ABSTRACT:

The purpose of this study was to determine the characteristics of intestinal absorption and metabolism of cimetidine. The initial finding of the appearance of cimetidine sulfoxide in rat and human jejunum from cimetidine perfusions had prompted an isolation of mucosal membrane transport and enterocyte metabolism contributions in earlier membrane vesicle and microsomal studies, respectively. In this report, perfusion studies in rat small intestine detail regional differences in intestinal elimination. Cimetidine S-oxide appears to a significantly greater extent in the jejunum compared with the ileum. Jejunal metabolite appearance is shown to be a function of the pH-dependent intracellular uptake of cimetidine. Cimetidine permeability decreases with increasing perfusion concentration in both jejunum and ileum. Similar permeability magnitudes and concentration dependence are observed in both regions. Perfusion studies with inhibitors of cimetidine mucosal transport and inhibitors of microsomal S-oxidation provide an inhibition profile suggesting that jejunal cimetidine permeability decreases with increasing intracellular cimetidine concentration. The data support a reduction in paracellular cimetidine absorption as controlled by intracellular cimetidine. This inference is drawn on the basis of mass balance. Because significant appearance of cimetidine S-oxide was previously found in human jejunal perfusions, this region-dependent intestinal elimination process detailed in rats may be relevant to drug plasma-level double peaks observed in clinical studies. Saturation of jejunal metabolism at typical oral doses may limit paracellular absorption of cimetidine in the jejunum and contribute to the double peak phenomenon and to absorption variability.

Cimetidine was the first H₂-receptor antagonist marketed to control gastric acid secretion (Somogyi and Gugler, 1983). It is currently sold as an over-the-counter product but continues to be remarkable in the number of literature reports documenting its role in drug interactions (Shinn, 1992; Guengerich, 1997). Cimetidine is well absorbed after oral administration but its absorption is highly variable and the appearance of a second plasma concentration maximum provides an unusual pharmacokinetic profile characteristic (Bodemar et al., 1979). Enterohepatic recirculation had been initially proposed to be responsible for the double peak (Veng Pedersen, 1981), but biliary elimination has been shown to not significantly impact drug plasma levels (Kaneniwa et al., 1986a). Gastric pH and emptying variability have been reported to influence the absorption pattern of cimetidine as a function of dose and time of administration (Oberle and Amidon, 1987). However, plasma level double peaks are also obtained in human intestinal perfusion of cimetidine (Voinchet et al., 1981). Cimetidine absorption had been shown to be lower in rat jejunum than in duodenum and ileum (Barber et al., 1979) and this absorption site dependence has been projected to account for plasma level double peaks in humans (Witcher and Boudinot, 1996). However, membrane transport contributions to this regional dependence and the mechanistic elements of cimetidine plasma level double peaking and absorption variability have not been resolved.

Most recently, cimetidine absorption in rat proximal jejunum has been shown to be exclusively via the paracellular pathway. This was based on data that indicated that intracellular cimetidine did not appreciably exit the basolateral membrane. Furthermore, intracellular cimetidine levels, as controlled by cellular uptake and elimination, appear to regulate paracellular absorption (Zhou et al., 1999). In this report, the role of jejunal S-oxidation in influencing cimetidine absorption was further explored by varying concentration and using inhibitors of cimetidine metabolism and transport in single-pass small intestinal perfusions in rats.

The current data suggest that cimetidine S-oxidation influences paracellular cimetidine absorption in rat jejunum by determining the magnitude of intracellular drug concentration. As intracellular uptake increases with luminal cimetidine concentrations beyond the capacity of jejunal cimetidine metabolism, intracellular cimetidine levels rise, leading to the restriction of paracellular transport and a reduction of drug absorption into the systemic circulation. The reduction in paracellular transport provides a greater driving force for intracellular uptake. This, in turn, amplifies the contribution of intracellular cimetidine metabolism to jejunal elimination, resulting in elevated cimetidine S-oxide levels in the jejunal lumen. Cimetidine S-oxide is not absorbed and does not enter the rat jejunal lumen from the blood (Hui et al., 1994). Thus, intestinal elimination of cimetidine is enhanced by...
inhibition of paracellular transport. At high luminal cimetidine concentrations, this form of self-inhibition depresses rat jejunal absorption. Based on cimetidine metabolite levels in human jejunum, it is proposed that this mechanism may account for double plasma level maxima. The concentration dependence and inhibition profile of this process may also contribute to the broad variability observed in cimetidine oral bioavailability.

