Proteinase-activated Receptor 1 Contributed to Up-regulation of Enkephalin in Keratinocytes of Patients with Obstructive Jaundice

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ABSTRACT

Background: Skin synthesis of endogenous opioids such as enkephalin is considered to be increased in cholestatic rodents, which may induce antinociception in cholestatic liver disease. No studies have reported yet the expression of skin enkephalin in patients with cholestasis.

Methods: Electrical pain threshold, postoperative morphine consumption, and skin enkephalin expression were measured in patients with jaundice (n = 18) and control patients (n = 16). Male Sprague–Dawley rats (n = 52) and human keratinocyte cell line HaCaT were used in vivo and in vitro studies, respectively. Nociceptive thresholds and plasma and skin levels of methionine-enkephalin were compared in protease-activated receptors-1–antagonized and control bile duct–ligated rats. In in vitro study, the effect on thrombin-induced enkephalin expression was examined and the role of extracellular regulated protein kinases 1/2 and p38 was investigated.

Results: The authors found that: (1) the electrical pain threshold (mean ± SD) was 1.1 ± 0.1 mA in control patients, whereas it was significantly increased in patients with jaundice (1.7 ± 0.3 mA); 48-h postoperative morphine consumption was approximately 50% higher in the control group than that in the group with jaundice; (2) Skin keratinocytes enkephalin expression was increased in the patients with jaundice; (3) Protease-activated receptors-1 antagonist 1 μg·kg⁻¹·day⁻¹ treatment to the bile duct–ligated rats significantly reduced plasma levels of methionine-enkephalin, nociceptive thresholds, and keratinocytes enkephalin expression; and (4) protease-activated receptors-1 activation induced enkephalin expression through phosphorylation of extracellular regulated protein kinases 1/2 and p38 in keratinocytes.

Conclusion: Protease-activated receptors-1 activation in peripheral keratinocytes may play an important role in the local synthesis of enkephalin during cholestasis. (Anesthesiology 2014; 121:127-39)

I t is well known that cholestatic liver disease is associated with increased levels of circulating endogenous opioids.¹² In patients and rodents with cholestasis, previous studies reported that the magnitude of the increase in plasma methionine-enkephalin levels ranged from two- to six-folds.²⁻⁴ Increased plasma endogenous opioid peptides not only impair the cardiovascular, liver, and renal functions⁵⁻⁷ but also induce pruritus and antinociception in cholestatic liver disease.⁸⁻⁹ In previous studies, we have also shown that the intraoperative requirements of desflurane, isoflurane, and remifentanil in patients with obstructive jaundice were decreased significantly compared with those in controls without jaundice.¹⁰⁻¹¹ However, little is still known about the mechanism of increased endogenous opioid synthesis in cholestatic liver diseases.

Recently, Nelson et al.¹² reported that increased synthesis of enkephalin in the skin, the body’s largest organ, may play a vital role in cholestasis-associated antinociception. Endogenous opioid peptides such as methionine-enkephalin was found in normal human skin keratinocytes, and its expression was significantly increased in patients with jaundice.¹² It also has been reported that during cholestasis, skin enkephalin expression and nociceptive thresholds are increased. The administration of protease-activated receptors-1 antagonist reduced skin enkephalin expression. Protease-activated receptors-1 receptor activation increases skin enkephalin expression and may serve as a novel therapeutic option for treatment of postoperative pain.

What We Already Know about This Topic

• In patients with biliary tract obstruction and jaundice, pain perception is significantly reduced and the means underlying this reduction in pain are not clear.

What This Article Tells Us That Is New

• In patients with cholestasis who were scheduled to surgery, postoperative morphine consumption was decreased. In skin biopsies, expression of enkephalin was significantly increased.

• In a parallel rodent study, in rats with experimentally induced cholestasis, skin enkephalin expression and nociceptive thresholds were increased. The administration of protease-activated receptors-1 antagonist reduced skin enkephalin expression.

• Protease-activated receptors-1 receptor activation increases skin enkephalin expression and may serve as a novel therapeutic option for treatment of postoperative pain.
expression could be up-regulated by chemical or physical stimuli. No human studies have reported yet skin enkephalin expression pattern in patients with cholestasis.

Previous studies have also shown that thrombin, a pluripotent serine protease which is generated in acute and chronic liver injury, can specifically increase skin keratinocyte proenkephalin messenger RNA (mRNA) expression through the activation of protease-activated receptors-1 (PAR₁). In fact, thrombin generation was increased in patients with obstructive cholestasis and it could be decreased by biliary drainage. In bile duct–ligated (BDL) rodents, PAR₁ antagonist could even protect against liver fibrosis, suggesting that PAR₁ was potentially activated in cholestatic liver diseases. These findings prompted us to test the hypothesis that thrombin, which is generated in cholestatic liver disease, can activate downstream PAR₁ signaling pathways and contribute to the increased peripheral endogenous opioids in chronic liver diseases.

