Sphincter of Oddi dysfunction produces acute pancreatitis in the possum

J W C Chen, A Thomas, C M Woods, A C Schloithe, J Toouli, G T P Saccone

Abstract

Background—Sphincter of Oddi dysfunction has been implicated as a cause of various forms of acute pancreatitis. However, there is no direct evidence to show that sphincter of Oddi dysfunction can cause obstruction of trans-sphincteric flow resulting in acute pancreatitis.

Aims—To determine if induced sphincter of Oddi spasm can produce trans-sphincteric obstruction and, in combination with stimulated pancreatic secretion, induce acute pancreatitis.

Methods—In anaesthetised possums, the pancreatic duct was ligated and pancreatic exocrine secretion stimulated by cholecystokinin octapeptide/secretin to induce acute pancreatitis. In separate animals, carbachol was applied topically to the sphincter of Oddi to cause transient sphincter obstruction. Sphincter of Oddi motility, trans-sphincteric flow, pancreatic duct pressure, pancreatic exocrine secretion, plasma amylase levels, and pancreatic tissue damage (histology score) were studied and compared with variables in ligation models.

Results—Acute pancreatitis developed following stimulation of pancreatic exocrine secretion with peptides after pancreatic duct ligation (p<0.05). Neither pancreatic duct ligation nor stimulation of pancreatic exocrine secretion with cholecystokinin octapeptide/secretin alone resulted in acute pancreatitis. Topical carbachol stimulated sphincter of Oddi motility abolished trans-sphincteric flow, and increased pancreatic exocrine secretion (p<0.05) and pancreatic duct pressure to levels comparable with pancreatic duct ligation (p<0.001). Carbachol application (with or without combined peptide stimulation) elevated plasma amylase levels (p<0.01) and produced pancreatic tissue damage (p<0.05). Decompression of pancreatic duct ameliorated these effects (p<0.05).

Conclusion—Induced sphincter of Oddi dysfunction when coupled with stimulated pancreatic secretion causes acute pancreatitis. This may be an important pathophysiological mechanism causing various forms of acute pancreatitis.

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Keywords: acute pancreatitis; sphincter of Oddi; cholecystokinin octapeptide; possum

Sphincter of Oddi (SO) dysfunction has been implicated as a possible mechanism in some forms of acute pancreatitis. SO dysfunction is defined as a manometric abnormality of the sphincter leading to impeded flow of bile or pancreatic juice. This abnormality has been shown to be associated with recurrent biliary-type pain and idiopathic recurrent pancreatitis.

SO dysfunction has been implicated as a pathophysiological mechanism in other forms of acute pancreatitis such as gall stone pancreatitis, and pancreatitis secondary to alcohol, scorpion envenomation, organophosphate poisoning, and octreotide treatment. It has been postulated that transient or induced SO dysfunction due to oedema or spasm may be the primary mechanism leading to pancreatic duct obstruction in these cases.

The SO is under neurohormonal control. As cholinergic innervation of the SO is stimulatory, it has been postulated that acute pancreatitis resulting from excessive cholinergic stimulation with scorpion venom may be secondary to SO spasm in the presence of stimulated pancreatic exocrine secretion. Previous animal studies have suggested pancreatic duct obstruction at the level of SO during cholinergic hyperstimulation induced acute pancreatitis but there is no direct evidence of increased SO activity. Pancreatic exocrine secretion and pancreatic duct pressure increased in the presence of cholinergic stimulation but it is uncertain if these changes are secondary to induced SO dysfunction. Even if SO dysfunction contributes to increased pancreatic duct pressure, this may not be the primary cause of all forms of acute pancreatitis, as suggested by some studies.

Australian Brush tailed possums (Trichosurus vulpecula) were used in this study because of their similarity to the human pancreatic and bile ducts arrangement that they come together and are regulated by an SO complex. This SO complex is longer and predominantly extraduodenal allowing for easier manometric monitoring and topical pharmacological manipulation. The Evans ducts drain through the same ampulla but there is no evidence of a common channel. Also, there is no evidence of an accessory duct (unlike the accessory duct of Santorini in humans), as assessed in over 200 possum pancreatic specimens. The comparative morphology of the SO between possums, humans, and other species has been described.

