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Gallbladder dyskinesia is associated with an impaired postprandial FGF19 response in critically ill patients.

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Abbreviations used in this paper: GI, gastrointestinal; ICU, intensive care unit; FGF19, fibroblast growth factor 19; IFALD, intestinal failure-associated liver disease; FXR, farnesoid x receptor; C4, 7-alpha-hydroxy-4-cholesten-3-one; GBEF, gallbladder ejection fraction; AUC, area under the curve; ALT, alanine aminotransferase; AST, aspartate aminotransferase; AP, alkaline phosphatase; GGT, gamma glutamyl transferase;

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ABSTRACT

Critical illness is associated with a disturbed regulation of gastrointestinal hormones resulting in functional and metabolic anomalies. FGF19 is an ileum-derived metabolic hormone induced by bile salts upon gallbladder emptying after enteral nutrient stimulation. Our aim was to study the nutrient-stimulated FGF19 response in 24 patients admitted to the intensive care unit (ICU) compared with 12 healthy controls. All subjects received intraduodenal high-lipid nutrient infusion for 120min. Blood was collected every 30min until 1 hour after infusion and gallbladder emptying was studied by ultrasound. Serum levels of bile salts and FGF19 were assessed. ICU-patients had significantly higher fasting bile salt serum levels compared with controls, while FGF19 serum levels were similar. In both groups, nutrient infusion elicited substantial bile salt elevations (P<0.001), peaking at 90min, albeit with a significantly lower peak in the ICU-patients (P=0.029). In controls, FGF19 was significantly elevated relative to baseline from 120min onwards (P<0.001). In ICU-patients, the FGF19 response was blunted, as reflected by significantly lower FGF19 elevations at 120, 150 and 180min (P<0.05) and significantly lower AUC values compared with controls (P<0.001). Gallbladder dysmotility was associated with the impaired FGF19 response in critical illness. The gallbladder ejection fraction (GBEF) correlated positively with FGF19 AUC values (ρ=+0,34, P=0.034). In 10 out of 24 ICU-patients gallbladder emptying was disturbed. These patients had significantly lower FGF19 AUC values (P<0.001). Gallbladder emptying and the FGF19 response were respectively disturbed or absent in patients receiving norepinephrine. ***Conclusions*****:** The nutrient-stimulated FGF19 response is impaired in ICU-patients, which is mechanistically linked to gallbladder dysmotility in critical illness. This may contribute to disturbed liver metabolism in these patients and has potential as a nutritional biomarker.

Keywords: critical illness; gallbladder dysmotility; bile salts; FGF19

INTRODUCTION

Critical illness is associated with disturbances in production and secretion of gastrointestinal (GI) hormones, and this may contribute to GI, immune and metabolic abnormalities.[1] Bile salts are endocrine signalling molecules that undergo enterohepatic circulation. By interacting with bile salt-sensing receptors, bile salts regulate the production of a number of GI hormones including Fibroblast Growth Factor 19 (FGF19).[2] Gallbladder motility is often impaired in critical illness, which could result in reduced entry of bile into the small intestine, and impaired enterohepatic bile salt signalling.[3] Thus, gallbladder dysfunction could contribute to disturbances in bile salt-regulated GI hormones.

FGF19 (termed Fgf15 in rodents) is an enterokine produced in response to bile salt reabsorption in the terminal ileum.[4, 5] Meal-induced elevation of FGF19 is governed by the bile salt-activated transcription factor Farnesoid X Receptor (FXR).[4, 5] FGF19 primarily targets the liver, which expresses both components (FGFR4 and β-klotho) required for FGF19 signalling.[6-8] (Pre)clinical studies revealed a myriad of functions of FGF19/Fgf15 including regulation of major metabolic pathways (e.g. energy, carbohydrate and lipid metabolism, bile salt and protein synthesis) and functional processes such as gallbladder relaxation, skeletal muscle mass homeostasis and GI motility.[5, 9-13] Considering the beneficial metabolic effects, FGF19 administration is evaluated as treatment of chronic liver diseases.[14-17] Reduced circulating FGF19 has been observed in non-alcoholic fatty liver disease (NAFLD), intestinal failure-associated liver disease (IFALD) and bile salt diarrhoea.[18-20] In IFALD, impaired FGF19-mediated repression of hepatic bile salt synthesis appeared to be the pathological mechanism leading to overproduction of bile salts, and was associated with hepatotoxicity.[19] Of note, critical illness has been associated with elevated bile salts and hyperbilirubinemia, indicating dysregulated bile salt homeostasis and secretory dysfunction.[21, 22]