Materials and Methods

Patients

This study was approved by the Institutional Ethics Committee (Eastern Hepatobiliary Surgery Hospital, Shanghai, China) and conducted from January 9, 2012 to June 13, 2012. Informed consent was obtained from each patient scheduling for elective surgery. Eighteen consecutive men with obstructive jaundice (serum total bilirubin level >20 μM) caused by a tumor in the bile duct or in the head of the pancreas were included in the study. Sixteen men with tumor in the head of the pancreas without jaundice (serum total bilirubin level <20 μM) were recruited as controls. All patients had American Society of Anesthesiologists physical status I or II. Exclusion criteria were (1) age greater than 70 yr or less than 20 yr; (2) body mass index greater than 30 kg/m²; (3) diabetes mellitus, cardiovascular, respiratory, or renal diseases; (4) hepatic encephalopathy, psychiatric illnesses, or neuropathy; (5) history of acute or chronic pain; and (6) medications known to affect pain threshold or a history of either alcohol or drug abuse. Abdominal skin tissue was obtained after elective surgery for immunohistochemistry analysis. The method used for measuring postoperative morphine consumption was the same as that described in the study by Lee et al. The patient-controlled analgesia device was set to deliver 1 mg of morphine as an intravenous bolus, with a lockout time of 8 min and no background infusion or limits. Then, first 48-h postoperative morphine consumption was recorded.

Animals

Male Sprague–Dawley rats (weighing, 220 to 250 g) were purchased from Shanghai SLAC Laboratory Animal Co. (Shanghai, China). All rats were maintained at a specific pathogen-free laboratory condition with 12-h light–dark cycles and had free access to food and water until the night before anesthesia. All animals received humane care, and the study protocol was approved by the Second Military Medical University Animal Care and Use Committee, China.

Bile Duct Ligation

The rats were either bile duct resected or sham-resected with isoflurane anesthesia as previously described. Cholestasis was confirmed by increased serum level of bilirubin as well as intact bile duct ligature and proximal dilation of the common bile duct at the time of sacrifice.

PAR₁ Antagonist SCH79797 Treatment

The rats were divided into five groups. Sham-operated group (SCH79797 1 μg·kg⁻¹·day⁻¹, n = 8), BDL group 1 (SCH79797 1 μg·kg⁻¹·day⁻¹, n = 12), and BDL group 2 (SCH79797 0.3 μg·kg⁻¹·day⁻¹, n = 12) were given SCH79797 (TOCRIS Bioscience, Bristol, United Kingdom) by daily subcutaneous injections for 4 continuous days, with the first injection starting at day 4 after surgery. Sham control group (n = 8) and BDL control group (n = 12) underwent administration of the same volume of sterile saline solution on the same days.

Measurement of Nociceptive Thresholds

Cutaneous Electrical Pain Threshold.

The pain threshold in human subjects after electric stimulation was measured by using a constant current stimulator (EP601C; Scientific and Educational Instrument Factory, Shanghai, China). Surface skin electrodes were placed caudal to the lateral malleolus at the innervation area of the sural nerve. The intensity of the electrical stimuli was raised (0.2 mA/s) until the subject reported pain feelings, then the stimulus intensity was recorded as pain threshold. Measurements were recorded three times in a 5-min interval and the mean values were used for analysis.

Mechanical Withdrawal Threshold.

Nociceptive responses to mechanical stimulation in rats were assessed by applying a series of von Frey filaments (Stoelting, Wood Dale, IL) with logarithmically incremental stiffness (from 0.41 to 15.10 g) as previously described. The 50% withdrawal threshold was calculated as the final mechanical withdrawal threshold.

Thermal Withdrawal Latency.

Nociceptive responses to thermal stimuli in rats were assessed by measuring paw-withdrawal latency in response to a radiant heat stimulus using a plantar test apparatus (Ugo Basile, Comerio, Italy). A maximum cutoff of 25 s was set to prevent tissue damage.

Measurement of Liver Enzymes and Plasma Levels of Thrombin–Antithrombin Complex and Methionine-Enkephalin

Plasma levels of total bilirubin, alanine aminotransferase, and aspartate aminotransferase were determined by using an automated analyzer (JEOL, Tokyo, Japan). Thrombin–antithrombin complex as a surrogate marker of thrombin...
generation was measured by using enzyme-linked immuno-
sorbent assay kits from USCNK (Wuhan, China). Plasma
level of methionine-enkephalin was measured by radioim-
unoassay kits from the Second Medical University
(Shanghai, China).

**Real-time Reverse-transcription Polymerase Chain
Reaction**

Total RNA was extracted from the liver and paw skin
tissue of the rats as well as cultured keratinocytes using TRIzol
(Invitrogen, Grand Island, NY) according to the manu-
facturer’s guidelines. One microgram of total RNA was
reverse-transcribed by using PrimeScript RT reagent kits
(TakaRa Biotechnology, Dalian, China). Real-time poly-
merase chain reaction (PCR) was performed using SYBR
Green PCR kits (Applied Biosystems, Foster City, CA) and
ABI 7900HT Fast Real-Time PCR System (Applied Biosys-
tems). Primers used are listed in table 1. Each target gene
expression level was normalized to the 18S ribosomal RNA
gene expression.

