Loperamide: studies on its mechanism of action

B K SANDHU, J H TRIPP, D C A CANDY, AND J T HARRIES

From the Institute of Child Health and The Hospital for Sick Children, Great Ormond Street, London

SUMMARY The effects of loperamide on net solute and water absorption, and prostaglandin E\textsubscript{2} (PGE\textsubscript{2}) and cholera toxin-induced secretion were studied in the rat jejunum using an in vivo steady-state perfusion technique. Loperamide stimulated absorption of fluid, electrolytes, and glucose and reversed PGE\textsubscript{2} and cholera toxin-induced secretion to absorption; this opiate analogue had no effect on cholera toxin stimulation of adenylate cyclase activity or the rise of tissue cyclic AMP (cAMP) concentrations. The opiate antagonist, naloxone, reduced the anti-secretory effects of loperamide without affecting tissue levels of cAMP. These results indicate that loperamide inhibits PGE\textsubscript{2} and cholera toxin-induced secretion, and that this phenomenon is independent of any direct effect that cholera toxin has on the adenylate cyclase system. The action of naloxone suggests, but does not prove, that loperamide exerts its effect via opiate receptors.

Loperamide, an opiate analogue, is a widely used anti-diarrhoeal agent and, until recently, its effects were attributed to an inhibitory action on smooth muscle tone and peristalsis mediated via both cholinergic and non-cholinergic systems.\textsuperscript{1,3} Karim and Adaikan,\textsuperscript{4} however, observed that loperamide modified prostaglandin E\textsubscript{2} (PGE\textsubscript{2}) induced secretion of fluid in the rat intestinal tract and they postulated that its anti-diarrhoeal action might be related not only to an effect on intestinal motility, but also on secretory processes.

We have recently been impressed by the beneficial effects of very large oral doses of loperamide (up to 4 mg/kg body weight) in some but not all infants with severe and life-threatening protracted diarrhoea (unpublished observations). On the basis of these clinical observations we suspected that the effects of the drug could not be explained solely on its action on smooth muscle, and that it was inhibiting small intestinal secretion of fluid and electrolytes. This prompted us to study the effects of loperamide, and its possible mechanism of action, on two well-established secretagogues, PGE\textsubscript{2} and cholera toxin, using a steady state perfusion technique in the rat jejunum in vivo.

The results of loperamide on cholera toxin-induced secretion have been briefly reported in a letter.\textsuperscript{5}

Methods

PERFUSIONS

All experiments were performed on male Wistar rats weighing 220–280 g after an overnight fast, during which water was allowed ad libitum; the designs of the experiments are shown in the Figure. Two hours before laparotomy the animals received intragastric loperamide (4 mg/kg body weight) dissolved in 1 ml 5\% (v/v) ethanol and water with omission of loperamide in controls. Anaesthesia was induced with intraperitoneal pentobarbitone (6 mg/kg), and maintained as necessary with intramuscular doses of 0.3 mg. The rectal temperature was maintained throughout the experiments at 37°C by overhead electric lamps. In the PGE\textsubscript{2} experiments the perfusions were essentially as described by Sladen and Harries.\textsuperscript{6} The abdomen was opened with a midline incision and 15–20 cm lengths of proximal jejunum (from the duodenojejunal junction) were prepared. An inlet catheter (vinyl tubing, bore 0.63 mm, diameter 1.4 mm, short hardness −70, portex) was inserted into the gut lumen through a 2 mm incision in the antimesenteric border of the gut and tied firmly in place with a circumferential ligature. Faecal material, if present, was removed from the loops by washing with isotonic saline at 37°C. A wider bore outlet catheter (bore 2 mm, diameter 3 mm, short hardness −70, portex) was similarly inserted into the distal end of the loop for the continuous collection of effluent and the
Loperamide: studies on its mechanism of action

1. **Figure** Experimental design: (1) effect of loperamide on absorption, and on prostaglandin $E_2$ ($PGE_2$) induced secretion; (2) effect of loperamide on cholera toxin (CT) induced secretion and of naloxone in this system.