In healthy subjects, systemic FGF19 levels peak 3 to 4 hours postprandially, following earlier elevation of bile salts at 1.5 to 2 hours after a meal.[23, 24] Thus far, fasting and nutrient-stimulated FGF19 levels have not been reported in critically ill patients. We hypothesized that patients with critical illness and associated gallbladder dysmotility, have an abrogated postprandial course of FGF19. The aim of this study was to compare the bile salt and the enteral FGF19 response after intraduodenal lipid infusion in patients admitted to the intensive care unit (ICU) and in healthy controls.

MATERIALS AND METHODS

Subjects and data collection

We analyzed clinical data and stored plasma samples of patients who were initially enrolled in a prospective observational comparison study to quantify gallbladder dysfunction during critical illness.[3] Description of the original study has been detailed elsewhere.[3] In short, twenty-four mechanically ventilated critically ill patients capable of receiving enteral nutrition were studied, as were a control group of twelve age- and gender-matched healthy subjects without known diseases of the hepatobiliary or GI tract.[3] None of the patients had confirmed intestinal inflammation or ischaemia of the ileal region.

Protocol

Briefly, both groups were fed intra-duodenally via a nasogastric tube after 8 hours of overnight fasting.[3] In both healthy controls and critically ill patients a small intestinal feeding catheter was inserted using an electromagnetic guidance technique.[3] All subjects received a high-fat meal (120 mL; 20% Intralipid from Baxter Healthcare, Deerfield, IL) infused post-pylorically at a rate of 2 kcal/min (60 mL•hour^{-1}) during a 2 hour interval. Both healthy controls and critically ill patients were investigated while lying in a supine position and the head of the bed was placed at an angle of 30 degrees.[3] Blood was collected prior to the nutrient infusion (-30, 0 min), at 30 minutes intervals during nutrient infusion (30, 60, 90, 120 min), and at two additional 30 minutes intervals after termination of the infusion (150 and 180 min). Blood was taken from an arterial line *in situ* for ICU patients, and from an intravenous

cannula placed in a peripheral vein for controls. For baseline values the average between -30 and 0 minutes was used. Gallbladder volume (mL) at 30-minute intervals from –30 to 180 minutes was previously assessed by three-dimensional ultrasound.[3] Gallbladder ejection fraction (GBEF) was defined as the percentage volume change between start (0 min) and completion of lipid infusion (120 min). Normal GBEF was considered to be >35%.[25] To determine presence of biliary sludge, static images of the gallbladder at -30 min were used.[3]

Analytical Procedures

Blood samples (EDTA anti-coagulated) were originally collected on ice, immediately centrifuged, and stored as plasma at –70°C, prior to dry-ice shipping to Maastricht University for additional analyses. Total bile salts were determined using an enzymatic cycling method according to the manufacturer's protocol (Diazyme Laboratories, CA, USA). FGF19 was assayed by sandwich ELISA as described previously.[26] Levels of 7-alpha-hydroxy-4-cholesten-3-one (C4), a systemic marker of bile salt synthesis, were determined as described previously.[27] If C4 levels were not detectable, values were set to the lower limit of detection, i.e. 0.1 ng/mL.

Statistics

Data are expressed as median [interquartile range] or mean±standard error of mean (SEM) when appropriate, and displayed as box and whisker plots with the 10th and 90th percentile, unless indicated otherwise. Significant differences between critically ill patients and healthy volunteers were evaluated with the Mann-Whitney U test. Correlations were evaluated by the Spearman's correlation test. Of two healthy subjects, plasma samples representing single time points (60 and 180 min, resp.) were not available (2.3% missing data). To avoid subject deletion, data of these subjects were included in the statistical analyses using multiple imputation method to estimate missing values. A Friedman repeated measures on ranks or two-way analysis of variance (ANOVA) was used to evaluate postprandial courses, with Dunn's multiple comparison test to compare differences between baseline and subsequent individual time points. Area under the curve (AUC) values were calculated using the trapezoidal rule at 0 min to 180 min (total AUC), and 120 to 180 min ('postprandial phase'). *P* values below 0.05 were considered statistically significant. For visual purposes, graphs are depicted as mean ±SEM. Statistical analyses were performed using GraphPad Prism 6.0 (GraphPad Software Inc., CA, USA) and SPSS 22.0 (IBM SPSS Inc, Chicago, Illinois, USA.