**Immunoblotting Analysis**

Fresh tissue of rat paw skin, liver, and cultured keratino-
cyes was homogenized in mammalian protein extrac-
tion reagent (Thermo Fisher Scientific, Rockford, IL)
plus Halt protease inhibitor cocktail (Thermo Fisher Sci-
entific). Blots were probed with the antibody of proen-
kephalin (1:100; Santa Cruz Biotechnology, Santa Cruz,
CA), phospho-extracellular–regulated protein kinases 1/2
(ERK1/2), and p38 (1:1,000; Cell Signaling Tech-
ology, Beverly, MA) at 4°C overnight. Beta-actin (Abcam, Cam-
bridge, MA) was used as an internal control. Immunore-
active proteins were visualized using chemiluminescent
substrate kits (Thermo Fisher Scientific) and recorded using
an image analyzer (Syngene, Cambridge, United Kingdom).
Analysis was performed on scanned images of blots using the
Image J software.*

**Immunohistochemical Evaluation**

Human abdominal and rat hind paw skin were embedded in
paraffin and sectioned into 8-μm-thick slices. The slices were
deparaffinized with dimethylbenzene and ethanol solutions.
Epitope retrieval was performed by incubating the slices for
20 min in 0.02 M citrate buffer (pH 6.0) heated to 97°C.
Immunohistochemical staining for methionine-enkephalin
(1:500; Immunostar, Hudson, WI) was performed using the
peroxidase complex kits and diaminobenzidine reagent were
obtained from Maxin Biotechnology Inc. (Fujian, China).
The slices were then lightly counterstained with hematoxylin
for microscopic examination. All the slides were observed
and photographed under an Olympus microscope (IX-70
OLYMPUS, Tokyo, Japan).


**Table 1.** Primer Sequences for Real-time Reverse-transcription
Polymerase Chain Reaction

<table>
<thead>
<tr>
<th>Target Gene</th>
<th>Primer Sequence (5' to 3')</th>
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<tbody>
<tr>
<td>Human PENK, forward</td>
<td>CGGTTCCCTGACACTTTGCACT</td>
</tr>
<tr>
<td>Human PENK, reverse</td>
<td>CACATCCATTTGCAAAGCCA</td>
</tr>
<tr>
<td>Human PDYN, forward</td>
<td>GCGGTCCCTTCTAGTTC</td>
</tr>
<tr>
<td>Human PDYN, reverse</td>
<td>CCTTCCCACACCGACTT</td>
</tr>
<tr>
<td>Human POMC, forward</td>
<td>GCGGACGTAAGGGTGTCACCTAA</td>
</tr>
<tr>
<td>Human POMC, reverse</td>
<td>TCTTGGCTTCTGAGGATG</td>
</tr>
<tr>
<td>Rat PENK, forward</td>
<td>GTGCGAAAGATAGGCAACCA</td>
</tr>
<tr>
<td>Rat PENK, reverse</td>
<td>CTGTGATAGCCATCCACCA</td>
</tr>
<tr>
<td>18S ribosomal RNA, forward</td>
<td>CGCGTACACATCCAAGGAA</td>
</tr>
<tr>
<td>18S ribosomal RNA, reverse</td>
<td>GCTGGAATTACCGCGGCT</td>
</tr>
</tbody>
</table>

PDYN = prodynorphin; PENK = proenkephalin; POMC = proopiocortisol.

**Culture of Human Keratinocyte**

HaCaT cells were cultured in Dulbecco’s Modified Eagle Medium supplemented with 10% fetal bovine serum, 100
units/ml penicillin, and 100 μg/ml streptomycin at 37°C in
5% CO2 atmosphere.26

**Challenge of HaCaT with Thrombin or PAR1, Agonist TFFLR-NH2**

Before challenge, the cells were plated in six-well culture plates and serum-starved overnight. The cells were first
challenged with increasing concentrations of thrombin
(Sigma, St. Louis, MO) (0.1, 1, and 5 U/ml) in a serum-
free medium for 6 h and then 24 h. To explore the role of
PAR1, in thrombin-induced proenkephalin expression, cells
were incubated with PAR1 antagonist SCH77977 (5 μM)
30 min before being challenged with thrombin (5 U/ml)
or PAR1 agonist TFFLR-NH2 (100 μM; TOCRIS Bioscience)
for 6 h.

**Immunoblotting Analysis of ERK1/2 and P38 Mitogen-activated Protein Kinase Pathways in Keratinocyte upon PAR, Activation**

Keratinocytes were plated in six-well culture plates and
serum-starved overnight and then treated with thrombin
(5 U/ml), SCH77977 (5 μM), and TFFLR-NH2 (100 μM)
for 6 h. The levels of phospho-ERK1/2 and phospho-p38
were examined. To block ERK1/2 and p38 activation, U0126
(10 μM; Cell Signaling Technology) and SB203580 (20
μM; Cell Signaling Technology) were incubated 1 h before
being challenged with thrombin (5 U/ml), TFFLR-NH2
(100 μM), and SCH77977 (5 μM) for 6 h.

