperative baseline level $(16.2 \pm 2.0) \times 10^9$/L to the	7

		peak (28.2 ± 5.5) × 10^9/L at 24 h postoperatively and then gradually resolved to normal (Figure 1A). The serum amylase concentration showed a significant increase (873.4 ± 118.8) U/L 1 h after surgery, then reached the highest value (2,077.6 ±637.3) U/L at 24 h after surgery, and essentially returned to normal (1,383.9 ± 218.8) U/L 3 days after surgery (Figure 1B). Statistical comparative analysis showed that the serum amylase concentration on Day 1 after surgery were significantly higher ($P < 0.05$) than that at baseline (700.9 ± 88.1) U/L.	
Outcomes and estimation	16	***Pathological findings*** The pancreatic tissues after IRE ablation showed different pathological changes over time. At 1 h after surgery, the ablation zone showed distinct acute edema and congestion with clear demarcation from the surrounding area (). H-E staining showed that some of the pancreatic acinar cells were obviously necrotic accompanied by interstitial congestion and edema, and focal hemorrhages were observed locally, but most cells were negative for TUNEL staining. On Day 1 after surgery, inflammatory cell infiltration was visible under the microscope, and the pancreatic lobule structure remained intact. A small number of apoptotic cells was seen in TUNEL staining and were mostly concentrated around the probes. On Day 7 after surgery, the size of the ablation zone reduced, and pancreatic tissue edema disappeared. H-E staining revealed pancreatic acinar cell atrophy in the ablation zone and increased cell eosinophilia, accompanied by the infiltration of a large number of inflammatory cells and fibrosis. TUNEL staining revealed that the area centered on	7-8

the probes in the ablation zone was strongly positive, and apoptotic expression was also seen in pancreatic ductal and vascular endothelial cells. On Day 28 after surgery, the ablation zone continued to decrease in extent compared with that on Day 7, the infiltration of inflammatory cells in the ablation zone was reduced and the fibrous tissue was proliferated. The positive rate of cells in TUNEL staining decreased, while the structure of pancreatic ducts and vessels in the ablation zone was still intact.

Observation by transmission electron microscopy showed that the pancreatic acinar cells in the ablation zone were atrophied, the nucleoli were broken and disappeared, the chromatin of the cells was highly pyknotic and condensed to the edge, and the endoplasmic reticulum appeared vacuolated (Fig. 4).

Effect of IRE ablation on the duodenum

After IRE, the duodenal segments in the ablation zone showed a gradually deepening color with local congestion and edema as the distance from the probes gradually shortened., and the peristalsis of the corresponding segment slowed down. Postoperative observations at different time points showed that there was no perforation or obstruction in the duodenum, and the edema gradually disappeared. The color of the duodenal serosa in the ablation zone was not significantly different from that of the normal segment(Fig.5). Normally rhythmic peristaltic waves were observed.

H-E staining (Fig. 6) revealed that the mucosal structure of the duodenum in the ablation zone was disorganized at 1 h after surgery, with obvious destruction of the villi structure and congestion of the

		mucosa with localized focal hemorrhage; no significant changes were observed in the manifestation on Day 1 after surgery; on Day 7 after surgery, dead mucosal epithelial cells were still visible under microscopy and signs of repair could be seen in all layers of the duodenum; on Day 28 after surgery, the duodenal structure did not significantly differ from that before surgery. Masson trichrome staining showed proliferation of blue-stained fibrous connective tissue in the ablation zone of the pancreas on Day 7 after surgery (Fig. 7A), with the structure of vascular and pancreatic duct extracellular matrix being intact without any loss(Fig. 7B and 7C). Continuous blue-stained collagen fibers was seen between the mucosa, submucosa, muscularis, and serosa, and the structure was intact, which did not differ significantly from that in the non-ablation zone.	
Adverse events	17	We did not find any intraoperative or postoperative massive hemorrhaging, biliary fistula, severe pleural effusion, pneumothorax, peripheral organ damage, or renal failure.	6
Discussion			
Interpretation/scientific implications	18	***Selection of experimental animals*** The safety of IRE ablation of hollow organs has been established long before this technique was applied clinically. Phillips *et al*.[13] preliminarily validated the safety of IRE ablation of hollow organs using the small intestine of Sprague Dawley rats as the target organ; however, the differences in anatomical structure and ablation protocols limit the reference significance of this study for the safety assessment of IRE ablation in the pancreatic head. Subsequently, Schoellnast and Luo *et al*.investigated the	9-13

feasibility of colorectal IRE ablation using pigs as experimental animals, indicating that it was feasible to use hollow organs of miniature pigs as IRE target organs. This has a guiding significance for simulating the application of IRE in the ablation of tumors in the corresponding human organs. However, due to the different target organs and anatomical positions, these studies did not provide meaningful clinical references for assessing the safety of IRE ablation of pancreatic head cancer on adjacent hollow organs. Therefore, the anatomical structure and position as well as the tolerance of the experimental animals to IRE were the main considerations in selecting the experimental subjects. The pancreas of miniature pigs is flat and attached to the inner mesentery of the duodenum in a "herringbone" shape; this anatomical position is similar to that of humans. Therefore, compared with rats, pigs are a relatively more ideal animal model for IRE ablation experiments in the pancreatic head region.