RESULTS

Subjects

Detailed clinical characteristics of the included patients have been reported previously[3], and parameters relevant for the present study are summarized in **Table 1.** Clinical data and plasma samples of twenty-four patients (mean age 54±16 years, 25% female) admitted to the ICU and twelve healthy volunteers (mean age 55±20 years, 33% female) were analyzed and compared. None of the healthy volunteers had prior GI diseases or biliary sludge.

Fasted levels of bile salts are elevated in critically ill patients

The bile salt-FXR-FGF19 regulatory axis is activated after nutrients enter the small intestine and elicit gallbladder contraction. First, we studied fasted plasma levels of bile salts, FGF19 and C4 in controls and ICU patients. At baseline, bile salt levels were significantly higher in ICU patients (1.6 [0.9-2.4] vs. 3.1 [1.6-9.1] µmol/L, *P*=0.024) (**Table 2**). Baseline levels of FGF19 and C4 were comparable in both groups (*P*=0.221 and *P*=0.151, respectively) (**Table 2**). Similar to findings reported by Vanwijngaerden *et al*., fasting bile salt levels were strongly correlated with total bilirubin levels (ρ = +0.64, *P*<0.001) in our study.[21]

Lipid infusion-induced FGF19 response is impaired in critical illness

Next, we studied the bile salt and FGF19 responses in both healthy controls and critically ill patients. Note that the FGF19 response refers to lipid infusion-induced changes in circulating FGF19 levels, rather than the hepatic response to this hormone. Excursions of bile salts and FGF19 following lipid infusion are illustrated in **Fig. 1** (see Supporting Figures S1 and S2 for the individual responses). Note that previously reported gallbladder volumes were included in the graphs to illustrate changes in gallbladder volume relative to bile salt and FGF19 excursions.[3] The bile salt and FGF19 responses were significant over time in both groups (*P*<0.001) (**Fig. 2A&B**). As expected, intraduodenal lipid infusion resulted in elevation of systemic bile salts. In healthy controls, bile salt levels were elevated relative to baseline from 60 min onwards (*P* values between <0.001 and 0.049) (**Fig. 2A**). Similar to controls, bile salt levels in ICU patients were elevated compared with baseline values from 90 min onwards (*P* values between <0.001 and 0.045) (**Fig. 2A**). Median bile salt levels at 90 min were higher in healthy controls (17.8 [9.4 to 25.6] vs 7.5 [2.1 to 18.4] µmol/L, *P*=0.028) (**Fig. 2A**). Furthermore, the total AUC of bile salts was higher in controls (1659 [1117 to 2109] vs 421 [261 to 1354] AUC, *P*=0.008, **Fig. 2D**).

FG19 levels in controls were elevated at 150 min (*P*=0.003) and 180 min (*P*=0.004) compared with baseline values (**Fig. 2B**). In ICU patients, FGF19 levels were elevated relative to baseline only at 180 min (*P*=0.013) (**Fig. 2B**). FGF19 levels were markedly lower in ICU patients compared with controls at 120 min (*P*=0.031), 150 min (*P*<0.001) and 180 min (*P*<0.001) (**Fig. 2B**). The total AUC was notably lower in ICU patients compared with controls (*P*=0.001 (**Fig. 2E**).

FGF19 signalling results in repression of bile salt synthesis, as reflected by lowering of systemic C4 levels 1-2 hours after postprandial peaking of FGF19.[24] In the studied time frame, intraduodenal lipid infusion did not affect C4 levels in controls (*P*=0.289) or ICU patients (*P*=0.202) (**Fig. 2C**).