**Experimental Procedures**

**Chemicals.** Cimetidine, \(\beta\)-glucose, 3-oxymethylglucose, \(\delta\)-mannitol, imipramine hydrochloride, chlorpromazine hydrochloride, erythromycin, neomycin sulfate, lincomycin, \(\beta\)-cyclodextrin, \(\delta\)-methionine, 2(\(\delta\)-morpholino)ethanesulfonic acid (MES), HEPES, and polyethylene glycol 4000 (PEG 4000) were purchased from Sigma Chemical Co. (St. Louis, MO). \(^{14}\)C/PEG 4000 was obtained from New England Nuclear (Boston, MA). Cimetidine sulfoxide was kindly provided by SmithKline Beecham Pharmaceuticals (King of Prussia, PA). All other chemicals were of reagent grade or HPLC grade.

**Rat In Situ Single-Pass Intestinal Perfusion.** Male Sprague-Dawley rats (Charles River Breeding Laboratories, Wilmington, MA) weighing 250 to 300 g were fasted overnight for 16 to 22 h with free access to water and anesthetized with an intramuscular injection of 87 mg/kg ketamine and 13 mg/kg xylazine before surgery. After anesthesia, rats were placed on a heating pad under a surgical lamp to maintain body temperature. A midline longitudinal abdominal incision was made and an inlet Teflon tube (0.42 cm diameter) was inserted into the jejunum at about 10 cm distal to the ligament of Treitz. Outlet Teflon tubes were inserted 8 to 10 cm proximal to the ileocecal junction and the inlet tube 8 to 10 cm proximal to the outlet. After cannulation, the abdomen was rinsed with isotonic saline, and covered with an isotonic saline-wetted gauze. The entire surgical area was then covered with parafilm to reduce evaporation. All inlet tubing was water-jacketed to maintain inlet perfusion solutions at 37°C. Inlet cannulae were connected to syringes that were placed in a perfusion pump (Harvard Apparatus Co., South Natick, MA). Drug solutions were perfused through the intestine at flow rates of 0.12 or 0.25 ml/min. After allowing 40 min to reach steady-state outlet concentrations, outlet perfusate samples were collected every 10 or 15 min for 90 min. When the experiment was completed, the perfused intestinal length was measured by dissecting the mesentery and blood vessels and placing the segment flat over a ruler whose surface was wetted with saline to prevent segment elongation.

**Perfusion Solutions.** Cimetidine solutions were made isotonic (290 ± 20 mOsm/kg) and buffered to the desired pH with MES or HEPES buffer. These perfusion solutions contained 5 mM potassium chloride, in the range of 135 mM sodium chloride for isotonicity adjustment, 10 mM MES and were adjusted to pH 5.5 or 6.5 with 10 N sodium hydroxide. In some studies, 10 mM sodium chloride for isotonicity adjustment, 10 mM MES and were

**HPLC.** The peak height and area were measured with a Shimadzu integrator (Model CR 501 Chromatopac; Shimadzu Corporation, Kyoto, Japan). Retention times for cimetidine and cimetidine sulfoxide were 7.5 and 12.8 min, respectively. The minimal levels of detection for cimetidine sulfoxide and cimetidine were 50 and 80 nM, respectively. A linear response was obtained for cimetidine and cimetidine sulfoxide standard curves (\(r = 0.997–1.000\)). Quantification of metabolite was obtained as the mean value of four to five steady-state outlet perfusate samples as determined from the standard curve. The metabolite HPLC peak from perfusions was confirmed as cimetidine sulfoxide by mass spectrometry analysis in a previous study (Hui et al., 1994). The original solutions and the effluent perfusate samples were also analyzed for \(^{14}\)C/PEG 4000 using liquid scintillation counting. A 500-ml aliquot was mixed with 5 ml of scintillation fluid (Ecoliter; ICN Pharmaceuticals, Costa Mesa, CA) and the amount of radioactivity was determined in a Beckman LS 6000 SC scintillation counter (Beckman Instruments, San Jose, CA).

