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The adherent gastrointestinal mucus gel layer: thickness and physical state in vivo

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The adherent gastrointestinal mucus gel layer: thickness and physical state in vivo. Am J Physiol Gastrointest Liver Physiol 280: G922–G929, 2001.—Divergent results from in vitro studies on the thickness and appearance of the gastrointestinal mucus layer have previously been reported. With an in vivo model, we studied mucus gel thickness over time from stomach to colon. The gastrointestinal tissues of Inactin-anesthetized rats were mounted luminal side up for intravital microscopy. Mucus thickness was measured with a micropipette before and after mucus removal by suction. The mucus layer was translucent and continuous; it was thickest in the colon (~830 μm) and thinnest in the jejenum (~123 μm). On mucus removal, a continuous, firmly adherent mucus layer remained attached to the epithelial surface in the corpus (~80 μm), antrum (~154 μm), and colon (~116 μm). In the small intestine, this layer was very thin (~20 μm) or absent. After mucus removal, there was a continuous increase in mucus thickness with the highest rate in the colon and the lowest rate in the stomach. In conclusion, the adherent gastrointestinal mucus gel in vivo is continuous and can be divided into two layers: a loosely adherent layer removable by suction and a layer firmly attached to the mucosa.

MUCUS IS SECRETED BY THE epithelial surfaces throughout the gastrointestinal tract from the stomach to the colon. It is a unique secretion in that it forms a gel adherent to the surface that provides a protective barrier between the underlying epithelium and the lumen containing noxious agents, destructive hydrolases, and microorganisms (2, 4, 16). The protective functions of this adherent mucus gel layer have mostly been studied (3, 12) in the stomach and duodenum, where it provides a stable microenvironment at the mucosal surface. The mucus layer is a balance between its secretory rate and its erosion through enzymatic digestion by luminal proteases and mechanical shear (2, 5). Thus continuous secretion of mucus maintains its protective mucosal barrier properties. However, the mucus layer can be compromised in pathological states such as Helicobacter pylori infection, peptic ulcer disease, and ulcerative colitis, during which both mucus thickness and structure are major targets (7, 31, 34, 35, 42, 47).

The functional efficacy of the adherent mucus layer depends on its thickness and stability in vivo as well as the physical and chemical properties of the gel. Various methods have been used to visualize and measure the thickness of the mucus layer in situ. The original methods for measuring mucus thickness consisted of observing unfixed sections of fresh mucosa using an inverted microscope (26) or estimating mucus thickness suggested to occur through restricted channel-like areas stretching out from the gland openings through the overlying adherent mucus layer (20, 21, 24). In this way, newly produced acid and pepsin are also prevented from diffusing freely through the mucus gel and accessing the mucosal surface.

The functions of the mucus layer in the small intestine and colon are less well defined. Throughout the gut, the viscous mucus secretion acts as a lubricant facilitating the passage of digestive matter and protecting the underlying epithelium from excessive mechanical stress. Moreover, within the unstirred layer of the mucus gel a stable microenvironment is created at the mucosal surface. The mucus layer provides a protective barrier against pathogens by acting as a physical barrier, having binding sites for the bacterial adhesins, maintaining high concentrations of secreted IgA and lysozyme at the epithelial surface, and acting as a free radical scavenger (2, 11, 13, 16, 30, 36, 38). At the same time in the colon, the mucus layer provides an essential environment for the enteric microflora (4, 28).

Regulation of mucus secretion has been coupled to neural, hormonal, and paracrine effects (2, 9, 15, 16, 23, 33, 40). Normally, the thickness of the adherent gastrointestinal mucus layer is a balance between its secretion rate and its erosion through enzymatic digestion by luminal proteases and mechanical shear (2, 5). Thus continuous secretion of mucus maintains its protective mucosal barrier properties. However, the mucus layer can be compromised in pathological states such as Helicobacter pylori infection, peptic ulcer disease, and ulcerative colitis, during which both mucus thickness and structure are major targets (7, 31, 34, 35, 42, 47).