The aims of the present study were to determine if (1) fixed obstruction by pancreatic duct

Abbreviations used in this paper: SO, sphincter of Oddi; CCK-8, cholecystokinin octapeptide.
ligation with stimulated pancreatic exocrine secretion by cholecystokinin octapeptide (CCK-8)/secretin and (2) transient SO obstruction with topical carbachol and stimulated pancreatic exocrine secretion alter plasma amylase levels and induce acute pancreatitis.

Table 1 Experimental groups

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CCK-8, cholecystokinin octapeptide; SO, sphincter of Oddi.

Methods

ANIMAL PREPARATION

Forty Australian Brush tailed possums of both sexes (1.5–3.5 kg) were prepared as previously described.13 14

Briefly, anaesthesia was induced with a combination of intramuscular ketamine (20 mg/kg Ketalar; Park Davis, Caringbah, NSW, Australia) and intramuscular xylazine (10 mg/kg, Rompun; Bayer, Botany, NSW, Australia). Although ketamine has been shown to affect SO motility in some species, the effects, if any, on possum SO motility would have abated following surgical preparation of the animal (about one hour) and a stabilization period of at least 15 minutes. The left femoral artery was cannulated and connected to a pressure transducer (Transpac IV, Abbot Ireland, Sligo, Republic of Ireland) for blood pressure monitoring. A tracheostomy was performed and the animal ventilated with a small animal ventilator (Phillips and Bird Inc., Richmond, Virginia, USA).

Pancreatic duct ligation with stimulated pancreatic exocrine secretion studies (groups A–E)

Five groups of animals (n=5) were subjected to pancreatic duct ligation or “pancreatic duct decompression” to characterise the effects of “fixed” pancreatic duct obstruction on the histological integrity of the pancreas and plasma levels of amylase (table 1). At laparotomy, a small choledochotomy was made in the common bile duct distal to the entry of the cystic duct. A single lumen side hole polyethylene manometry catheter (OD 1 mm, ID 0.6 mm) and a polyethylene bile diversion tube (OD 1.2 mm, ID 0.8 mm) were inserted (fig 1).13 14 The manometry catheter, to measure SO motility, was connected to a minimally compliant pneumatic pump (Arndorfer Medical Specialties Inc, Greenvale, Wisconsin, USA) and a pressure transducer. The pancreatic duct proximal to the SO was incised and one end of a polyethylene catheter (OD 1 mm, ID 0.5 mm) was inserted proximally 1–2 mm and secured with a 6.0 silk suture. In animals subjected to ligation of the pancreatic duct without decompression (groups B–D), the other end of this tube was connected to a pressure transducer with zero set at the level of the SO (fig 1A). In the pancreatic duct decompression groups (A, E), the end of the polyethylene catheter was set at a point about 1 cm lower than the duodenum to collect pancreatic juice for determination of pancreatic exocrine secretion volume and amylase secretion rate (fig 1B). All preparations were allowed to stabilise for at least 15 minutes prior to collection of juice or pancreatic duct ligation. Synthetic CCK-8 and secretin (porcine, Auspep, Parkville, Victoria, Australia) were dissolved in saline containing 0.01% bovine serum albumin (Sigma Chemical Co., St Louis, Missouri, USA) and administered as bolus injections.
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Figure 2 Experimental protocol for blood collection and peptide administration. Experiments were carried out over an eight-hour period during which hourly plasma samples (small arrow, top) were taken for amylase measurement. In groups C, D, E, and H, which were subjected to secretin or cholecystokinin octapeptide (CCK-8) stimulation, increasing intravenous bolus injection volumes (heavy arrow, bottom) were given within the first two hours, then doses of 5 µg/kg were administered at 30-minute intervals from two to five hours after ligation or start of the experiment. Eight hours after ligation, animals were killed and tissues collected for subsequent histological examination.

