Effect of luminal pH on the output of bicarbonate and PGE$_2$ by the normal human stomach

J R Crampton, L C Gibbons, and W D W Rees

From the Department of Gastroenterology, Hope Hospital, University of Manchester School of Medicine, Salford

SUMMARY The gastric output of bicarbonate and prostaglandin E$_2$ has been calculated using a perfusion technique before and after instillation of 100 mM hydrochloric acid into the stomach of seven healthy volunteers. A significant increase in bicarbonate output occurred from 258±38 μmol/30 min during the basal period to 531±86 μmol/30 min after return of the intragastric pH to neutral (p<0.05). Prostaglandin E$_2$ output also increased significantly from 410±136 pmol/30 min to 1002±194 pmol/30 min (p<0.05). The changes were caused mainly by an increase in gastric secretory volume with only non-significant increases in concentrations of bicarbonate and prostaglandin E$_2$. The results suggest that mechanisms exist to adjust the rate of gastric bicarbonate secretion to the prevailing intraluminal pH and that this may occur through the release of prostaglandin E$_2$.

The existence of an alkaline secretion by gastric and duodenal mucosa of experimental animals and man has now been established. Evidence indicates that it is able to create a pH gradient across the adherent mucus gel and that this ‘mucus-bicarbonate’ barrier may constitute a first line defence against acid damage. In order for such a barrier to remain intact under varying intraluminal conditions the rate of bicarbonate secretion may alter according to luminal pH. Evidence from animal experiments both in vitro and in vivo indicates that this can occur and that the response may be due to endogenous prostaglandins. This study has examined whether gastric bicarbonate secretion in man can be influenced by luminal acid.

Methods

MEASUREMENT OF GASTRIC BICARBONATE SECRETION

This was according to a modification of a method previously described. After an overnight fast seven healthy volunteers (aged 22–54, mean 32 yr) swallowed a multilumen polyethylene tube which was positioned by fluoroscopy with its tip in the second or third part of the duodenum (Fig. 1). Ranitidine was administered (150 mg orally one hour before the study followed by 25 mg/h iv during perfusion) to maintain an intragastric pH between 6 and 7. Resting gastric contents were aspirated before perfusion and all saliva was removed with a dental sucker for the duration of the experiment. Under these conditions salivary contamination accounts for only 3% of measured gastric bicarbonate. The stomach was perfused with $^3$H-polyethylene glycol (12.5 μCi/l in saline at pH 7.4; 2 ml/min) and the duodenum with $^{14}$C-polyethylene glycol (12.5 μCi/l, in saline at pH 7.4; 2 ml/min). Aspiration sites were
positioned in antrum and distal duodenum. Samples from the aspiration sites were collected by continuous suction at 10 min intervals for measurement of marker concentration. One millilitre samples were separated on ice and used for the measurement of prostaglandin E₂ concentration. In the middle of each sampling period a separate 1 ml aliquot was aspirated using a closed cooled syringe for immediate determination of pH and pCO₂.

**Analytical Methods**

Concentrations of ³H-PEG and ¹⁴C-PEG in the samples were measured by liquid scintillation counting (LKB Wallace 2000 Beta Counter, one ml aspirate with 10 ml PCS scintillant) with quenching correction by the external standards channels ratio method. The pH and pCO₂ of the samples were measured immediately using a Corning 170 Blood Gas Analyser where pH was greater than 6 and a Radiometer Copenhagen pH meter 28 when the pH was strongly acidic using the same calibration buffers. Prostaglandin E₂ concentrations were measured by radioimmunoassay after extraction into 2 ml ethyl ether, evaporation and resuspension into 1 ml radioimmunoassay buffer. Pasteur antiserum was used and the interassay coefficient of variation for standards was 6%. In these experiments assays of gastric samples at two fold dilutions gave similar results (105±9%, mean±SD, n=4). Additional experiments using exogenous PGE₂ addition revealed a good correlation between amount added and amounts measured (measured calculated as 101±17% added, mean±SD, n=8) suggesting very low cross reactivity with potentially interfering substances. Furthermore the PGE₂ antiserum used showed selective reactivity with material chromatographing with PGE₂.

**Experimental Design**

After an equilibration period of two hours basal bicarbonate secretion was measured for 60 minutes. The gastric perfusate was then changed to ³H-PEG in 100 mM HCl (100 mM HCl plus 50 mM NaCl to maintain osmolality, at pH 1·6; 2 ml/min). The acidified marker was perfused for 30 minutes after which the original perfusate at pH 7·4 was recommenced. Aspiration continued throughout so that bicarbonate secretion during the pre and post acid periods could be calculated.