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ness over inverted mucosa with a slit lamp and pachymeter (8). Histological methods employing organic fixatives and paraffin embedding have proven unsuccessful because dehydration of the gel causes severe shrinkage and loss of the adherent mucus layer (2, 25, 29, 44). A recently developed histological method (25) has successfully circumvented these problems. These different techniques have yielded varying results and have usually only covered a limited region of the gastrointestinal tract. The potential for loss and shrinkage of the mucus gel with in vitro techniques makes it essential that methods are used in which the mucus gel can be observed in vivo. Extensive studies (21, 40, 41) have been made using intravital microscopy to observe gastric and duodenal mucus in vivo, and more recently (10), confocal microscopy has been applied to study the gastric mucus layer in an in vivo system.

In this study, we used a micropipette technique with intravital microscopy to study mucus gel thickness and accumulation rate in each segment of the gastrointestinal tract over time. In this way, we obtained results that are comparable and project an image of the characteristics and stability of the mucus gel layer in vivo from the gastric corporal region down to the colon. In particular, we show for the first time in vivo that there are two forms of mucus gel: a suction-removable layer and an underlying firm adherent gel layer.

**MATERIALS AND METHODS**

**Animal Preparation**

Male Wistar rats weighing ~200 g were fasted for 18–24 h before induction of anesthesia but were allowed free access to drinking water. They were anesthetized by intraperitoneal administration of thiobutabarbital sodium (Inactin, 120 mg/kg). Body temperature was maintained at 37–38°C with a heating pad regulated by a rectal thermistor probe.

The rats were tracheotomized to facilitate spontaneous breathing. A cannula containing heparin (12.5 IU/ml) dissolved in isotonic saline was placed in the right femoral artery to monitor blood pressure. The femoral vein was can-
duled for continuous infusion of a modified Ringer solution containing 10 mmol/l NaCl, 10 mmol/l NaHCO3, 1.2 mmol/l CaCl2, 1.2 mmol/l KCl, 1.6 mmol/l NaH2PO4, 2.5 mmol/l glucose, and 1.2 mmol/l MgCl2, all adjusted to pH 7.4 with NaOH. The content was determined by automatic back titration (ABU 91 autoburette with TIM 90 titration manager; Radiometer, Copenhagen, Denmark) to the pH of the applied saline solution.

**Mucus Gel Thickness Measuring System**

Briefly, glass micropipettes (custom glass tubing; OD, 1.2 mm; ID, 0.6 mm; Rederick Haer, Brunswick, ME) were pulled to a tip diameter of 1–2 μm (40). They were siliconized to obtain a nonsticky surface, which facilitates repeated measurements.

Before the first measurement, the mucus gel was covered with enough carbon particles (activated charcoal, extra pure, Kebo Lab) suspended in saline to visualize the surface of the otherwise near-transparent gel. The micropipettes were held by a micromanipulator (Leitz, Wetzlar, Germany) and pushed into the mucus gel at an angle (a) of 35–45° to the cell surface. The distance (l) from the luminal surface of the mucus layer to the epithelial cell surface of the mucosa or the top of the villi was measured with a “digimatic indicator” (IDC series 543; Mitutoyo, Tokyo, Japan) connected to the micromanipulator. The mucus gel thickness (T) could then be calculated from the formula $T = l \times \sin a$. The measurements were made at three to seven different spots or villi over the mucosal surface, which were memorized and used on every measurement occasion throughout the experiment.

**Mucus Accumulation Measurement**

Mucus accumulation was determined by measuring total mucus thickness at regular intervals, before and after removal by suction of as much as possible of the adherent mucus gel layer. Before removal, the mucus gel was covered with enough carbon particles to properly visualize the entire mucus gel surface. A vacuum suction pump connected to a PE-10 cannula was used to suck off the mucus, with care taken to avoid contact with the underlying cell layer. The procedure was carried out under observation through the stereomicroscope.

**Experimental Protocol**

In all animals, blood pressure and body temperature were monitored continuously during the entire experiment.

**Corpus.** Mucus measurements were made in the corpus of six animals. Each animal was allowed a recovery period of 2 h after the stomach was mounted to attain a stable blood pressure and spontaneous acid secretion. Total mucus thickness was measured at 20-min intervals over 80 min to determine basal mucus accumulation rate. As much as possible of the mucus gel was then removed by suction, and mucus accumulation was measured over the next 140 min. Measurements were made immediately after mucus removal, at 20-min intervals over 80 min, and at 140 min after mucus removal. Acid secretion was followed at 20-min intervals throughout the experiment.