Absent or impaired gallbladder emptying is associated with an impaired FGF19 response after nutrient-stimulation

Because gallbladder contraction is followed by entry of bile salts into the duodenum, subsequent reabsorption of bile salts in the ileum causes activation of ileal FXR and stimulation of FGF19 synthesis. Thus, FGF19 synthesis follows gallbladder contraction. Note, bile salts levels at 90 min correlated positively with FGF19 levels at 180 min (ρ = +0.38, *P*=0.023) (data not shown). Our results

showed that GBEF is positively correlated (ρ = +0.34, *P*=0.045) with the AUC of FGF19 in all subjects (**Fig. 3A**). Additionally, residual gallbladder volume after 30 min (when the largest absolute volume change has occurred), was negatively correlated with the AUC of FGF19 across all subjects (ρ = -0.56, *P*<0.001) (**Fig. 3B**).

Thus, patients with absent or impaired GBEF (i.e. below <35%) (n=10) had lower FGF19 AUC values than patients with GBEF ≥35% (n=14) (*P*=0.096) (**Fig. 3C**). Note that all healthy subjects had GBEF values >71%. Moreover, gallbladder wall thickness, which is increased in patients with gallbladder dysmotility, was negatively correlated with the AUC of FGF19 (ρ = -0.39, *P*=0.019) (**Fig. 3D)**. Considering the temporal phases (i.e. prandial versus postprandial) of the nutrient-stimulated FGF19 response, it is noteworthy to mention that correlations between FGF19 AUC and GBEF, gallbladder volume at 30 min, and gallbladder wall thickness, were stronger when using (postprandial) FGF19 $AUC_{120\text{-}180\ min}$ values (**Supporting Fig. S3A-C**). The marked difference in FGF19 excursion between ICU patients with absent or impaired gallbladder emptying and controls was maintained when using postprandial $AUC_{120\text{-}180\ min}$ values (*P*<0.001) (**Supporting Fig. S3D**). Biliary sludge, observed only in the patient population, was negatively correlated with FGF19 AUC values (ρ = -0.34, *P*=0.042) and postprandial FGF19 AUC values (ρ = -0.63, *P*<0.001) (**Supporting Fig. S3E&F**).

In this study, we demonstrate that gallbladder dysmotility is associated with an impaired FGF19 response. We further investigated whether the postprandial bile salt response was also affected. First, the GBEF was not related to bile salt AUC values (ρ = +0.28, *P*=0.095) (Fig. **3E).** However**,** the residual gallbladder volume at 30 min was negatively correlated with bile salt AUC values (ρ = -0.41, *P*=0.013) (Fig. **3F**)**.** Furthermore, ICU patients with absent or impaired gallbladder emptying had lower bile salt AUC values compared with controls (*P*=0.020) (**Fig. 3G**). Finally, gallbladder wall thickness was negatively correlated with bile salt AUC values (ρ = -0.41, *P*=0.014) (**Fig. 3H**).

As can be appreciated from the individual response curves (**Supporting Fig. S2**) and AUC values (**Fig. 2D&E**), FGF19 levels are virtually unaffected by lipid infusion in a number of ICU patients. Careful examination of clinical data revealed that patients receiving norepinephrine for hemodynamic support had no appreciable FGF19 response following lipid infusion (P_{time}=0.911, **Fig. 4A**). In this patient subgroup, the median FGF19 levels were 0.076 ng/mL and 0.095 ng/mL at baseline and 180 min, respectively (**Fig. 4A)**. In contrast, patients not receiving norepinephrine had a significant FGF19 response (*P*<0.001) and levels were significantly elevated relative to baseline at 150 min (*P*=0.007) and 180 min (*P*<0.001) (**Fig. 4A)**. Finally, patients receiving norepinephrine (n=9) had lower GBEFs (11% [-4 to 45] vs 71% [48 to 87], *P*=0.029) and lower AUC of FGF19 (*P*=0.012) compared with patients without administration of norepinephrine (**Fig. 4C&D**), further delineating the association between gallbladder contraction and the nutrient-stimulated FGF19 response.