**Data Analysis.** Data were generated from each rat by averaging at least five perfusate collection samples at steady state. The amount of cimetidine sulfoxide detected in the perfusate is calculated as the fraction of drug metabolized (\(F_{\text{met}}\)).

\[ F_{\text{met}} = \frac{\text{luminal cimetidine sulfoxide}}{\text{luminal cimetidine loss}} = \frac{\text{luminal cimetidine sulfoxide (mM)}}{[\text{inlet cimetidine} - \text{outlet cimetidine (mM)}]} \]

Luminal cimetidine sulfoxide and outlet cimetidine concentrations were corrected for water transport across intestinal membrane. Intestinal water flux \((J)\) in microliters per minute per centimeter is calculated at a given flow rate, \(Q\) (microliters per minute), per centimeter of perfused intestinal length \((L)\) as \(^{14}\)C disintegration per minute using the following equation (Lu et al., 1998):

\[ J = \frac{{^{14}}}{{^{12}}} \text{dpm}_{\text{outlet}} - \frac{{^{14}}}{{^{12}}} \text{dpm}_{\text{inlet}} \times \frac{Q}{L} \]

Positive values of \(J\) imply net water absorption whereas negative values indicate net water secretion. Effective cimetidine permeability \((P_{\text{eff}})\), using a modified boundary model developed by Johnson and Amidon (1988), is computed according to the following equation:

\[ P_{\text{eff}} = \frac{Q \left( 1 - \frac{C_{\text{inlet}}}{C_{\text{outlet}}} \right)}{2 \pi RL} \]

where \(C_{\text{outlet}}\) is the exit cimetidine concentration corrected for water transport in the perfusate and \(C_{\text{inlet}}\) is the input drug concentration. A water transport correction is obtained by multiplying the drug outlet-to-inlet concentration ratio by the marker inlet-to-outlet dpm ratio. \(R\) and \(L\) are intestinal radius and length of the perfused segments, respectively. The \(R\) value used in this study was estimated to be 0.23 cm (Yuasa et al., 1988). The \(P_{\text{eff}}\) is a measure of drug lost across the apical membrane of the intestinal epithelia including both intracellular and paracellular drug transport. Permeability defines the rate of absorption in this rat perfusion system and has been correlated with the fraction of drug absorbed from solution in human clinical studies as assessed by plasma level pharmacokinetic profiles (Amidon et al., 1988). A corrected value for the effective permeability \((P_{\text{eff}corr})\) was calculated using a molar summation of luminal cimetidine and cimetidine sulfoxide as \(C_{\text{inlet}}\) in the above equation. This corrected value is reflective of net systemic drug absorption in the presence of intestinal drug elimination. Data are presented as mean ± S.E. Statistical differences were determined by either Student’s \(t\) test or ANOVA, as appropriate.
**Results**

Previous work had identified cimetidine S-oxide in the lumen after jejunal perfusions of cimetidine in rats and two human subjects (Hui et al., 1994). In the earlier studies in rats, significantly lower levels of the S-oxide had been observed in ileal compared with jejunal cimetidine perfusions (Hui et al., 1994). Furthermore, a maximum ratio of metabolite to initial perfusion drug concentration had been observed in the jejunal above 0.4 mM for perfusion cimetidine concentrations from 0.1 to 4 mM. Therefore, 0.4-mM drug concentrations were used in pH-dependence and metabolism-inhibition studies. Rat jejunal perfusions of 0.4 mM cimetidine S-oxide at pH 6.5 and perfusion flow rate of 0.12 ml/min resulted in water transport-corrected permeabilities of zero, confirming that the metabolite is not appreciably absorbed. Furthermore, reduction of the metabolite to the parent drug was not detectable in the outlet perfusate.

Recent studies in jejunal epithelia had determined that the cellular origin of metabolite production was the microsomal cell fraction (Lu et al., 1998). Although drug oxidation is rarely mediated by intestinal bacteria (George and Renwick, 1987), this was confirmed by comparing jejunal appearance of metabolite in antibiotic-treated versus untreated rats. Antibiotic pretreatment did increase the variability in S-oxide appearance from 0.4 mM jejunal cimetidine perfusions but untreated rats. Antibiotic pretreatment did increase the variability in S-oxide appearance from 0.4 mM jejunal cimetidine perfusions but untreated rats. Antibiotic pretreatment did increase the variability in S-oxide appearance from 0.4 mM jejunal cimetidine perfusions but untreated rats. Antibiotic pretreatment did increase the variability in S-oxide appearance from 0.4 mM jejunal cimetidine perfusions but untreated rats.