**Antrum.** Measurements were made in six animals. Each animal was allowed 2–3 h to stabilize after the antrum was...
mounted until a stable blood pressure was attained and a nonacidic pH in the mucosal chamber was ascertained. The solution in the mucosal chamber was replaced at 20-min intervals throughout the experiment. Mucus measurements were made as described above for the corpus.

**Duodenum.** The duodenum was studied ~2 cm from the pylorus in seven animals. Each animal was allowed a recovery period of ~1 h after the duodenum was mounted. The recovery period for these animals was shorter than for animals in the corpus and antrum studies because the mucus gel slowly became opaque over time, making it difficult to perform thickness measurements before mucus removal. Total mucus thickness was measured, to the tops of the villi, at 15-min intervals for 90 min before the first mucus removal. Subsequently, mucus thickness was measured at 15-min intervals for another 90 min. The mucus gel was removed by suction for a second time, and a final mucus thickness measurement was taken immediately.

**Jejunum.** The mucus gel was studied 15 cm from the pylorus in six animals. Each animal was allowed to recover for 1 h after the intestine was mounted, because the mucus gel became opaque over time similar to that in the duodenum. Mucus thickness was measured as described above for the duodenum.

**Ileum.** The mucus gel in the ileum was studied 5 cm proximal to the cecum in eight animals. The animals were allowed a recovery period of 1–2 h. In three animals, the mucus gel became too opaque to allow accurate measurements before the first mucus removal. In five animals, successful measurements were made at 15-min intervals for 45 min. After the first mucus removal, measurements were made at 15-min intervals for 30 min and thereafter at 30-min intervals for another 60 min. Mucus was removed by suction a second time, and a final measurement was made.

**Colon.** Measurements were made 1–2 cm distal to the cecum in 11 animals. The animals were allowed to recover for 1–2 h. Total mucus thickness was measured at 15-min intervals for 90 min before the first mucus removal. Mucus thickness was then measured at 15-min intervals for another 90 min. The mucus gel was removed by suction a second time, and mucus thickness was measured immediately. The measurements were made to the mucosal surface at the top of the observed mucosal folds.

**Chemicals and solutions**

Inactin was purchased from Research Biochemicals International (Natick, MA), and heparin was from Kabi Pharmacia (Stockholm, Sweden). The modified Ringer solution contained 120 mM NaCl, 2.5 mM KCl, 25 mM NaHCO$_3$, and 0.75 mM CaCl$_2$, which were all purchased from Kebo Lab.

**Statistics**

All values are presented as means ± SE. Statistical significance was determined by using an ANOVA factorial analysis (followed by Fischer’s protected least-significant difference (PLSD) test) to compare the mucus thickness values between different groups. Differences in accumulation rate were determined by comparing (using an ANOVA factorial analysis followed by Fischer’s PLSD test) the accumulation rates for corresponding time intervals between different groups. Student’s t-test for unpaired measurements was used to compare single mucus thickness values. The level of significance was set at $P < 0.05$. All statistical calculations were performed on a Macintosh computer using Statview-SE and Graphics software (Abacus Concepts, Berkeley, CA).

**RESULTS**

**Corpus**

A clear mucus gel covered the corporal mucosa in its basal state immediately after the stomach was mounted. In some rats, a loose, sloppy mucus layer easily detached from the mucous gel due to the shear forces when the mucosal chamber was filled with saline, leaving a continuous adherent gel layer. Total mucus thickness (189 ± 11 μm) (Fig. 1) did not change over the first 80 min (Fig. 2 and Table 1). Over one-half of this mucus layer was removed by suction, leaving a firmly adherent mucus layer 80 ± 5 μm thick attached to the mucosal surface (Fig. 1). This mucus layer was continuous with a relatively smooth surface, could not be removed by further suction or wiping with a cotton swab (in pilot experiments), and was consistent from one experiment to another. After removal of the loosely adherent mucus, there was a progressive increase in mucus thickness. This increase was rapid during the first 20 min but decreased with time (Fig. 2 and Table 1). The spontaneous acid secretion at the beginning of the experiment was 0.14 ± 0.05 μeq·min$^{-1}$·cm$^{-2}$ and remained stable until the last 20-min period (200 min later) when it significantly increased to 0.5 ± 0.18 μeq·min$^{-1}$·cm$^{-2}$.