**Calculation of Results**

Effective gastric and duodenal volumes were calculated according to marker dilution and perfusion rate. Duodenogastric reflux was calculated according to the amount of ¹⁴C-PEG appearing in the gastric aspirate. Free bicarbonate concentration was calculated according to the Henderson-Hasselbach equation and added to the CO₂ bicarbonate (pCO₂× solubility constant (0·031)) to give a figure for total bicarbonate concentration. Bicarbonate output was calculated as the product of volume and concentration and was corrected for refluxed bicarbonate. Prostaglandin E₂ output likewise was the product of prostaglandin E₂ concentration and volume. All outputs were expressed as mean±SEM per 30 minutes. Differences before and after acid perfusion were assessed by a paired t-test for significance.

**Results**

**Gastric pH and pCO₂**

Mean basal gastric pH under these circumstances was 6·40±0·10. During acid perfusion (Fig. 2) gastric pH fell reaching a nadir after 30 minutes of 2·21±0·14 and thereafter gradually rose as the infused acid was cleared. The mean resting pCO₂ was 35·9±3·1 mm Hg which increased to a maximum of 88·9±10·8 mm Hg during acid perfusion and fell again to levels close to basal as the pH was restored to near neutral.

**Bicarbonate Concentration**

Basal bicarbonate concentration in the gastric aspirate was 3·58±0·24 mmol/l. It was not possible to measure accurately bicarbonate concentration when the gastric pH fell below 5. At or below this pH, virtually all the bicarbonate present is in the form of CO₂ which equilibrates rapidly with air within the gastric lumen. This process is rapid at high levels of pCO₂ and thus causes inaccuracies of pCO₂ measurement. Under basal conditions where pCO₂ is similar to that occurring in plasma the losses are minimal. Furthermore high values of pCO₂ are inaccurately measured by instruments calibrated for blood gas analysis. In these experiments, however, bicarbonate concentration can be measured once the pH returns to near neutral. Bicarbonate concentration in the aspirated samples was at its highest in the 30 minute period after acid instillation (4·61±0·28 mmol/l) although the difference from basal was not statistically significant (p=0·3).
Effect of luminal pH on the output of bicarbonate and PGE$_2$ by the normal human stomach

SECRETORY VOLUMES
Basal secretory volume was calculated as \(28.6 \pm 5.6\) ml/30 min which increased to \(75.5 \pm 17.5\) ml/30 min after acid perfusion \((p<0.05)\) and thereafter declined to levels close to basal \((32.6 \pm 9.7\) ml/30 min\) (Fig. 3). Marker recovery ranged between 32 and 86% \((\text{mean} 62\%)\) and was consistent for individuals.

BICARBONATE OUTPUT
Gastric bicarbonate output increased in the 'post acid' period from a basal of \(258 \pm 38\) pmol/30 min to a peak of \(531 \pm 86\) pmol/30 min after restoration of neutral pH (Fig. 4). Calculation of refluxed bicarbonate indicated that there was no alteration in duodenogastric reflux \((\text{basal refluxed bicarbonate} 89 \pm 26\) pmol/30 min compared with \(55 \pm 22\) pmol/ min after acid).

PROSTAGLANDIN E$_2$ OUTPUT
Prostaglandin E$_2$ concentrations reached their highest in the 'post acid' period \((20 \pm 5\) pmol/ml compared with \(14 \pm 4\) pmol/ml in the basal period) although the difference failed to reach significance \((p=0.2)\). When expressed as an output, however, there was a significant increase in prostaglandin E$_2$ output from a basal of \(411 \pm 136\) pmol/30 min to \(1002 \pm 194\) pmol/30 min \((p<0.05)\) which declined as the pH was restored to normal (Fig. 5).