**Statistical Analysis**

Data are expressed as mean ± SD or mean ± SEM. Analy-
sis was performed using SPSS 16.0 (IBM SPSS Statis-
tics, Chicago, IL). Comparisons between two groups
were analyzed using Student t test. Data on mechanici-

cal and thermal pain thresholds were analyzed by two-
way repeated-measures ANOVA followed by Bonferroni
Results

Electrical Pain Threshold, Postoperative Morphine Consumption, and Skin Methionine-enkephalin Expression in Patients with Obstructive Jaundice

The two groups were not different in age, weight, and body mass index (table 2). Serum concentrations of total bilirubin, bile acids, and alanine aminotransferase were significantly higher in patients with jaundice (table 2). Preoperative pain threshold in response to electrical stimuli was also shown in figure 1A; in control patients, electrical pain threshold was 1.1 ± 0.1 mA, whereas it was significantly increased in patients with jaundice (1.7 ± 0.3 mA). The 48-h morphine consumption was significantly reduced in the patients with jaundice compared with that in the control group (fig. 1B). Immunohistochemistry analysis of the skin tissues revealed that in patients with obstructive jaundice, methionine-enkephalin was strongly expressed in the stratum spinosum and stratum basale of the epidermis, which are mainly constituted by the keratinocytes (fig. 2).

Animal Model of Cholestasis

The BDL rats developed biochemical evidence of liver injury and cholestasis as demonstrated by increases in total bilirubin, alanine aminotransferase, and aspartate aminotransferase compared with the sham control rats at day 8 (table 3). The concentration of thrombin–antithrombin complex in plasma was also significantly increased in the BDL rats as compared with that of the sham control rats at day 8 (table 3).

PAR<sub>1</sub> Antagonism Reduced Skin Enkephalin Expression in the BDL Rats

We next examined the potential effects of PAR<sub>1</sub> antagonism on skin and liver enkephalin expressions in the BDL rats. Immunoblotting and PCR results suggested that both skin proenkephalin mRNA and protein expression in the BDL control group significantly increased as compared with those of the sham control group, whereas PAR<sub>1</sub> antagonism reduced the increased skin proenkephalin synthesis in the BDL group 1 rats (fig. 3, A and B). Preabsorption test (fig. 3C) with human recombinant proenkephalin protein confirmed the specificity of the primary antibody in immuno blotting analysis. Immunohistochemistry of the sections of rat glabrous hind paw skin revealed that methionine-enkephalin was strongly expressed in the keratinocytes of the epidermis in the BDL control rats, evidenced by the brown stripe spanning through the stratum spinosum and stratum basale of the epidermis (fig. 3D), whereas PAR<sub>1</sub> antagonism treatment (SCH79797, 1 μg·kg<sup>-1</sup>·day<sup>-1</sup>) reduced methionine-enkephalin expression in the keratinocytes of the epidermis of the BDL group 1 rats. Immunoblotting and PCR results revealed that liver proenkephalin mRNA and protein expression in the BDL control group were higher than those in the sham control group; PAR<sub>1</sub> antagonism treatment (SCH79797, 1 μg·kg<sup>-1</sup>·day<sup>-1</sup>) had no effect in reducing the increased liver enkephalin synthesis in the BDL group 1 rats (fig. 4).

PAR<sub>1</sub> Antagonism Decreased Nociceptive Thresholds and Plasma Levels of Methionine-enkephalin in the BDL Rats

As previously described, BDL caused increased nociceptive threshold in response to both thermal and mechanical

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**Table 2. Demographic Data**

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Obstructive Jaundice</th>
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<tbody>
<tr>
<td>n</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>Age, yr</td>
<td>53.6 ±9.0</td>
<td>55.2 ±9.6</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>63.2 ±4.7</td>
<td>64.1 ±10.3</td>
</tr>
<tr>
<td>BMI, kg/m&lt;sup&gt;2&lt;/sup&gt;</td>
<td>21.8 ±1.2</td>
<td>23.0 ±3.1</td>
</tr>
<tr>
<td>Total bilirubin, μmol/l</td>
<td>10.5 ±3.4</td>
<td>183.6 ±117.8</td>
</tr>
<tr>
<td>Bile acids, μmol/l</td>
<td>9.4 ±6.3</td>
<td>70.3 ±49.8</td>
</tr>
<tr>
<td>Albumin, g/l</td>
<td>42.4 ±2.5</td>
<td>36.6 ±3.9</td>
</tr>
<tr>
<td>ALT, U/l</td>
<td>26.8 ±14.5</td>
<td>143.3 ±85.3</td>
</tr>
</tbody>
</table>

All values except n are expressed as mean ± SD.