(0.25–1.25 ml) via the femoral vein, at 30 minute intervals for a total of 10 injections over five hours. The initial dose (0.5 µg/kg each) of CCK-8/secretin was followed by increasing doses from 1 to 5 µg/kg, and maintenance of this dose for a further three hours (fig 2). The final dose was given at five hours after pancreatic duct ligation.

Transient SO obstruction studies (groups F–H)

An inflow catheter was inserted into the common bile duct together with the manometry catheter to measure trans-sphincteric flow, as previously reported (fig 1C). Briefly, a polyethylene inflow catheter (OD 1.2 mm, ID 0.8 mm) was positioned in the common bile duct proximal to the manometry catheter, secured with a ligature, and connected to a saline filled reservoir suspended from a force transducer (FT03, Grass Instruments, Quincy, Massachusetts, USA) acting as an electromagnetic balance. As trans-sphincteric flow proceeds, the weight of the reservoir decreases and the rate of change (slope) represents trans-sphincteric flow (fig 3A). Aliquots of saline (1 ml) were delivered into the reservoir at regular intervals to maintain a relatively constant inflow pressure. Cessation of trans-sphincteric flow was indicated as an upward slope as complete obstruction at the SO resulted in transfer of the manometry catheter perfusate into the saline reservoir via the inflow catheter. Stimulation of SO activity to induce transient trans-sphincteric obstruction was achieved by multiple topical application (2.5 µl) of carbachol (Sigma), initially 0.001 M, then at 0.01 M. Carbachol was applied topically using a pipette and placed directly onto the extraduodenal portion of the SO. Duration of topical carbachol induced cessation of trans-sphincteric flow through stimulation of SO was 1–10 minutes, with initial applications causing longer lasting effects. Cessation of trans-sphincteric flow was induced for a total of five hours (fig 3B). No additional carbachol was applied except for a test dose immediately prior to sacrifice of the animals at eight hours after induction of SO obstruction.

In groups F and H, pancreatic duct pressure was measured for the duration of the experiment by insertion of a polyethylene T-tube catheter (OD 1.0 mm, ID 0.5 mm) into the pancreatic duct just proximal to the SO. This catheter was then connected to a saline filled pressure transducer (fig 1C). Group H was also subjected to CCK-8/secretin stimulation, as for groups D and E. In group G, carbachol was administered at the same concentrations used to stimulate cessation of trans-sphincteric flow, as indicated above. However, the pancreatic duct was decompressed by cannulation, as described above (fig 1D). All transducers were connected to a MacLab recording system (AD Instruments, Castle Hill, NSW, Australia). The possum’s body temperature was maintained by a homeothermic warming blanket (Harvard Instruments, Boston, Massachusetts, USA). On completion of the experiment, all animals were killed with a lethal dose of sodium pentobarbitone (Lethabarb, Virbac, Peakhurst, NSW, Australia).

Blood pressure (mm Hg), plasma amylase concentration (U/l), pancreatic amylase secretion (U/h), pancreatic exocrine volume secretion (ml/8 h), SO manometry (mm Hg), trans-sphincteric flow (µl/min), pancreatic duct pressure (mm Hg), and pancreas histology score (see below) were measured. The biliary portion of SO manometry was measured in all animals to confirm the presence of spontaneous activity throughout the studies and the effects of peptides and carbachol but SO activity was not quantified. The manometry of the pancreatic portion of SO was measured in pre-
Based on modification of Spormann et al.\textsuperscript{16} listed in table 2. All data are expressed one way ANOVA. A p value <0.05 was regarded as significant. Changes in pancreatic secretion were analysed using repeated measures analysis of variance (ANOVA). Changes in pancreatic secretion rate, amylase output, histology scores, and pancreatic duct pressure were analysed using one way ANOVA. A p value <0.05 was regarded as significant. All data are expressed as mean (SEM) unless otherwise stated. The study was approved by the Animal Welfare Committee of Flinders University.