It had been shown that cimetidine S-oxide appearance was substantial in jejunal jejunal perfusions at pH 6.5 but negligible in ileal perfusions at pH 7.5 (Hui et al., 1994). Jejunal S-oxide levels as a function of perfusion pH showed a maximum at pH 6.5, which coincided with a maximum in cimetidine jejunal permeability (Table 1) from drug perfusions at 0.4 mM. Although ileal metabolite levels were higher from perfusions at pH 6.5 versus pH 7.5, they are significantly lower than those from jejunal perfusions at pH 6.5 (Table 1). At a physiologically relevant pH of 7.5 in the ileum, ileal S-oxide appearance is negligible and ileal cimetidine permeability is equivalent to metabolite-corrected jejunal permeability from 0.4 mM cimetidine perfusions at pH 6.5 (Table 1).

Because little metabolite is produced in ileal perfusion, effective permeability calculations are not affected by metabolite production, and the amount of drug loss from the lumen reflects systemic drug absorption. The permeability of cimetidine in the ileum is constant at low concentrations (Fig. 1), indicating that the amount of drug loss is proportional to the amount available for absorption. As had been determined in a previous study, reduced permeability at higher perfusion concentrations is not the result of saturation of carrier-mediated transport at the apical membrane but rather a dose-dependent restriction of paracellular transport (Zhou et al., 1999). If jejunal permeability is calculated from drug loss in perfusate and not corrected for metabolite appearance, an unusual permeability profile is obtained (Fig. 2A). However, when luminal drug concentration is corrected for luminal metabolite appearance, the permeability profile and permeability magnitudes (Fig. 2B) in the jejunum are comparable to those observed in the ileum (Fig. 1). The magnitude of luminal metabolite appearance is also observed to level off at high drug concentrations (Fig. 3). The ratio of jejunal metabolite appearance to drug loss (Fmet) is proportional to perfusion concentration over the lower perfusion drug-concentration range and levels off at about 0.9 at higher perfusion concentrations (Fig. 4). Given the definition of Fmet when metabolism is saturated at higher drug concentrations, the increase in Fmet indicates that cellular uptake rather than metabolism is limiting metabolite appearance. Otherwise, Fmet would decrease at higher perfusion concentrations. Permeability was not influenced by perfusion flow rate at any of the concentrations studied (Figs. 1 and 2).

**TABLE 1**

**Cimetidine metabolism and transport in rat jejunum and ileum**

<table>
<thead>
<tr>
<th>Intestinal Segments</th>
<th>Luminal pH</th>
<th>Fmet</th>
<th>Poff</th>
<th>Poff,corr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jejunum</td>
<td>5.5</td>
<td>0.196 ± 0.122</td>
<td>0.289 ± 0.152</td>
<td>0.078 ± 0.042</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td>0.726 ± 0.036</td>
<td>0.573 ± 0.055</td>
<td>0.142 ± 0.019</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>0.069 ± 0.037</td>
<td>0.037 ± 0.014</td>
<td>0.035 ± 0.013</td>
</tr>
<tr>
<td>Ileum</td>
<td>6.5</td>
<td>0.120 ± 0.073</td>
<td>0.093 ± 0.025</td>
<td>0.079 ± 0.021</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>0.005 ± 0.003</td>
<td>0.129 ± 0.018</td>
<td>0.128 ± 0.017</td>
</tr>
</tbody>
</table>

**FIG. 1.** Effective ileal permeability (Poff) of cimetidine as a function of steady-state drug perfusion concentration at pH 7.5.

Negligible appearance of S-oxide metabolite in the ileum provides for straightforward permeability calculations as a function of lumenal drug loss. Poff at 2 and 4 mM are significantly lower than Poff at any of the lower concentrations (P < .05).
However, at the highest drug perfusion concentration (4 mM), $F_{\text{met}}$ was significantly lower at the slower perfusion rate than at the faster perfusion flow rate (Fig. 4).