Discussion
In order to provide effective mucosal protection the mucus-bicarbonate barrier needs to be maintained in a dynamic equilibrium with luminal acid and pepsin so that the pH gradient is preserved and the epithelium undamaged. The mucus gel layer, an important constituent of the barrier, is under a state of continued erosion by luminal pepsin and replenishment occurs by fresh production or secretion of preformed mucus. Bicarbonate secretion into the mucus gel is continually neutralised by luminal acid creating a pH gradient and steady state secre-
tion in able to maintain the gradient under most luminal conditions. Evidence from in vitro experiments indicates that under acidic conditions where luminal pH falls below 1.4, the gradient may be overwhelmed. It is likely, however, that in vivo secretion of bicarbonate is modulated by various neurohormonal control mechanisms which may increase bicarbonate output in accordance with increased requirements. One mechanism which may be of importance in maintaining the integrity of the mucus-bicarbonate barrier is a response of epithelial bicarbonate secretion to luminal acid. Experiments in dogs with Heidenhain pouches indicate that bicarbonate secretion by the pouch is increased dramatically by the instillation of acid into the main stomach. In addition in vitro experiments on isolated mucosa using a paired chamber with a common serosal side solution show that acidification of one mucosa is capable of increasing bicarbonate secretion by the other. In man a response of proximal duodenal bicarbonate secretion to luminal acid has been demonstrated and this has been shown to be attenuated in patients with duodenal ulcer but no studies to date have examined the effect of luminal pH on gastric bicarbonate secretion. Because this response may play an important role in the dynamics of gastric mucosal protection we have examined the effect of acid on bicarbonate output by the normal human stomach.

Our results indicate that acid perfusion produces an increase in gastric secretory volume. The secretion contains more bicarbonate than in the resting state and the output is significantly increased. The response represents a doubling of the basal rate even though in these experiments the luminal pH fell only to 2. It is possible that higher increments may be seen in the presence of lower pH levels which are frequently achieved in vivo under normal conditions. Although bicarbonate output could not be measured during acid perfusion the increase in volume occurred while the pH was low and that combined with the high pCO2 levels suggests that bicarbonate secretion was actually increased during acid perfusion.

Furthermore the increase in secretory volume may itself be important as mathematical analysis of a model of the mucus-bicarbonate barrier indicates volume flux as a vital component of the equilibrium. In these experiments the measured change in bicarbonate output observed occurred on return of the pH to near neutral. Although an apparently late response it is important to appreciate that return to neutrality occurred in the experimental situation due to aspiration of acid, which may be very different to normal gastric acid disposal which is likely to be slower.

There are a number of possible mechanisms for the response to intraluminal acid observed in this study. Gastric bicarbonate secretion may be stimulated by cholinergic agents, calcium, cGMP, E and F-type prostaglandins, CCK, and pancreatic glucagon. Similarly inhibition of bicarbonate secretion by indomethacin implies that endogenous prostaglandins are involved in regulating basal secretion. Prostaglandin E2 analogues have been shown to increase gastric epithelial bicarbonate secretion in vitro. In high doses in man this effect can also be demonstrated. In lower doses, however, prostaglandin E2 analogues do not stimulate bicarbonate secretion in man but do prevent the inhibition induced by aspirin or taurocholate indicating that endogenous prostaglandins are implicated in modulating basal secretion. Animal experiments have suggested that the response to luminal acid occurs via local release of prostaglandins. A recent study has reported that acid instillation into the human stomach increases luminal prostaglandin E2 output and clearly the similar effect shown in our study may be responsible for the secretory response observed.

The increased output of prostaglandin E2 observed in these experiments may be important both in relation to the bicarbonate response and to other mechanisms of mucosal protection. Prostaglandin E2 is capable of increasing mucus gel thickness and release, increasing mucosal blood flow, affecting epithelial cell surface hydrophobicity and cellular restitution after injury, all of which are likely to be important in mucosal protection. The prostaglandin E2 output rose in our studies as the pH fell and declined again as neutrality was restored indicating the close relationship between pH and secretory response by gastric mucosa.

In conclusion these experiments indicate the presence of an autoregulatory mechanism which may be capable of maintaining the gastric mucus-bicarbonate barrier and mucosal integrity under varying luminal acidity. Studies to evaluate the integrity of this response in patients with peptic ulcer disease would clearly be of interest.

The authors wish to thank Ms J Rostron for secretarial assistance and the Department of Medical Illustration for preparing the figures. Dr Crampton is in receipt of a North West Regional Health Authority Grant.

References


Effect of luminal pH on the output of bicarbonate and $\text{PGE}_2$ by the normal human stomach

3 Heylings JR, Garner A, Flemström G. Regulation of gastroduodenal $\text{HCO}_3^-$ by luminal acid in the frog in vitro. *Am J Physiol* 1984; 246 (Gastrointest Liver Physiol 9); G235–42.