Loop was returned to the abdominal cavity. The solutions were infused continuously at 0.46 ml/min (Harvard 975 syringe pump), and were warmed by passage through the inlet catheter in a water bath at 37°C. After an equilibration period of 30 minutes, three consecutive 10 minute collections of effluent were obtained. The perfusate contained (mmol/l) NaCl (130), KCl (4), glucose (2), NaHCO$_3$ (25), and polyethylene glycol 4000 (3 g/l) with 5 μCi/l of $^{14}$C polyethylene glycol; $PGE_2$ was added to the basic perfusate in a concentration of 0.2 mmol/l, the pH was adjusted to 7.0 with CO$_2$ and the osmolality of the solution was 290 mosmol/kg.

A low (2 mmol/l) concentration of glucose was chosen, as luminal disappearance will reflect active transport and/or mucosal metabolism, and thus tissue viability. In all the experiments the concentration of glucose in the effluent ranged from 1.3 to 1.6 mmol/l. The dose of $PGE_2$ was that which consistently induced secretion of water, as established in preliminary experiments. The mean percentage recovery of $^{14}$C polyethylene glycol for all the perfusions was 100 (range 95–105). At the end of the three 10-minute collection periods the animal was killed by cardiac puncture.

In the cholera toxin experiments a blind loop was initially constructed from the proximal 15–20 cm of jejunum as described by Harries and Sladen, and cholera toxin (75 μg dissolved in 0.75 ml perfusate) was instilled into the loop, which was returned to the peritoneal cavity for two hours. The loop was then rinsed with perfusate and prepared for perfusion as in the $PGE_2$ experiments; the composition of the perfusate was identical with the basic perfusate used in the $PGE_2$ experiments. A second series of experiments with cholera toxin were carried out to study the effects of naloxone on the observed effects of loperamide on cholera toxin-induced secretion: naloxone was administered subcutaneously in two divided doses of 1.6 mg/kg at 4 and 4.5 hours as shown in the Figure. As with $PGE_2$ the dose of naloxone was chosen on the basis of preliminary experiments, and the timing of its subcutaneous injection was based on studies in rats showing a half-life of 30 to 40 minutes.

A low (2 mmol/l) concentration of glucose was chosen, as luminal disappearance will reflect active transport and/or mucosal metabolism, and thus tissue viability. In all the experiments the concentration of glucose in the effluent ranged from 1.3 to 1.6 mmol/l. The dose of $PGE_2$ was that which consistently induced secretion of water, as established in preliminary experiments. The mean percentage recovery of $^{14}$C polyethylene glycol for all the perfusions was 100 (range 95–105). At the end of the three 10-minute collection periods the animal was killed by cardiac puncture.

In the cholera toxin experiments a blind loop was initially constructed from the proximal 15–20 cm of jejunum as described by Harries and Sladen, and cholera toxin (75 μg dissolved in 0.75 ml perfusate) was instilled into the loop, which was returned to the peritoneal cavity for two hours. The loop was then rinsed with perfusate and prepared for perfusion as in the $PGE_2$ experiments; the composition of the perfusate was identical with the basic perfusate used in the $PGE_2$ experiments. A second series of experiments with cholera toxin were carried out to study the effects of naloxone on the observed effects of loperamide on cholera toxin-induced secretion: naloxone was administered subcutaneously in two divided doses of 1.6 mg/kg at 4 and 4.5 hours as shown in the Figure. As with $PGE_2$ the dose of naloxone was chosen on the basis of preliminary experiments, and the timing of its subcutaneous injection was based on studies in rats showing a half-life of 30 to 40 minutes.

**Analyses**
The initial solutions and effluent were analysed for sodium and potassium by flame photometry.
(Corning-E EL), chloride by coulometric titration (Corning-E EL), and glucose by hexokinase-G6PDH method (BCL, Lewes, UK); 500 μl aliquots in duplicate were counted in Rialuma scintillant (LKB Instruments Ltd, Croydon, UK) for 14C in an LKB (Wallac) scintillation counter. Loperamide was supplied by Janssen Pharmaceutica Ltd, Marlow, Buckinghamshire, PGE2 obtained from Upjohn Ltd, Crawley, Sussex, and CT Batch VT 2210 supplied by Wellcome Research Laboratories, Beckenham, Kent.