ALT = alanine aminotransferase; BMI = body mass index.
We further tested whether PAR1 antagonist can lower the nociceptive thresholds in BDL rats. Sham surgery did not significantly modify nociceptive response to thermal or mechanical stimuli through the study period in the sham control rats (data not shown), whereas mechanical (fig. 5A) and thermal (fig. 5B) nociceptive thresholds of the BDL control rats significantly increased from day 6 to day 8 as compared with baseline (day 0). After subcutaneous injection of PAR1 antagonist SCH79797 (1 $\mu$g·kg$^{-1}$·day$^{-1}$) starting on day 4 for 4 consecutive days, both thermal and mechanical nociceptive thresholds were decreased in the BDL group 1 rats with no significant difference between day 8 and baseline for both thermal and mechanical thresholds. SCH79797 at a dose of 0.3 $\mu$g·kg$^{-1}$·day$^{-1}$ did not reduce the increased nociceptive thresholds in BDL group 2 rats compared with baseline (fig. 5, A and B). SCH79797 at 1 $\mu$g·kg$^{-1}$·day$^{-1}$ did not alter nociceptive threshold in the sham-operated rats.

As shown in figure 5C, plasma level of methionine-enkephalin was significantly higher in the BDL control rats than that of the sham control rats at day 8. After subcutaneous injection of PAR1 antagonist SCH79797 (1 $\mu$g·kg$^{-1}$·day$^{-1}$) for 4 consecutive days, the BDL group 1 rats showed reduced plasma methionine-enkephalin level compared with that in the BDL control group, whereas the comparison between the BDL group 2 and the BDL control group showed no statistical significance.

**Thrombin Induced Proenkephalin Expression through PAR1 in Cultured Keratinocytes**

Next, we investigated whether PAR1 agonist thrombin was able to increase the expression of the three endogenous opioid precursors, namely, proenkephalin, proopiomelanocortin, and prodynorphin in HaCaT cells. Thrombin at concentrations of 0.1, 1, and 5 U/ml provoked a dose-dependent increase in proenkephalin mRNA expression in cultured HaCaT cells after 6- and 24-h incubation periods (fig. 6A). An approximately 4.5-fold increase in proenkephalin mRNA expression was observed when cells were incubated with 5 U/ml of thrombin for 24 h. Thrombin at the concentration of 5 U/ml failed to stimulate proopiomelanocortin and prodynorphin mRNA expressions after a 6- or 24-h incubation period (fig. 6, B and C). Immunoblotting analysis in HaCaT cells also revealed that thrombin increased proenkephalin protein synthesis in a dose-dependent manner after 6- and then 24-h incubation periods (fig. 6D). Preabsorption test (fig. 6E) with human recombinant proenkephalin protein also confirmed the specificity of the primary antibody in immunoblotting analysis.

As thrombin could also activate PAR2 and PAR3, we used TFLLR-NH$_2$, a selective agonist peptide of PAR1, to investigate whether thrombin could also activate PAR2 and PAR3.
at a concentration of 100 μM, which was able to induce an up to three-fold increase in proenkephalin protein expression in cultured HaCaT cells after a 6-h incubation period, whereas PAR_1 antagonist SCH79797 at a concentration of 5 μM abolished both thrombin- (5 U/ml) and TFLLR-NH_2-induced expression of proenkephalin mRNA and protein at 6 h after incubation (fig. 7, A and B).

PAR_1 Activation Induced Proenkephalin Expression through ERK1/2 and p38 Mitogen-activated Protein Kinase Pathways in HaCaT Cells

Thrombin (5 U/ml) and TFLLR-NH_2 (100 μM) induced phosphorylation of ERK1/2 and p38 mitogen-activated protein kinase (MAPK) in cultured HaCaT cells after a 6-h incubation period. PAR_1 antagonist SCH79797 (5 μM) not only

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**Fig. 3.** Effects of protease-activated receptors-1 antagonism on enkephalin expression in the paw skin tissues of bile duct-ligated (BDL) rats. Eight days after surgery, preproenkephalin messenger RNA (mRNA) (A) and proenkephalin protein (B) expression were evaluated by real-time reverse-transcription polymerase chain reaction and immunoblotting analysis in the paw skin tissues of the BDL and sham-operated rats. Results represent an increase in order of magnitude as compared with sham-operated rats (means ± SEM, n = 6 in each group). Preproenkephalin mRNA and proenkephalin protein expression were increased in the skin of the BDL rats compared with those of the sham-operated rats, and this increase was reduced by SCH79797 (1 μg·kg⁻¹·day⁻¹) administration. (C) Western blot results for BDL rat paw skin tissue samples before (not preabsorbed [NP]) and after (preabsorbed [P]) preabsorption with human recombinant proenkephalin protein (2 μg/ml; Abnova, Taiwan, China). The band was attenuated when the antibody was preabsorbed with human proenkephalin recombinant protein, implying contribution from primary antibody to this binding pattern. (D) Immunohistochemistry for methionine-enkephalin in paw skin tissues shows that compared with the sham-operated rats, the distribution of methionine-enkephalin–positive staining cells in the BDL rats spans through stratum spinosum and extend into stratum basale of the epidermis. SCH79797 (1 μg·kg⁻¹·day⁻¹) administration reduced methionine-enkephalin expression in epidermis of the BDL rats, whereas it had no effects in the sham-operated rats. Sch = SCH79797 1 μg·kg⁻¹·day⁻¹. 
inhibited thrombin- and TFLLR-NH₂-induced phosphorylation of ERK1/2 but also abolished thrombin- and TFLLR-NH₂-induced phosphorylation of p38 MAPK (fig. 8, A and B).