A 10-fold reduction in jejunal cimetidine permeability (uncorrected for $S$-oxide appearance) is observed when 0.4 mM cimetidine is coperfused with 5 mM methimazole (Fig. 5A). Reductions in permeability (3- to 4-fold) are generated by cimetidine coperfusion with L-cysteine, L-methionine, chlorpromazine, and imipramine. However, when steady-state cimetidine permeability is corrected for the appearance of metabolite, only methimazole and the amino acids actually reduce cimetidine absorption (Fig. 5B). Methimazole eliminates measurable appearance of cimetidine $S$-oxide in the jejunal lumen (Fig. 6) in parallel with the reduction in corrected permeability to near zero (Fig. 5B). Although both chlorpromazine and imipramine significantly reduce metabolite levels (Fig. 6), they do not affect the corrected cimetidine permeability (Fig. 5B). Decreases in the appearance of cimetidine $S$-oxide are statistically significant with coperfusion of L-methionine, whereas metabolite variability in the presence of erythromycin does not result in statistically significant changes in $F_{\text{met}}$ (Fig. 6).

### Discussion

Cimetidine plasma profiles from oral administration under fasted conditions often show a secondary maximum that is not observed when the drug is administered with a meal (Bodemar et al., 1979). The two plasma level maxima typically occur between 1 and 2 h and between 3 and 4 h after oral cimetidine administration. Given the relatively short elimination half-life of cimetidine and the fact that this double peak time frame coincides with intestinal transit time, variable absorption rate down the length of the intestine is anticipated to contribute to drug plasma level observations. Enterohepatic recirculation (Veng Pederson and Miller, 1980), intestinal bacterial reconversion of biliary metabolite (Gugler et al., 1981), variable gastric emptying (Oberle and Amidon, 1987), and region-dependent absorption (Hui et al., 1994) have all been proposed to account for these observations.

The extent of biliary secretion of cimetidine and metabolites has been shown to be insufficient to contribute to a second plasma level peak (Kaneniwa et al., 1986a). Although variable gastric emptying has been indicated to play a partial role (Oberle and Amidon, 1987), plasma level double peaks are also obtained from human intestinal perfusion of cimetidine (Voinchet et al., 1981). This study indicates that a decreased rate of absorption in the jejunum as compared with
lower small intestine may contribute to plasma level double peaks and variable absorption. The first plasma level peak is generated by cimetidine absorption as the drug enters the proximal small intestine from the stomach. Then, after a slowing of the absorption rate in the jejunum coincident with systemic drug elimination, a secondary increased rate of drug absorption in the lower small intestine may generate the second plasma level peak.

Cellular uptake of cimetidine across the mucosal membrane of the small intestine includes a potential-dependent pathway and an organic cation-proton exchange mechanism (Piyanpolrungroj et al., 1999). mucosal transport by cimetidine-proton exchange favors drug secretion into the jejunal lumen as mucosal microclimate pH in the jejunum is lower than intracellular pH (Daniel et al., 1989). P-glycoprotein has also been reported to promote apical exit of cimetidine from epithelial cells (Dudley and Brown, 1996). Basolateral facilitative diffusion (Zhang et al., 1998) is proposed to favor drug transport into the cell with subsequent secretion into the intestinal lumen. Consistent with this secretory pathway, it has recently been demonstrated that intracellular cimetidine does not appreciably exit the cell across the basolateral membrane, indicating that basolateral facilitative diffusion may be predominantly unidirectional (Zhou et al., 1999). Because basolateral exit does not occur to any appreciable extent, cellular uptake and metabolism determine intracellular cimetidine levels and cimetidine intestinal absorption is predominantly paracellular.

Based on mass balance inferences, data from this study indicate that increased intracellular cimetidine concentrations reduce drug absorption by the paracellular pathway. The decrease in cimetidine permeability at concentrations above 0.4 mM in both ileum and jejunum is consistent with this mechanism of transport inhibition (Figs. 1 and 2). Whereas saturation of carrier-mediated transport more commonly accounts for permeability decreases with increasing concentration, coperfusion with methimazole supports the paracellular mechanism. Previous studies have shown that methimazole inhibits cimetidine S-oxidation by flavin monoxygenase in the small intestine (Lu et al., 1998) and does not influence cimetidine transport across rat jejunal brush-border membrane (Piyanpolrungroj et al., 1999). In conjunction with jejunal perfusion data, these observations are consistent with cimetidine transport by a paracellular rather than transcellular pathway (Zhou et al., 1999). It is projected that the basolateral membrane limits transcellular cimetidine absorption and that intracellular cimetidine levels will rise with methimazole inhibition of intracellular cimetidine sulfoxidation (Fig. 6). The observed depression in cimetidine absorption rate (Fig. 5, A and B) could be projected from a reduction in drug concentration gradient driving force across cellular mucosal membranes resulting from an elevation of intracellular drug levels. High intracellular drug concentrations would be projected to promote passive permeation across the basolateral membrane. At high cimetidine perfusion concentrations, the fact that almost all drug returns to the jejunal lumen either as metabolite or unmetabolized cimetidine indicates that the basolateral membrane is the primary barrier for transcellular absorption. This is consistent with in vitro data in Caco-2 cells (Gan et al., 1998) and rat small intestinal tissue (Collett et al., 1999), showing that H2-antagonists are preferentially transported in the basolateral to apical direction.