Lipid-infusion elicited significant bile salt responses in both patients receiving norepinephrine and patients not receiving norepinephrine (*P*<0.001) (**Fig. 4B**). In contrast to the FGF19 response, ICU patients receiving norepinephrine had a comparable bile salt response as patients not receiving norepinephrine (bile salt AUC value, *P*=0.433) (**Fig. 4E**).

Discussion

Critically ill patients may encounter disturbed production of bile salt-regulated enterokines. In this context, we studied intestinal FGF19 production following post-pyloric nutrient infusion in critically ill patients and compared this with responses in age- and gender-matched healthy controls. The major novel finding of this study is that the nutrient-stimulated response of FGF19 is impaired in critically ill patients. Moreover, our data support that gallbladder dysmotility is related and may be the cause of the impaired postprandial FGF19 response observed in these patients.

A previous study in humans demonstrated that low circulating FGF19 in the fasted state is associated with bile salt toxicity-related liver injury.[19] Data from the present study show that fasted serum levels of FGF19 in healthy controls and ICU patients are comparable, while ICU patients show elevated fasted bile salt levels. Similar to previous reports in critically ill patients, fasted bile salt levels were higher in ICU patients in the present cohort.[21, 22] Elevated bile salt levels in ICU patients may be explained by altered hepatic expression of bile salt transporters.[21]

Enteric passage of the bile salt pool is critical for activation of intestinal FXR and subsequent production of FGF19 in the ileum. Thus far, few studies addressed the nutrient-stimulated FGF19 response in humans.[23, 24] Similar to our earlier observations, bile salt concentrations peaked at 2 hours and FGF19 levels >3 hours after meal ingestion.[23] In addition, we observed that gallbladder emptying preceded the bile salt/FGF19 response indicating that enteral delivery of biliary bile salts induces FGF19 production. ICU patients with absent or low gallbladder emptying had low FGF19 AUC values in the postprandial phase.

Remarkably, the (post)prandial FGF19 response was virtually absent in ICU patients. The abrogated FGF19 response in ICU patients occurred despite an apparently normal postprandial plasma bile salt response, although the AUC was lower compared with healthy controls. The lack of correlation between the bile salt and FGF19 response could be explained by gallbladder dysmotility. Despite, an apparently normal plasma bile salt response, gallbladder dysmotility could contribute to reduced enteral bile salt delivery. Note that gallbladder volume at 30 min correlated negatively with the postprandial response of FGF19, indicating that high residual gallbladder volume (due to impaired emptying) is associated with low induction of FGF19 levels in the postprandial phase. Catecholamines inhibit contraction of the gallbladder by activating adrenoreceptors located in the biliary epithelium, therefore, administration of norepinephrine could contribute to impaired gallbladder emptying. Indeed, patients receiving norepinephrine had a virtually absent postprandial FGF19 response, and postprandial AUC values were significantly lower compared with ICU patients not treated with norepinephrine. However, given the systemic effects of norepinephrine and the more severe clinical condition of ICU patients receiving this drug, these results need to be interpreted with caution. Nonetheless, gallbladder dysmotility could be a contributing factor to the impaired postprandial FGF19 response. Note, additional analysis indicated that systemic inflammation, here assessed by circulating levels of IL6 at baseline, had no effect on FGF19 levels at baseline or the FGF19 response following lipid infusion (**Supporting Fig. S4**). This suggests that the intestinal FXR/FGF19 axis is not negatively affected by an acute phase response.

What other etiological factors, apart from gallbladder dysmotility, could underlie the divergent FGF19 response in ICU patients compared with healthy controls? Intestinal dysmotility is a frequent

problem observed in ICU patients.[28] Hence, diminished propagation of anterograde pressure waves in the biliary-digestive system could lead to slow delivery of bile salts to the distal part of the small intestine.[29] Furthermore, intestinal inflammation is related to low ileal *FXR* expression and therefore low FGF19 production, in pediatric intestinal failure.[30] In critical illness, bile salt malabsorption likely caused by inflammation of the intestinal epithelium could contribute to reduced FXR activation. Although, intestinal inflammation was not assessed in our study, baseline values of plasma FGF19 in controls and ICU patients showed no dissimilarities. Finally, it could also be theorized that increased critical illness-associated cell death at the intestinal level could contribute to an impaired FXR function or nuclear localization.[31] Further studies are needed to investigate the etiology underlying the impaired postprandial FGF19 response.