To examine whether PAR₁ induced proenkephalin expression through activating ERK1/2 and p38 MAPK, cultures of HaCaT cells were incubated with U0126 or SB203580, then challenged with thrombin or TFLLR-NH₂. After a 6-h incubation period, U0126, an ERK inhibitor at the concentration of 10 μM, attenuated both thrombin- (5 U/ml) and TFLLR-NH₂- (100 μM) induced proenkephalin expression. SB203580 (20 μM), a selective inhibitor of p38 MAPK, also showed inhibitory action on thrombin- or TFLLR-NH₂-induced proenkephalin expression (fig. 8C).

Discussion

In the current study, we observed that skin keratinocytes enkephalin expression and pain threshold were significantly increased in both patients with obstructive jaundice and cholestatic rats. Subcutaneous administration of PAR₁ antagonist not only reduced the enkephalin synthesis in the skin keratinocytes but also decreased the plasma level of methionine-enkephalin and nociceptive thresholds in cholestatic rats. However, the same amount of PAR₁ antagonist did not alter nociceptive thresholds and peripheral enkephalin expression in the sham-operated rats. In in vitro experiments, thrombin- and PAR₁ agonist–induced enkephalin expression was observed in cultured keratinocytes, and the contribution of ERK1/2 and p38 MAPK pathways to the enkephalin expression induced by PAR₁ activation was determined in cultured keratinocytes.

In accordance with the study by Nelson et al.,¹² we measured the nociceptive thresholds at days 4, 6, and 8 after BDL surgery in this study, and several studies had proved that there was no significant difference between BDL models and controls on locomotor activity, rearing and grooming behaviors, defecations, and body weight within 10 to 13 days after BDL surgery.²⁷⁻²⁹ Hence, it can be conclude that the change in nociceptive thresholds in BDL model within 8 days in our study is due to a specific change in pain transmission rather than a sign of lethargy or malaise.

Enkephalin in vivo was breakdown by action of two zinc metallopeptidases—the neutral endopeptidase neprilysin (NEP) and aminopeptidase N (APN).³⁰ According to previous researches, both NEP and APN were supposed to be increased in both patients with cholestasis and animal models.³¹⁻³³ This suggests that enkephalin degradation is actually increasing during cholestasis; the increased circulating enkephalin level in cholestasis is mainly due to increased production of enkephalin in vivo. Regarding on the relations among thrombin, NEP, and APN, previous researches also reported that thrombin could induce up-regulation of NEP in human umbilical vein endothelial cells and stimulate APN activity in human glomerular mesangial cells.³⁴,³⁵ Hence, the treatment of PAR₁ antagonism in our study should be reducing the NEP and APN activity and increasing the enkephalin levels in BDL models. However, this contrasted with our observation that PAR₁ antagonism reduced the enkephalin level in BDL model, suggesting that the effect of PAR₁ antagonism on NEP and APN activity is not the primary therapeutic effect.
Consistent with previous investigations,36,37 in this study, we also found that liver enkephalin expression is increased in BDL rats. And PAR1 antagonism had no effect in reducing the increased liver enkephalin synthesis in BDL rats. This means that PAR1 antagonism decreased plasma levels of methionine-enkephalin in the BDL rats may mainly affect skin keratinocytes rather than hepatocytes. Results from other recent studies12,38 also support the idea that cholestasis is associated with increased cutaneous production of endogenous opioids. Moreover, previous studies have identified opioid receptors on the cutaneous nerve endings, and opiates or local endogenous opioids have been shown to induce antinociception by activating these receptors.39–41 In cholestatic rodents, it had been proven that intraplantar injection of naloxone methiodide could reverse the increased pain thresholds which we had observed in this study.12 Because naloxone methiodide only blocks receptors on peripheral nerve endings, this strongly suggesting that increased skin endogenous opioid peptides during cholestasis may mediate the cholestasis-associated antinociception through activating these cutaneous nociceptors.