Effect of IRE ablation on the duodenum

Consistent with reports in the literature, IRE ablation of the pancreatic head did not cause severe duodenal-related injury for the following possible reasons: 1) The IRE effect targets the cell membrane and does not affect the extracellular matrix and other skeletal structures; thus, the structural integrity of the duodenum is preserved, providing the basis for subsequent injury repair; 2) the principle of IRE killing cells is based on inducing apoptosis, thereby causing a mild local inflammatory response, which is conducive to the growth and migration of new cells; 3) the vasoprotective effect of

IRE did not significantly affect the blood supply to any layer of the duodenum; 4) the high renewal rate of mucosal epithelial cells in the small intestine allows rapid repair of the damaged duodenum; and 5) a study showed that the pluripotent stem cells of duodenal glands can be induced to differentiate into epithelial cells to form new villi structures in the small intestine, promoting the recovery of duodenal structure and function.

Notably, in the present study, when IRE ablated the head of the pancreas, we found extensive congestive changes in the mucosa and submucosa of the duodenum early after surgery, localized mucosal tissue detachment, and hemorrhagic manifestations; such acute stress changes suggested the risk of stress ulcer bleeding in the GI tract after IRE of tumors in the head of the pancreas. Consistent with the actual clinical situation, it is common for pancreatic head adenocarcinoma to invade the duodenum, and there have been clinical reports on GI bleeding after IRE. Therefore, although experimental animal studies have shown that IRE ablation of the pancreatic head does not result in severe long-term complications after ablation, such as duodenal perforation, the reference significance of its acute stress changes for the safety of IRE ablation of tumors in the head of the pancreas in clinical practice still warrants further investigation of the clinical application of this emerging technology in this special region of the pancreatic head.

Effect of IRE on pancreatic tissue and ductal structure in the ablation zone of the pancreatic head

In our study, no abdominal necrosis

and exudation was observed in the gross specimen at any time point, suggesting that no significant pancreatic fistula occurred after IRE ablation. The blood test results suggested that IRE can cause an inflammatory response in the first 24 h after surgery, and the white blood cell count would return to normal three days after surgery, indicating that this inflammatory response caused by IRE is only a stress response to this procedure during the acute phase of trauma. Additionally, the trend of the white blood cell count also suggested that IRE does not increase the risk of perioperative abdominal infection, thus validating the safety of IRE ablation in the head of the pancreas from another perspective. Notably, the trend of postoperative serum amylase also only showed a transient increase in the acute phase, while the long-term serum amylase level suggested that there was no evidence showing that IRE ablation of the pancreatic head could induce chronic pancreatitis. Combined with previous reports in the literature, we analyzed the reasons why IRE ablation of the pancreatic head did not induce severe pancreatitis, which may be as follows: 1) IRE ablation of the pancreas has a precise and limited scope, and its damage on the pancreatic tissue is limited to a localized area; 2) the ablation using a fine needle probe (19G) is less traumatic to the pancreas and can effectively prevent direct damage to the pancreatic duct; and 3) unlike other thermal ablation methods such as RFA or cryoablation, IRE does not damage the extracellular matrix, effectively protecting the integrity of the pancreatic duct structure in the ablation zone and avoiding pancreatic fistula.

The histopathological findings corroborated these results. The ablation

		zone of the pancreatic head showed different changes at different time points during the 4 weeks after IRE ablation, which was consistent with the findings of Edward *et al*. Necrosis of pancreatic acinar cells was found 1 h after ablation, suggesting that IRE ablation can cause morphological changes of cells in the ablation zone at an early stage after the procedure. From Day 1 to Day 28 after ablation, the ablation zone showed a series of pathological changes from a massive accumulation of inflammatory cells to gradual regression and from atrophy and death of pancreatic acinar cells to a proliferation of fibrous connective tissue, which confirmed that IRE could produce irreversible damage to pancreatic tissues. However, such damage was not coagulation necrosis but apoptosis. This mechanism of IRE was confirmed by results of TUNEL staining. We found that pancreatic ductal and vascular endothelial cells were also positive in TUNEL staining, suggesting that IRE ablation also induced apoptotic effects on cells of ductal structures, such as vessels and pancreatic ducts. Nevertheless, IRE did not damage their structural integrity and function, demonstrating that important ductal structures in the pancreatic head could be preserved while target cells were destroyed.	
Generalizability/translation	19	Although the effectiveness of IRE ablation of the pancreatic head and the safety of vital ductal structures and adjacent organs were validated in this study, it was limited as the study aimed to generate an IRE model in normal pancreatic tissue of pigs, which failed to truly simulate the tumor model that invades the peripheral vessels of the pancreatic head and duodenum.	13

		Additionally,owing to the difference between the microenvironment of tumor and that of normal tissues, there is still uncertainty on whether the same results would be obtained if tumor cells are present. IRE ablation to the pancreatic head may be safe and feasible without long-term damage to the surrounding vital structures. However, risks of stress injuries in acute phase should be brought to our attention. In the future, in vitro studies of IRE ablation on various human pancreatic cancer cell types should be conducted to optimize parameters and techniques of pancreatic IRE ablation in clinical settings, and further studies are needed to investigate the mechanism of tissue repair and regeneration after IRE.	
Funding	20	no	