Adenylate cyclase activity was measured as described by Tripp et al. with the following modifications: the media were preincubated at 37°C for five minutes, 100 μl of mucosal homogenate was incubated in 500 μl of medium, the basal activity assay being incubated for 10 minutes and the fluoride stimulated assay for five minutes.

cAMP was assayed using a kit (Radiochemical Centre, Amersham, Buckinghamshire) by homogenising the freeze-clamped biopsies in 0.5 ml EDTA (4 mM) buffer at 4°C and measuring cAMP by protein binding assay after precipitating homogenate protein by boiling. Protein concentration of the homogenate was measured using a Coomassie blue dye binding method.

Calculations

Using 14C polyethylene glycol as a non-absorbable marker absorption rates of fluid and solute were calculated from standard formulae, and in each rat a mean value was obtained from the three 10-minute collection periods. The significance of the difference between mean values was assessed by the unpaired Student’s t test.

Results

Effect of Loperamide on Absorption and on PGE2 Induced Secretion (Table 1)

Pre-treatment with loperamide itself enhanced absorption of water (p<0.05), sodium (p<0.05), chloride (p<0.005), sodium (p<0.05), chloride (p<0.005), glucose (p<0.05). PGE2 induced secretion of water (p<0.001), sodium (p<0.001), potassium (p<0.001), and chloride

Table 1 Effect of loperamide on absorption and on PGE2 induced secretion

<table>
<thead>
<tr>
<th></th>
<th>Water (μl)</th>
<th>Sodium (μmol)</th>
<th>Potassium (μmol)</th>
<th>Chloride (μmol)</th>
<th>Glucose (μmol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controls (8)</td>
<td>+28.3 ±2.3</td>
<td>+4.4 ±0.3</td>
<td>+0.06±0.01</td>
<td>+1.9±0.9</td>
<td>+0.03±0.02</td>
</tr>
<tr>
<td>Loperamide-treated (8)</td>
<td>+40.1±4.7</td>
<td>+6.3±0.8</td>
<td>+0.08±0.02</td>
<td>+5.3±0.02</td>
<td>+0.40±0.04</td>
</tr>
<tr>
<td>PGE2 perfusion (8)</td>
<td>-7.3±1.1</td>
<td>-1.15±0.29</td>
<td>-0.11±0.02</td>
<td>-1.37±0.62</td>
<td>+0.15±0.01</td>
</tr>
<tr>
<td>Loperamide-treated + PGE2 perfusion (8)</td>
<td>-7.4±2.4</td>
<td>+1.6±0.6</td>
<td>-0.02±0.02</td>
<td>+0.71±0.5</td>
<td>+0.23±0.02</td>
</tr>
</tbody>
</table>

+ Net absorption; − net secretion; values are given as mean ± SEM.
Figures in parentheses denote number of animals in each group. NS: not significant.
P values refer to values immediately above and below.

Table 2 Effects of cholera toxin (CT), loperamide, and naloxone on water absorption, tissue adenylate cyclase activity and cyclic AMP levels

<table>
<thead>
<tr>
<th></th>
<th>Water absorption (μl/min/g wet weight)</th>
<th>Adenylate cyclase (pmol/mg protein/min)</th>
<th>Cyclic AMP (pmol/mg protein)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basal</td>
<td>Fluoride-stimulated</td>
<td></td>
</tr>
<tr>
<td>Controls</td>
<td>+27.9±3.0 (6)</td>
<td>4.56±0.77 (6)</td>
<td>3.06±0.13 (5)</td>
</tr>
<tr>
<td>CT treated</td>
<td>−24.0±2.3 (8)</td>
<td>8.58±2.03 (6)</td>
<td>15.16±2.21 (6)</td>
</tr>
<tr>
<td>Loperamide+CT treated</td>
<td>+12.3±3.5 (9)</td>
<td>9.84±1.77 (6)</td>
<td>16.97±2.37 (6)</td>
</tr>
<tr>
<td>Loperamide+CT+naloxone treated</td>
<td>−11.7±5.3 (5)</td>
<td>NS</td>
<td>5.80±0.18 (5)</td>
</tr>
<tr>
<td>CT+naloxone treated</td>
<td>−17.5±3.4 (5)</td>
<td>NS</td>
<td>5.57±0.12 (5)</td>
</tr>
</tbody>
</table>