**Results**

**PANCREATIC DUCT PRESSURE**

Pancreatic duct pressure in groups B, C, and D with a catheter in situ were 4.2 (0.7), 2.6 (0.6), and 4.4 (0.8) mm Hg, respectively. These pressures increased to a mean of 17.8 (1.3), 18.0 (1.2), and 16.0 (1.2) mm Hg, respectively (p<0.001), within one hour of injection. Topical carbachol application induced a sustained increase in SO motility, with pancreatic duct pressure associated with cessation of trans-sphincteric flow (fig 3). Pancreatic duct pressure (prior to carbachol stimulated SO obstruction) was 5.6 (0.5) and 4.3 (0.7) mm Hg in groups F and H, respectively. Following topical carbachol administration to achieve cessation of trans-sphincteric flow, pancreatic duct pressure in the non-decompressed groups (groups F and H) increased to a peak of 18.4 (0.7) and 21.0 (1.1) mm Hg, respectively. The increase in pancreatic duct pressure was comparable with that of pancreatic duct ligation above.

**PLASMA AMYLASE AND PANCREATIC JUICE COLLECTION**

In all animals, 1 ml of arterial blood was collected prior to laparotomy as a baseline measurement, at the beginning of induction of pancreatitis (time 0; fig 2), and then hourly for plasma amylase analysis. Blood samples were collected in EDTA tubes, centrifuged at 2000 rpm for 10 minutes, and plasma stored at −20°C overnight. For experiments with pancreatic duct decompression, after a 30 minute stabilisation period, pancreatic juices were collected hourly, with the secretion rate determined gravimetrically. Plasma and pancreatic juice amylase activity was measured using enzymatic colorimetric spectroanalysis (Boehringer Mannheim, Meylan, France) in a centrifugal analyser (Cobas Bios, F Hoffmann-La Roche, Basle, Switzerland). Plasma amylase levels were expressed as a percentage of baseline levels.

**Histological analysis**

The pancreas of each animal was harvested at eight hours, immediately fixed in 10% buffered formalin for 24–48 hours, and the head, neck, body and tail separated by dissection. Following paraffin embedding, sections were stained with haematoxylin-eosin and examined by a single pathologist blinded to the experimental protocol. A histology score was generated based on a modification of Spormann's criteria.\textsuperscript{16} The histological features assessed are listed in table 2.

**STATISTICAL ANALYSIS**

Changes in plasma amylase levels were analysed using repeated measures analysis of variance (ANOVA). Changes in pancreatic secretory rate, amylase output, histology scores, and pancreatic duct pressure were analysed using one way ANOVA. A p value <0.05 was regarded as significant. All data are expressed as mean (SEM) unless otherwise stated. The study was approved by the Animal Welfare Committee of Flinders University.

**Figure 4** Plasma amylase profile (% of baseline) of various experimental groups (indicated by bold italics) as a function of time. Significant increases in plasma amylase were noted in groups D, F and H compared with the sham (A), pancreatic duct ligation only (B), pancreatic duct decompressed (E), and carbachol administration with pancreatic duct decompression (G) groups. *p<0.05 compared with the sham group (repeated measures ANOVA). Data are mean (SEM) (n=5 animals per group).
PANCREATIC EXOCRINE VOLUME AND AMYLASE SECRETION
Administration of CCK-8/secretin without pancreatic duct ligation (group E) significantly increased (p<0.02) pancreatic exocrine amylase secretion (496.3 (109.3) U) compared with the sham group (39.4 (17.4) U), but pancreatic secretion volume (5.6 (1.4) ml for group E v 2.1 (0.5) ml for sham) was not significantly changed. Topical carbachol however, significantly increased (p<0.05) pancreatic exocrine secretion volume (7.9 (2.0) ml) compared with the sham group (2.1 (0.5) ml) without significantly increasing pancreatic amylase secretion (241.4 (110.6) U for carbachol stimulated groups v 39.4 (12.4) U for the sham group).