A key function of FGF19 is regulation of hepatic bile salt synthesis, which can be assessed by measuring systemic levels of an intermediate in the bile salt synthetic pathway, *viz*. C4. Changes in C4 levels can be used as a functional readout of FGF19 activity.[32] Note, FGF19 and C4 levels at baseline correlated across all subjects in the present study ($\rho = -0.58$, $P=0.001$) (data not shown). Postprandial changes in C4 were not apparent in either group, which is likely related to the relatively short time frame of the intervention. In an earlier study, we demonstrated that C4 levels started to decline approximately one hour after the postprandial FGF19 peak.[21] It is conceivable that FGF19 levels have not yet peaked at three hours after start of the lipid infusion. Baseline C4 levels were comparable in ICU patients and healthy controls (**Table 1**). At present it is unclear whether the postprandial FGF19 response in ICU patients is only delayed, or impaired in the long run. Similar C4 levels at baseline suggest that homeostatic control of bile salt synthesis is maintained. Studies delineating the metabolic consequences of low postprandial levels of FGF19 ICU patients are needed.

Findings from this study offer new research perspectives in care of critically ill patients. Enteral feeding of critically ill patients is still a matter of debate in terms of feeding pattern (bolus vs. continuous feeding), parenteral supply, and timing of feeding.[33] Because FXR responds to nutrients in the intestinal lumen and exerts its metabolic actions in the liver through FGF19, postprandial FGF19 could be used as an enteral nutrient tolerance marker. In fact, FGF19 is produced in the most distal part of the small intestine, whereas other intestinal hormones (e.g. PYY and GLP1/2) are secreted by entero-endocrine L cells located more proximally in the small intestine. Therefore, considering that the digestive motility of the duodenum is often normal in ICU patients, assessment of postprandial FGF19 levels may be a better alternative to evaluate functional nutritional handling.

In conclusion, we observed an impaired postprandial response of FGF19 in critically ill patients. Findings demonstrate that gallbladder dysmotility is associated with the abrogated response. Further studies are needed to study the exact etiology and long-term metabolic consequences of reduced postprandial levels of FGF19 in critical illness. Finally, use of postprandial FGF19 as a marker for enteral nutritional handling warrants further research.

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TABLES

Table 1. Patient characteristics

Item	ICU patients (n = 24)	Healthy volunteers (n = 12)	P-value

Table 2. Fasted bile salts, FGF19 and C4 levels in healthy controls and critically ill patients.

Item	Healthy controls (n = 12) median [IQR]	ICU-patients (n = 24) median [IQR]	P-value
Bile salts (μmol/L)	1.6 [0.9 to 2.4]	3.1 [1.6 to 9.1]	**0.024**
FGF19 (ng/mL)	0.10 [0.07 to 0.14]	0.08 [0.06 to 0.13]	0.221
C4 (ng/mL)	18.8 [10.3 to 31.5]	5.0 [1.0 to 28.0]	0.151
Age (years)	54 ± 16	55 ± 20	0.946
Sex			
Female (n, %)	6 (25%)	4 (33%)	0.650
Body mass index (kg/m²)	29 ± 6	24 ± 4	**0.010**
Mean blood glucose (mmol/L)	7.1 ± 2.1	5.5 ± 0.5	**0.001**
Gallbladder wall thickness (cm)	0.41 [0.37 to 0.55]	0.25 [0.20 to 0.27]	**0.000**
GEBF† (%)	51 [9 to 83]	78 [2 to 83	**0.001**
Admission diagnosis (n (%))			
Respiratory	15 (63%)	-	-
Neurological	3 (13%)	-	-
Sepsis	3 (13%)	-	-
Post-surgery	2 (8%)	-	-
Trauma	1 (4%)	-	-
APACHE II score	17 ± 6	-	-
SOFA score	8 ± 4	-	-
Day of ICU admission	5 ± 4	-	-
Vasopressor support *n* (%)	9 (38%)	-	-
Acute renal failure* *n* (%)	7 (29%)	-	-
Antibiotic support *n* (%)	19 (79%)	-	-
Hospital mortality *n* (%)	9 (38%)	-	-
Liver tests (median [IQR])			
ALT (IU/L)	34 [23 to 47]	-	-
AST (IU/L)	31 [35 to 72]	-	-
GGT (IU/L)	79 [35 to 186]	-	-
ALP (IU/L)	97 [65 to 150]	-	-
Total bilirubin (μmol/L)	7 [4 to 17]	-	-
Biliary sludge (severity score, *n*)			
0	7	12	-
1	7	-	-
2	8	-	-
3	1	-	-
4	1	-	-