**Antrum**

A clear mucus gel 274 ± 41 μm thick covered the antrum (Fig. 1). Again, in some cases, a loose, sloppy mucus was easily detached from the mucous gel when the mucosal chamber was filled with saline immediately after mounting the antrum. There was no change in the thickness of this mucus layer during the first 80 min (Fig. 2 and Table 1). Suction removed about two-fifths of the mucus layer, leaving a 154 ± 16-μm-thick, firmly adherent, continuous mucus layer over the mucosal surface (Figs. 1 and 2). A rapid replacement of the mucus removed by suction ensued with a constant rate during the first 60 min followed by a more reduced rate during the last 80 min (Fig. 2 and Table 1). In a few animals the mucus gel closest to the mucosal surface became slightly opaque over time.

**Duodenum**

Immediately after the duodenum was mounted, the mucus gel was translucent and continuous. It had an even surface and did not follow the contours of the villi (Fig. 1). The mucus gel became opaque over time, starting from the surface of the villi and moving upward with the mucus accumulation. A loose, sloppy mucus layer up to 600 μm thick was seen in a few animals. This mucus was easily detached from the underlying adherent mucus gel, and it attached to the micropipette used in the measurements or was flushed off the first time the solution in the chamber was changed. In general, the adherent mucus layer over the duodenum was more loosely attached than that in the stomach.
The mean mucus thickness of the mucus layer immediately after the equilibration period was 170 ± 38 μm and increased continuously during the first 90-min period (Fig. 3 and Table 1). With careful suction, practically the whole mucus gel layer could be removed down to and between the villi. The opaque mucus closest to the villi was thicker than the translucent mucus gel and was somewhat more resistant to removal, especially in the space between villi. The mean thickness of the remaining firmly adherent mucus gel varied from 6 to 24 μm (mean thickness, 16 ± 3 μm) in the six animals (Figs. 1 and 3). However, in individual animals the thickness could vary between different areas in a patchy manner and be absent on individual villi immediately after suction. The increase in mucus thickness after removal by suction was less rapid than that before removal (Table 1). The second removal of the mucus gel (at 190 min) was easier, and the remaining firmly adherent mucus layer was 10 ± 3 μm thinner than that after the first removal (at 90 min) (Fig. 3).

Fig. 1. A schematic figure showing the thicknesses of the 2 mucus gel layers in vivo in the corpus, antrum, midduodenum, proximal jejunum, distal ileum, and proximal colon of the rat gastrointestinal tract. The mucus gel layer was continuous and did not follow the contours of the villi in the intestine. However, on removal of the loosely adherent layer, mucus was also removed between the villi, leaving behind a firmly adherent mucus layer attached to the mucosa. In the stomach and colon, the firmly adherent layer was continuous, but in the small intestine the firmly adherent layer had a patchy distribution and was absent on individual villi. Both mucus gel layers were translucent. The loosely adherent mucus layer was removable by careful suction, whereas the firmly adherent mucus layer was not. The table presents values for mucus thickness as means ± SE for each group.

Fig. 2. Total mucus thickness over time before and after removal of the loosely adherent mucus layer in the corpus (●; n = 6) and antrum (○; n = 6) of the rat stomach. Values are means ± SE and represent the total mucus thickness at each time point. *P < 0.05, corpus vs. antrum.
Table 1. Mucus accumulation rates in gastrointestinal tract before and after mucus removal by applied suction

<table>
<thead>
<tr>
<th></th>
<th>Before Removal (0–80 min), µm/min</th>
<th>After Removal, µm/min</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–20 min</td>
<td>20–40 min</td>
<td>40–140 min</td>
</tr>
<tr>
<td>Corpus</td>
<td>−0.04 ± 0.1</td>
<td>0.9 ± 0.1</td>
<td>0.06 ± 0.04</td>
</tr>
<tr>
<td>Antrum</td>
<td>−0.08 ± 0.1</td>
<td>1.3 ± 0.3</td>
<td>0.3 ± 0.08*</td>
</tr>
</tbody>
</table>

Values are means ± SE for each interval. By multiplying the values by 100 the volume-secretion rate in nl·min⁻¹·cm⁻² may be obtained. ND, not determined. *P < 0.05, antrum vs. corpus at same time interval. †P < 0.05, ileum vs. other areas of small intestine at same time interval. (ANOVA followed by Fischer’s protected least-significant difference test).