+ Net absorption; − net secretion; values are given as mean ± SEM.
Figures in parentheses denote the number of animals in each group; NS: not significant.
P values refer to values immediately above and below.
Loperamide: studies on its mechanism of action

(p<0.005) and inhibited glucose absorption (p<0.001). Pre-treatment with loperamide reversed secretion of water (p<0.001), sodium (p<0.001), and chloride (p<0.02) to absorption, though rates of absorption did not return to normal control values; secretion of potassium was reduced (p<0.01). Glucose absorption was enhanced but the values were not statistically different from the PGE$_2$ group not given loperamide.

**Effects of CT, Loperamide and Naloxone on Water Absorption, Tissue Adenylate Cyclase Activity, and cAMP Levels (Table 2)**

Cholera toxin induced secretion of water (p<0.001), and increased basal adenylate cyclase activity (p<0.005) without affecting fluoride-stimulated activity; cholera toxin had a similar effect on tissue cAMP levels (p<0.001). Loperamide reversed secretion of water to absorption (p<0.001) but had no effect on adenylate cyclase activity or cAMP levels. Naloxone reduced the antisecretory effects of loperamide (p<0.005), absorption of water reverting to secretion without any effect on tissue cAMP.

**Discussion**

This study clearly demonstrates that in large doses loperamide markedly inhibits small intestinal secretion induced by cholera toxin and PGE$_2$, and supports our clinical observations that the effects of the drug in patients with severe protracted diarrhoea may in part be due to its antisecretory properties. This is in keeping with our findings that the small intestine is in a secretory state in such children.

Previous studies have shown a close temporal relationship between tissue cAMP concentrations, adenylate cyclase activity and the onset of secretion after exposure of the small intestine to cholera toxin, as well as to other agents which increase tissue cAMP, suggesting that the secretory process is intimately linked to the cAMP system.

Prostaglandin-induced secretion closely mimics that produced by cholera toxin in terms of tissue cAMP changes and electrical phenomena; there are differences, however, in the secretion suggesting that the two secretagogues act via different or additional mechanisms.

In the present experiments loperamide inhibited cholera toxin induced secretion without any effect on the increased activity of adenylate cyclase or the tissue concentrations of cAMP. Moreover, naloxone which reduced the anti-secretory effects of loperamide also had no effect on tissue cAMP levels. These observations suggest that loperamide acts at a point distal to the increase in tissue cAMP in modifying the secretory process. The finding that PGE$_2$ inhibited glucose absorption is in agreement with previous reports, and is in marked contrast to the lack of any effect of cholera toxin on glucose absorption, which is also in agreement with both our and other previous studies. In addition, loperamide itself enhanced absorption of water, electrolytes, and glucose from an isotonic buffer containing glucose, and partially reversed the effects of PGE$_2$ on water and electrolytes transport.

Although this study has not defined the precise mechanism(s) by which loperamide modifies cholera toxin and PGE$_2$ induced secretion, the results suggest that the effects of the opiate analogue do not result from a direct effect on the cyclic AMP system. The data indicate that the antisecretory actions of loperamide occur via a naloxone sensitive mechanism, and as naloxone is an opiate antagonist, this in turn suggests that the effects of loperamide may be mediated by opiate receptors. However, only one concentration of the agonist and antagonist was investigated in the present study and additional studies directed towards demonstrating a dose-related effect of antagonist and agonist activity would add support to the notion that opiate receptors are involved.

BKS thanks Janssen Pharmaceuticals Ltd for financial support. DCAC acknowledges the financial support of the Rayne Foundation. The authors would like to thank Dr R O Thompson, Wellcome Research Laboratories, Beckenham, UK, for generously providing the cholera toxin.

**References**


4. Karim SMM, Adika PG. The effect of loper-


Pierce NF, Carpenter CCJ, Elliott HL, Greenough WB. III. Effects of prostaglandins, theophylline, and cholera exotoxin upon transmucosal water and electrolyte movement in the canine jejunum. Gastroenterology 1971; 60:22-32.