Cimetidine transport into jejunal epithelial cells across the lateral membrane lining the paracellular pathway may account for the surprising increase in mucosal absorption observed over the concentration range from 0.08 to 0.4 mM (Fig. 2A). To explain this concentration dependence, “systemic” permeability (corresponding to the fraction metabolized) is defined as the rate of absorption corrected for the appearance of luminal metabolite. This determines the rate at which drug would be available to the systemic circulation from paracellular transport, because intracellular drug that is not metabolized is secreted back into the intestinal lumen. Systemic cimetidine absorption is unchanged over this concentration range, as indicated by the corrected permeability data (Fig. 2B). Defining “apical” permeability (corresponding to the fraction metabolized) as the rate of drug lost from the intestinal lumen refers to drug traversing the paracellular pathway and drug that enters epithelial cells beyond the apical membrane. The increase in apical permeability (uncorrected for metabolism) from 0.08 to 0.4 mM is the result of cellular cimetidine uptake across both apical and lateral membranes. Over this lower concentration range, intracellular drug concentrations may not be sufficiently high to saturate metabolism, and epithelial elimination increases the inward cimetidine flux across the apical and lateral membranes by maintaining sink conditions inside the cell. Essential to this interpretation, it has been shown that cimetidine sulfoxide does not compete with cimetidine for secretory transport across rat jejunal brush-border membrane vesicles (BBMV; Piyanpolrungroj et al., 1999) and that the metabolite is not absorbed in jejunal perfusions. Thus, as cimetidine perfusion concentration increases, metabolism becomes saturated and intracellular cimetidine levels increase to affect a dose-dependent restriction of the paracellular transport.

Reduced paracellular absorption is coincident with increases in intracellular drug uptake and controls jejunal elimination at higher cimetidine concentrations. At low cimetidine perfusion concentrations (0.08–0.4 mM), both apical permeability (Fig. 2A) and metabolized fraction (Fig. 4) increase proportionally as intracellular cimetidine is eliminated by microsomal metabolism and metabolite import into the jejunal lumen. At high concentrations (0.4–4 mM), the capacity for metabolism and/or apical elimination is exceeded. Under these conditions, it is projected that intracellular drug concentrations increase to levels that can affect paracellular restriction of drug absorption. This is supported by the fact that both Psupply and corrected PEff decrease as concentrations increase over the higher concentration range (Fig. 2) whereas Fmet levels off between 0.8 and 0.9 (Fig. 4). The fact that the ratio of metabolite appearance to drug loss is close to 1 at high luminal cimetidine concentrations suggests that most of the drug uptake beyond the apical membrane is not absorbed systemically but secreted back across the apical membrane as the S-oxide metabolite.
Permeability and $F_{\text{met}}$ were not dependent on perfusion flow rate except at 4 mM cimetidine where a statistically lower $F_{\text{met}}$ was recorded with slower versus faster perfusion flow rate (Fig. 4). Lumenal sulfoxide appearance at 2 mM cimetidine was statistically greater at the slower versus the faster flow rate (Fig. 3). Because cimetidine paracellular transport is inhibited more extensively at higher lumenal cimetidine concentration, lumenal drug loss predominately represents intracellular drug uptake with subsequent metabolite elimination into the lumen. $F_{\text{met}}$ at higher cimetidine concentration is close to 1 and so a statistical difference in flow rate or concentration dependence would not be expected. The higher production of metabolite at the slower flow rate (Fig. 3) indicates that greater drug uptake rather than lower drug metabolism accounts for lower $F_{\text{met}}$ values. A slower perfusion flow rate would be projected to provide a longer jejunal residence time and, therefore, a greater potential for drug uptake and lumenal metabolite appearance. A possible explanation is that a decrease in the thickness of an aqueous diffusion boundary layer at the higher flow rate reduces the aqueous resistance to cellular drug uptake. This would provide the strongest dependence of metabolite production on flow rate at a concentration approaching metabolic saturation.