Thrombin is generated during the time of tissue damage in several organs including liver and participates in the process of tissue repair through proteolytic activation of PAR1, PAR3, and PAR4.42,43 Recent studies revealed that endogenous activation of PAR1 can induce analgesia by triggering production of skin proenkephalin in vivo,18 suggesting that in pathological conditions when an endogenous PAR agonist such as thrombin is increased, there may be an endogenous pathway of nociception control through...
PAR₁ activation. In this study, we found that the BDL rats presented higher level of thrombin generation than that by the sham-operated rats at day 8, demonstrated by increased plasma level of thrombin–antithrombin complex. This was consistent with the results of previous clinical trials, whereby generation of thrombin was increased in the presence of cholestasis in patients with obstructive jaundice. Hence, it can be inferred that the increased peripheral opioidergic tone

Fig. 6. Effect of thrombin on proenkephalin, proopiomelanocortin, and prodynorphin expression in Hacat cells. Cells were incubated with various concentrations of thrombin at 37°C for a period of 6 and 24 h, respectively. Preproenkephalin (A), proopiomelanocortin (B), and prodynorphin (C) messenger RNA (mRNA) expressions were evaluated by real-time reverse-transcription polymerase chain reaction (n = 6 in each group). Proenkephalin protein expression (D) was evaluated by immunoblotting analysis (n = 4 in each group). These results show that thrombin up-regulated mRNA and protein expression of proenkephalin, and thrombin had no effect on proopiomelanocortin and prodynorphin mRNA expression. (E) Western blot results for Hacat cell lysate samples before (not preabsorbed [NP]) and after (preabsorbed [P]) preabsorption with human recombinant proenkephalin protein (2 μg/ml). The band was attenuated when the antibody was preabsorbed with human proenkephalin recombinant protein, implying contribution from primary antibody to this binding pattern. Data are expressed as mean ± SEM. Ctr = control.

Fig. 7. Effects of protease-activated receptors-1 (PAR₁) antagonist on thrombin- or TFLLR-NH₂-induced proenkephalin expression in HaCaT cells. Cells were incubated with thrombin (5 U/ml), PAR₁ antagonist SCH79797 (5 μM), PAR₁ agonist TFLLR-NH₂ (100 μM), at 37°C for a period of 6 h. Proenkephalin messenger RNA (mRNA) (A) and protein (B) expressions were evaluated by real-time reverse-transcription polymerase chain reaction (n = 5 in each group) and immunoblotting analysis (n = 4 in each group). Results indicate that PAR₁ agonist and thrombin increased proenkephalin expression in HaCaT cells, whereas SCH79797 inhibited thrombin-induced proenkephalin mRNA and protein expression. Data are expressed as mean ± SEM. Ctr = control; Sch = SCH79797; TF = TFLLR-NH₂; Th = thrombin.
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is mediated by the endogenous activation of PAR₁ in the course of cholestasis, and PAR₁ antagonism may be a treatment strategy for increased endogenous opioid-associated complications in cholestatic diseases.

Keratinocytes are abundant in skin and have been reported to express PAR₁. In addition, keratinocytes express three opioid precursors, namely proopiomelanocortin, proenkephalin, and prodynorphin. In the current study, we observed increased expression of methionine-enkephalin in keratinocytes in the epidermis of patients with jaundice and the BDL rats, and it was reduced by PAR₁ antagonism in the BDL rats. This result suggests that PAR₁ activation in BDL may stimulate releasing of enkephalin from keratinocytes, which in turn produces antinociception by acting on opioid receptors of the cutaneous nerve endings. In the in vitro study, PAR₁ activation only induced higher expression of proenkephalin in keratinocytes, whereas proopiomelanocortin and prodynorphin mRNA expressions showed no change. This result was consistent with previous reports and may explain why the magnitude of the increased activity of plasma methionine-enkephalin was highest after BDL. It was also reported that PAR₁ and PAR₃ are both expressed in keratinocytes as thrombin receptors, but the relation between PAR₃ and opioid pathway has not been reported. In the in vitro study, we found that PAR₁ antagonist ameliorated thrombin-induced proenkephalin expression, suggesting that this effect is mainly mediated by PAR₁ in cultured keratinocytes.

To further explain the mechanism on enkephalin synthesis in keratinocytes, two major downstream MAPK