*ALP, alkaline phosphatase; GEBF, gallbladder ejection fraction; APACHE, acute physiology and chronic health evaluation; GGT. Gamma-glutamyl transpeptidase; SOFA, sequential organ failure assessment. *Acute renal failure was diagnosed as per RIFLE (Risk, Injury, Failure, Loss of kidney function, End-stage kidney disease) criteria. Data are mean ± SD or median + interquartile range [IQR]. Table is adapted from Plummer et al. 2016.[3]*

TABLES

IQR, interquartile range; FGF19, fibroblast growth factor 19; C4, 7-alpha-hydroxy-4-cholesten-3-one

FIGURE LEGENDS

Fig. 1. Gallbladder volume, bile salt and FGF19 dynamics after nutrient infusion.
Gallbladder volume (black line), bile salts (grey striped line) and FGF19 (black intermittent line) dynamics during lipid infusion (0 to 120 min) and 'postprandially' (120 to 180 min) in healthy controls and ICU patients. Data points are depicted as mean ± SEM. Note, to illustrate the bile salt and FGF19 excursions, previously published gallbladder volume are depicted in this graph.[3]

Fig. 2. Plasma excursions after nutrient infusion in healthy controls and ICU patients. (A) Bile salt, **(B)** FGF19 and **(C)** C4 responses**.** Total AUC values of (**D**) bile salts and (**E**) FGF19 in controls and ICU patients. Note, the lined rectangle in **Fig. 2E** resembles FGF19 non-responders. Data points are depicted as mean ± SEM. Significant differences between controls and ICU patients at the various time points are reflected by asterisks *, P <0.05; **, P <0.01, ***, P <0.001). Box-Whisker pots with 10th to 90th percentile.

Fig. 3. Gallbladder dysmotility is associated with an impaired nutrient-stimulated FGF19 response in ICU patients. (A, E) Correlation between GBEF (%), (**B, F**) gallbladder volume (mL) and (**D, H**) gallbladder wall thickness (mm) with FGF19 or bile salt AUC values. Open circles depit data points from ICU patients and filled circles represent data from healthy controls. (**C, G**) FGF19 AUC values were compared between ICU patients with normal gallbladder emptying, absent or impaired emptying, and controls.

Fig. 4. ICU patients receiving norepinephrine are associated with a virtually blunted FGF19 response.
(A) Plasma course of FGF19 and (**B**) bile salts in ICU patients with and without norepinephrine administration and comparison of (**C**) GBEF and (**D**) FGF19 and (**E**) bile salt AUC values between ICU patients receiving and not receiving norepinephrine. Significant differences between ICU patients with and without norepinephrine at the various time points are reflected by asterisks *, P <0.05 and **, P <0.01.