PLASMA AMYLASE
Plasma amylase gradually decreased over the course of the experiment in the sham group (A), pancreatic duct ligation alone group (B), and CCK-8/secretin stimulation with pancreatic duct decompression group (E) (fig 4). Pancreatic duct ligation and simultaneous administration of CCK-8/secretin (group D) however resulted in significant hyperamylasaemia compared with the sham as well as the pancreatic duct decompressed group (E) (p<0.005). Possums subjected to carbachol stimulated SO obstruction (groups F and H) displayed a significant increase in plasma amylase levels (p<0.01) which peaked at 5–6 hours from the onset of carbachol administration (fig 4). Additional stimulation with CCK-8/secretin (group H) failed to significantly increase plasma amylase levels compared with the carbachol alone group F (p=0.06). When the pancreatic duct was decompressed (group G), plasma amylase levels were comparable with those in the sham group.

ACUTE PANCREATITIS HISTOLOGY
Ligation of the pancreatic duct with secretin stimulation alone (group C), or with a combination of CCK-8 (group D) induced changes which included parenchymal oedema, and focal peripheral and central parenchymal fat necrosis (fig 5) resulting in a significantly increased histology score (p<0.05) compared with the sham group (fig 6). Mild changes with local oedema and inflammatory changes were noted in the sham group (A) which was subjected to the same degree of surgical

Figure 5 Representative histology slides of haematoxylin-eosin stained sections of possum pancreas from the sham group (A), pancreatic duct ligation with secretin/CCK stimulation group (B), carbachol induced acute pancreatitis group (C) and carbachol induced SO obstruction in combination with secretin/CCK stimulation group (D). Minimal change is noted in (A) (sham). In (B) and (C), destruction of pancreatic acini with necrosis and inflammatory infiltration (a) is noted. Haemorrhage in these sections is also noted (b). In (D), diffuse parenchymal oedema (c) is noted with mild peripheral inflammatory infiltrate (d). (Original magnification x25.)

Figure 6 Pancreatitis histology score of various groups of animals (bold, italics, as defined in table 1). Acute pancreatitis histology scores were significantly increased in animals subjected to pancreatic duct obstruction with either secretin (group C), or secretin with cholecystokinin octapeptide (CCK-8) administration (group D), in animals subjected to carbachol stimulated transient sphincter of Oddi obstruction alone (group F) or with CCK-8/secretin administration (group H). Data are mean (SEM) (n=5 animals per group). *p<0.02 compared with the sham group (group A); **p<0.05, ***p<0.01, ****p<0.02 compared with groups A, B, E, and G (ANOVA).
dissection and handling as the other groups. The histology scores for pancreatic duct ligation alone (group B) and pancreatic duct decompression with secretin/CCK-8 stimulation (group E) were not significantly different from the sham histology score (fig 6). Carbachol induced transient SO obstruction with or without CCK-8/secretin stimulation (groups F and H) resulted in significantly increased pancreatic damage—that is, higher histology score (p<0.001 and p<0.02, respectively) compared with the sham group (fig 4). Decompression of the pancreatic duct despite carbachol stimulated SO obstruction (group G) did not result in significant histological changes. Histology scores for the ligation and CCK-8/secretin stimulation group (D) were comparable with those of the transient SO obstruction by carbachol group (F) (fig 6).

Discussion
For the first time, we have shown that transient obstruction of the SO produced by carbachol administration resulted in hyperamylasaemia and histological changes consistent with acute pancreatitis. These changes were comparable with those induced in possums with combined pancreatic duct ligation and CCK-8/secretin administration, a well established method on inducing hyperamylasaemia and acute pancreatitis in other species. In both the carbachol induced and pancreatic duct ligation with secretin/CCK-8 models, the concurrent increase in pancreatic duct pressure with a combination of pancreatic exocrine stimulation was necessary to produce hyperamylasaemia and acute pancreatitis.