Fig. 8. Protease-activated receptors-1 (PAR₁) activation induced proenkephalin expression through phosphorylation of extracellular regulated protein kinases 1/2 (ERK1/2) and p38 in HaCaT cells. Cells were incubated with thrombin (5 U/ml), SCH79797 (5 μM), TFLNR-NH₂ (100 μM) at 37°C for 6 h. (A) Phospho-ERK1/2 (p-ERK1/2) expression was increased after thrombin and TFLNR-NH₂ incubation for 6 h, whereas SCH79797 coincubation abolished this effect. (B) PAR₁ antagonist SCH79797 also inhibited thrombin- and TFLNR-NH₂-induced phosphorylation of p38. Cells were incubated with thrombin (5 U/ml), TFLNR-NH₂ (100 μM), U0126 (10 μM), SB203580 (10 μM) at 37°C for 6 h. Results show that proenkephalin expression was increased after PAR₁ agonist TFLNR-NH₂ incubation, and this increase was reduced by U0126 and SB203580. The values shown are mean ± SEM for four separate experiments performed in duplicate. Ctr = control; SB = SB203580; Sch = SCH79797; TF = TFLNR-NH₂; Th = thrombin.
cascades, namely, mitogen-activated ERK1/2 and stress/ 
cytokine-activated p38 were examined. Thrombin and PAR1 
agonist TFLLR-NH2, activated p38 and ERK1/2 in kerati-
nocytes, and the addition of PAR1 antagonist SCH77977 
almost abolished thrombin-induced phosphorylation of 
p38 and ERK1/2, suggesting that thrombin activates p38 
and ERK1/2 MAPK pathways mainly through PAR1. These 
results are consistent with a recent study on dermal fibro-
basts, which found that thrombin induced interleukin-8 
release via activation of ERK1/2 and p38 MAPK signaling 
pathways.48 On the basis of the established theory that pro-
enkephalin expression may be regulated by p38 and ERK1/2 
MAPK pathways,49 we sought the direct link between p38 
and ERK1/2 MAPK activation and proenkephalin expres-
sion in keratinocytes by using phosphorylation inhibitors 
U0126 and SB203580. We observed that proenkephalin 
expression induced by thrombin and PAR1 agonist was 
reduced when incubated with U0126 or SB203580, which 
suggests that p38 and ERK1/2 MAPK pathways are directly 
involved in the process of PAR1 activation–induced proen-
kephalin expression in keratinocytes.

In some newly published clinical trial studies, PAR1 
antagonist was used as a novel antiplatelet agent to reduce 
the risk of cardiovascular death or ischemic events in patients 
with cardiovascular diseases, but it had the side effect of 
inducing moderate or severe bleeding.50 SCH77977 as a 
potent, selective nonpeptide PAR1 antagonist was used 
as a monotherapy at 10 μg/kg with the effect of reduc-
ing myocardial infarction size in a rat model of myocardial 
ischemia–reperfusion injury.51 In the pilot study, we used 
SCH77977 at 10 μg/kg in BDL rats and the treatment 
reduced nociceptive thresholds; however, we observed 
abnormal bleeding after subcutaneous injection, thus we 
reduced the dose of SCH77977 to 1 and 0.3 μg/kg, and no 
abnormal bleeding was observed, suggesting that low-dose 
PAR1 antagonist in vivo can reduce peripheral production 
of opioids and avoid bleeding.

There are some limitations in our study. First, the alanine 
aminotransferase levels in patients with obstructive jaundice 
were higher than that of the control patients, we cannot 
exclude the possibility that diminished metabolism due to 
liver damage may account for the diminished need for post-
operative morphine in our patients with jaundice. Second, 
PAR1 is expressed in a variety of cell types.52 Although the 
study by Martin et al.18 had concluded that the antino-
ciceptive effects of PAR1 agonist were mediated through 
increasing mRNA expression of the endogenous opioid 
precursor proenkephalin in keratinocytes rather than by a 
direct action of neurons. We cannot exclude the possibility 
that PAR1 inhibition in other types of cells may contribute 
to its antienogenous opioid-releasing effects in the BDL 
rats. Third, there are other types of proteases other than 
thrombin such as cathepsin G, granzyme A, and trypsin, 
which have been shown to activate PAR1 and are all released 
in the context of inflammation.18,45 Thus, there are many 
potential candidates that can activate PAR1 in pathological 
conditions.

In conclusion, the current study demonstrates that skin 
enkephalin levels were increased in both patients with jaun-
dice and cholestatic models. These results may have direct 
relevance to increased pain thresholds during cholestasis. 
Our data also suggest that PAR1 activation in keratinocytes 
may play an important role in the local synthesis of endog-
enous opioids during cholestasis and support the hypoth-
thesis that PAR1 antagonists may be a potential therapeutic 
approach to prevent increased opioidergic tone–associated 
complications in patients with cholestasis.

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Competing Interests

The authors declare no competing interests.

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“Hands-On” Teaching by Chevalier Jackson

Nearly 40 years after inventing his namesake “U-shaped” laryngoscope, Chevalier Jackson, M.D. (1865–1958) emerged from clinical retirement to teach “broncho-esophagology” during World War II to postgraduates at Temple University in Philadelphia. The ambidextrous “Chev” Jackson would turn his back to the class and, with chalk sticks in both hands, simultaneously draw out the left and right halves of any teaching diagrams on the blackboard or on poster paper. He accomplished a similar two-handed feat in 1943 by creating this pastel (left) of the upper airway and the bronchial branches. Since Dr. Jackson could sign his name with either hand or simultaneously, from opposite ends of his signature, with both hands, please inspect his autograph on this piece (right) and decide for yourself: did Dr. Jackson use one hand or two? This pastel is part of the Wood Library-Museum’s Nicholas Samponaro Collection. (Copyright © the American Society of Anesthesiologists, Inc.)

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