Figure 1

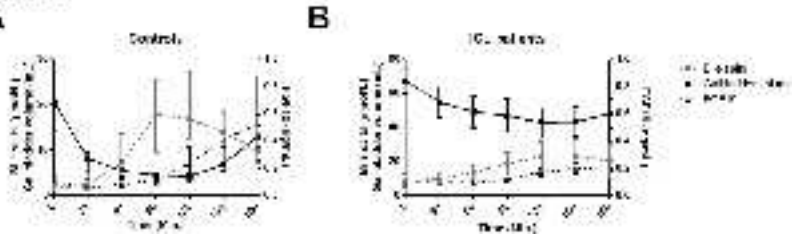

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Figure 2

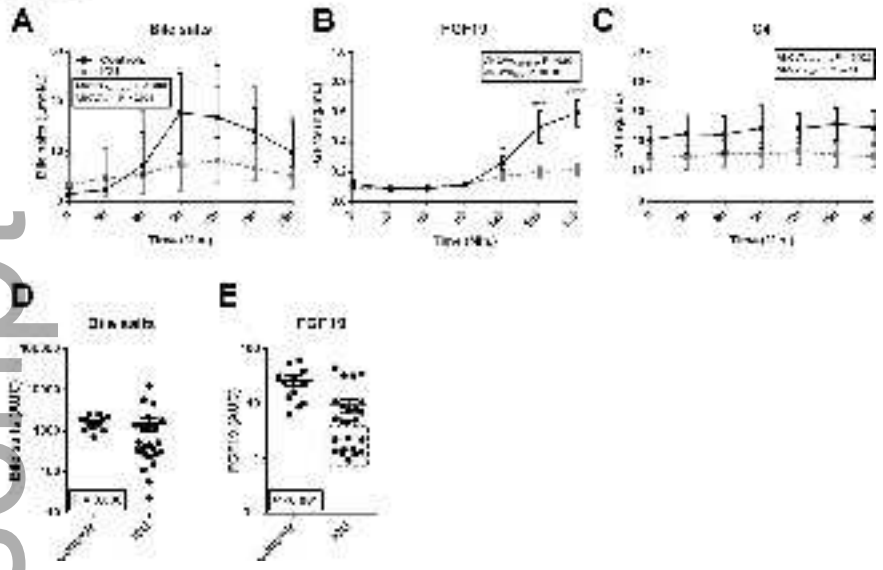

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Figure 3

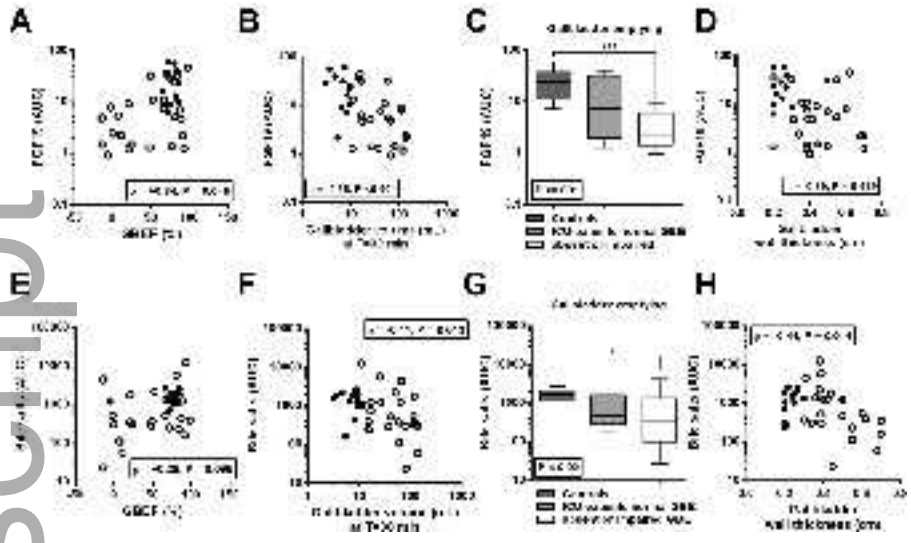

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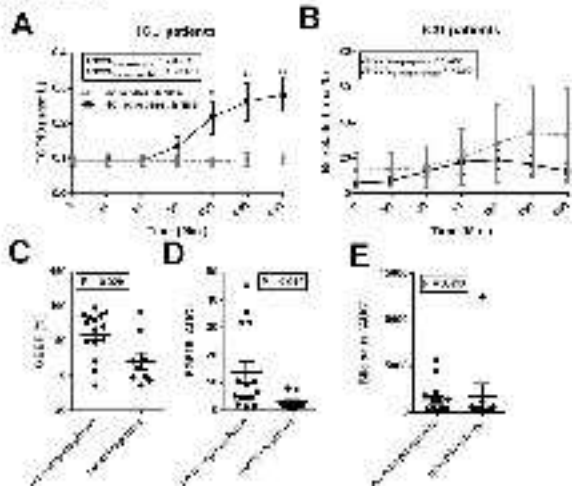
Figure 4



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