The increase in pressure in the pancreatic duct was similar whether it followed pancreatic duct ligation or was induced by carbachol administration. The increase in plasma amylase in all cases corresponded with the increase in pancreatic duct pressure following pancreatic duct ligation or stimulated SO obstruction in combination with pancreatic exocrine stimulation. When the pancreatic duct was decompressed by a polyethylene tube in the duct in these groups, plasma amylase decreased over the duration of the experiment. These findings indicate that pancreatic duct obstruction resulting in an increase in pancreatic duct pressure in combination with pancreatic exocrine stimulation is required to produce hyperamylasaemia and not pancreatic exocrine stimulation alone. It is not surprising to find that the combination of carbachol induced SO obstruction in the presence of CCK-8/secretin stimulation resulted in the highest increase in plasma amylase levels suggesting that secretion against an obstructed pancreatic duct is the cause of hyperamylasaemia in these cases. Although topical application of carbachol also stimulated exocrine pancreatic secretion volume, this did not result in a significant rise in plasma amylase or histology score when the pancreatic duct was decompressed, indicating that SO stimulated pancreatic duct obstruction coupling is essential in causing acute pancreatitis.

Pancreatic dissection and handling resulted in localised mild histological changes. When the animals were subjected to pancreatic duct ligation and CCK-8/secretin stimulation, a significant increase in pancreatitis histology score was noted. The pancreatitis occurred mainly in the head of the pancreas and was associated with diffuse oedema, peripheral necrosis of 1–2 cells thick, as well as areas of parenchymal necrosis. Similar changes were also noted in groups subjected to carbachol stimulated SO obstruction with or without additional peptide stimulation. This pancreatitis in possums is different from that noted after cerulein administration in the rat where high serum amylase levels associated with mainly pancreatic oedema is reported. The severity of acute pancreatitis in possums following pancreatic duct occlusion is greater than that produced in mice following pancreatic duct ligation but less severe compared with ligation of the biliopancreatic duct of the opossum.

In this study, possums were used as the motility of the SO has been well characterised. The SO of the possum acts as a variable resistor in modulating bile and pancreatic secretion and its responses to hormonal and drug stimuli are very similar to humans. Possums have not been used previously in the study of acute pancreatitis and consequently pancreatic duct ligation studies were performed. Previous studies have shown that pancreatic duct obstruction coupled with pancreatic exocrine stimulation in animal models can result in hyperamylasaemia with oedematous pancreatitis. The severity of pancreatitis varies in different species using similar stimuli, but also varies with different stimuli used to produce pancreatitis. Our study showed that mild to moderate pancreatitis was produced by SO obstruction combined with increased pancreatic exocrine secretion. Furthermore, carbachol induced acute pancreatitis was similar to acute pancreatitis which may be produced following idiopathic SO dysfunction, or SO dysfunction following passage of a gall stone through the SO in biliary pancreatitis.

SO dysfunction has been implicated as a possible cause of various forms of acute pancreatitis, including idiopathic recurrent pancreatitis, gall stone pancreatitis, as well as pancreatitis due to scorpion toxin envenomation and drugs such as octreotide. Although it has been postulated that SO dysfunction either in the form of stenosis (oedema or SO hyper trophy) or dyskinesia (tachydybia, induced spasm) leads to partial or complete obstruction of the pancreatic duct resulting in pancreatitis, this mechanism has not been demonstrated directly. Our results in possum strongly implicate SO dysfunction as one of the causative factors for production of pancreatitis. In particular, the changes in SO motility produced by carbachol clearly indicates that together with increased secretion by the pancreas, this is an essential combination in the production of this form of pancreatitis.

We have demonstrated that the SO, which is strategically placed to modulate pancreatic and bile flow, can cause pancreatitis when stimulated to contract during periods of elevated
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pancreatic exocrine secretion. Therefore, simultaneous SO dysfunction (impeding flow) combined with elevated pancreatic exocrine secretion may be an important pathophysiological mechanism underlying various forms of acute pancreatitis. This newly described possum model will also enable the study of the role of SO motility in other forms of acute pancreatitis where SO dysfunction has been implicated.

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