Ileal cimetidine absorption demonstrates a similar self-inhibition profile (Fig. 1) in the absence of metabolite elimination into the lumen. Although the ileum might be expected to be more sensitive to paracellular restriction in the absence of cimetidine $S$-oxidation, the ileum is typically exposed to lower concentrations of drug because it is distal to upper intestinal absorption sites. The similarity in ileal and jejunal permeability concentration dependence (Figs. 1 and 2B) indicates that jejunal elimination and a restricted paracellular pathway promotes less cimetidine absorption in the jejunum as compared with the ileum based on exposure to higher lumenal drug concentration. Region-dependent absorption in rats has been reported, showing cimetidine plasma levels were higher from duodenal and ileal administration than from jejunal administration (Kaneniwa et al., 1986b). A similar finding has been documented in human subjects for ranitidine (Gramatte et al., 1994).

Regional differences in permeability and metabolite production are also observed with respect to perfusion pH. Whereas the uncorrected permeability reflects the sum of intracellular drug uptake and paracellular absorption into the systemic circulation, metabolite-corrected permeability defines the rate of systemic drug absorption. The fact that changes in perfusion pH significantly alter $F_{\text{met}}$ and $P_{\text{eff}}$ but do not alter corrected $P_{\text{eff}}$ indicates that changes in pH primarily affect cimetidine intracellular uptake and subsequent lumenal secretion. This is consistent with the fact that intracellular pH and metabolism should not be influenced by changes in perfusion pH. Jejunal cimetidine $P_{\text{eff}}$ was maximal at pH 6.5, whereas ileal $P_{\text{eff}}$ was relatively insensitive to the lumenal pH change. Initial cimetidine uptake overshoot of equilibrium in rat jejunal BBMV was maximal at an intravesicular pH of 5.7 when extravascular pH was 7.4 (Piyapolrungroj et al., 1999) indicative of mediated cimetidine secretion across the apical membrane. Cimetidine sulfoxide did not compete with cimetidine uptake in this vesicle preparation. The in vitro and in vivo data indicate that the relative contributions of cimetidine secretion and absorption to jejunal permeability are highly dependent on mucosal microclimate pH, which is lower in the jejunum than in the ileum (Daniel et al., 1989).

Imipramine strongly inhibited initial cimetidine uptake by rat jejunal BBMV (Piyapolrungroj et al., 1999) but proved a weak inhibitor (compared with methimazole) of cimetidine $S$-oxidation in jejunal microsomes (Lu et al., 1998). The perfusion data obtained in this study, indicate that cimetidine transport across the mucosal membrane is inhibited by imipramine because both uncorrected $P_{\text{eff}}$ and $F_{\text{met}}$ are decreased by imipramine but corrected $P_{\text{eff}}$ is not. This contrast in inhibition results between methimazole and imipramine also suggests that intracellular cimetidine is controlling absorption of cimetidine by rat jejunal epithelia. Imipramine’s inhibition of cimetidine uptake and methimazole’s greater inhibition of metabolism favor greater intracellular cimetidine concentrations with methimazole.

Methionine inhibition of cimetidine $S$-oxidation in jejunal microsomes was similar in magnitude to that observed with imipramine (Lu et al., 1998). In contrast to imipramine, methionine did not inhibit cimetidine uptake by jejunal BBMV (Piyapolrungroj et al., 1999). Because methionine does not reduce cellular cimetidine uptake but does inhibit metabolism, a reduction in both $P_{\text{eff}}$ and corrected $P_{\text{eff}}$ is observed. The fact that no significant change is observed in $F_{\text{met}}$ may be accounted for by the fact that cimetidine metabolism parallels lumenal drug loss. This is consistent with projecting greater intracellular levels of cimetidine with methionine compared with imipramine in perfusion. This data further support a role for intracellular cimetidine levels in regulating cimetidine transport across paracellular pathways.

Based on these in situ studies as well as BBMV transport and microsomal metabolism studies, a mechanism for cimetidine transport and metabolism in the jejunum is proposed (Fig. 7). Cimetidine is absorbed paracellularly and intracellular uptake is mediated by pH-dependent and potential-dependent processes in parallel with facilitative uptake across the lateral membrane lining the paracellular pathway. Paracellular transport is regulated by intracellular cimetidine concentrations as a function of intracellular uptake and metabolism. Although cimetidine elimination is substantial in the jejunum and not the ileum, self-inhibition of absorption is significant in both regions. Cimetidine elimination in the jejunum is amplified by self-inhibition of transport at higher drug concentrations. This will not usually occur in the ileum because it is distal to sites of upper intestinal absorption and therefore is exposed to lower drug concentrations. This is projected to result in region-dependent absorption underlying the clinical observation of plasma level double peaks. Based on this absorption mechanism, lumenal variables including cimetidine dose, rate of dosage form release, and meal ingestion should effect cimetidine oral bioavailability and absorption variability through their impact on lumenal cimetidine concentrations in upper versus lower small intestine.

Although our earlier report indicated that cimetidine $S$-oxide appearance in the jejunal lumen was greater in rats than humans (Hui et
and the scaling factor, \( j \), between rat and human is
\[
j = \frac{C_{\text{rat}}}{C_{\text{human}}} = \frac{L_{\text{rat}}}{L_{\text{human}} \times F_{\text{rat}} \times \frac{r_{\text{rat}}}{r_{\text{human}}} \times \frac{F_{\text{human}}}{F_{\text{rat}}} \times \frac{t_{\text{rat}}}{t_{\text{human}}}}
\]

2. Mass transport of drug or metabolite is rate limiting. When mass transport is rate limiting, the extent of intestinal drug metabolism is proportional to the probability, \( Q \), of a drug molecule encountering the surface in different diameter tubes, assuming even distribution of membrane transport and enzymatic metabolism. As shown in the following figure, the transit time for drug solution flow through a tube is:
\[
t = \frac{L}{F} = \frac{\pi r^2 L}{F}
\]
The radial diffusion time for flow from the luminal center to the wall of the tube is:
\[
f = r^2 \frac{T}{T}
\]
The ratio of the tube surface area to volume is:
\[
f = \frac{\text{Area}}{\text{Volume}} = \frac{2\pi r L}{\pi L} = \frac{2}{r}
\]
The probability, \( Q \), of a drug molecule encountering the surface is positively related to \( t \), \( T \) inverse, and \( f \) as follows.
\[
Q \propto t \cdot f \cdot \frac{1}{T} \times \frac{\pi r L \cdot 2D}{r \cdot r' \cdot F} \times \frac{L}{r \cdot F}
\]
Therefore, the scaling factor, \( j \), between rat and human is
\[
j = \frac{Q_{\text{human}}}{Q_{\text{rat}}} = \frac{L_{\text{rat}}}{L_{\text{human}} \times F_{\text{human}} \times \frac{r_{\text{rat}}}{r_{\text{human}}} \times \frac{F_{\text{human}}}{F_{\text{rat}}} \times \frac{t_{\text{rat}}}{t_{\text{human}}}}
\]

In a previous report by Hui et al. (1994) comparing intestinal cimetidine metabolite production from rat versus human jejunal perfusions, the jejunal, diameter, length, and perfusion rate were 0.23 and 1.25 cm, 10 and 50 cm, 0.12 and 10 ml/min in rat and human, respectively. Using the scaling factor-derived estimates outlined above, cimetidine metabolism is projected to be 88-fold greater in rat than human. When luminal concentration is limited by dosage form release rate, the probability of cimetidine absorption was measured to be 3 and 6% of initial drug concentration over 50 cm of jejunum in two human subjects. Based on geometric considerations, the corresponding metabolism in rats would be projected to be over 100% and 9 to 18% of initial drug perfusion concentration for luminal mass transport and metabolism rate limits, respectively. Given that metabolism formation occurred at 20% in the rat in this study, metabolism limitations would appear to play a more significant role in controlling the extent of intestinal metabolism production than luminal transport differences. Given the assumptions made, these calculations also indicate that the extent of metabolism production in the human jejunum is significant and similar to that in rat jejunum. Luminal metabolism formation results from the sequential events of luminal drug transport to the epithelial membrane, intracellular drug uptake, intracellular drug metabolism, and metabolite excretion into the lumen. Thus, the fact that luminal drug transport is not rate limiting to metabolite formation is consistent with membrane control of intracellular cimetidine uptake and subsequent metabolism and metabolite elimination into the intestinal lumen as detailed in Results and Discussion.

References