Jejunum

The mucus gel was similar to that in the duodenum, although no loose, sloppy mucus was observed. With time, opaque, thick mucus was secreted from the villi, making mucus measurements difficult. The mean mucus thickness immediately after the equilibration period was 123 ± 4 µm (Fig. 1), and this increased continuously during the first 90-min period before mucus removal (Fig. 3 and Table 1). After mucus removal by suction, a very thin layer of firmly adherent mucus (mean thickness, 15 ± 2 µm) remained, similar to that in the duodenum (Fig. 1). In the jejunum as well, individual villi tips could be completely devoid of mucus immediately after suction. Mucus thickness started to increase immediately after removal and continued at an even rate for 90 min (Fig. 3 and Table 1). The second removal of mucus (at 190 min) left behind a 15 ± 3-µm-thick, firmly adherent mucus layer, in all aspects similar to that observed after the first mucus removal (at 90 min).

Ileum

The mucus gel layer in the ileum (mean thickness, 480 ± 47 µm) was significantly thicker than in the first part of the small intestine as described above (Fig. 1). The mucus gel was initially translucent but became opaque over time, making measurements difficult and in some cases impossible. In five animals, a rapid continuous increase in mucus thickness was observed for 45 min (Fig. 3 and Table 1). This was a significantly higher rate of increase than that observed in the duodenum and jejunum. In all eight animals, the mucus gel layer, including the opaque mucus, was easily removed by suction to leave again a thin, uneven, and discontinuous mucus layer (mean thickness, 29 ± 8 µm) firmly adherent to the villi tips (Fig. 1). The accumulation rate for the last 90 min was not significantly different from that in the duodenum and jejunum (Fig. 3 and Table 1). A 29 ± 4-µm-thick, discontinuous mucus layer remained after the second mucus removal (at 190 min), which was similar to that after the first removal (at 90 min).

Colon

The colonic mucus gel was translucent and very thick (mean thickness, 830 ± 110 µm) with a sloppy appearance (Fig. 1). Like the corpus but unlike the small intestine, the mucus gel in the colon remained clear throughout the experiment and showed no sign of becoming opaque. There was a rapid increase in mucus gel thickness during the first 90-min period (Fig. 4 and Table 1). The loosely adherent upper mucus gel layer was easily removed by suction (at 90 min). A firmly adherent mucus gel layer with a mean thickness of 116 ± 51 µm remained attached to the mucosal surface (Figs. 1 and 4). This mucus layer was continuous, covering the entire mucosal surface, and had a relatively even surface. A rapid increase in thickness of the

![Fig. 3. Total mucus thickness over time in the rat small intestine before and after removal of the loosely adherent mucus layer.](image)
mucus gel layer followed during the next 90-min period (Fig. 4 and Table 1). After the second mucus removal (at 190 min), a 67 ± 1-μm-thick, firmly adherent layer remained (Fig. 4). This layer was significantly thinner than that after the first mucus removal (at 90 min).

**DISCUSSION**

This study measures mucus thickness and secretion after its partial removal, from stomach to colon, in the rat in vivo by intravital microscopy. Key findings for all regions of the gut studied are as follows: 1) the mucus layer is continuous and substantially thicker than in previous measurements made in vitro (2, 6, 25, 29, 39, 43, 44) and 2) the mucus layer consists of two components, a loosely adherent gel that can be removed by suction and an underlying firmly adherent gel that remains. The relative thickness of the two component layers of the mucus gel varies for different regions of the gut. Thus in the stomach, the thickness of the firmly adherent mucus component is 80 and 154 μm for the corpus and antrum, respectively, with an overlying layer, of similar thickness, of loosely adherent mucus that can be removed by suction. In contrast, in the small intestine, practically all of the mucus gel could be removed by suction to leave a very thin discontinuous mucus gel layer, with several tops of the villi apparently free of mucus. In these studies, the mucus between villi was also removed during the suction procedure, which otherwise would offer an ~500-μm-thick layer covering the crypts and the basal villus epithelium. In the colon (mean mucus thickness, 830 μm), and to a lesser extent the ileum, the mucus layer was very thick (up to 4-fold thicker) compared with that in other regions of the gut. Most of the difference in mucus thickness was due to the loosely adherent mucus. Thus in the colon, 86% of the mucus layer was removed by suction to leave a firmly adherent gel of similar thickness to that in the stomach.

During resting conditions, mucus thickness was constant over time in the stomach. A most interesting observation was that removal of the loosely adherent mucus layer by suction stimulated the accumulation of new mucus in the stomach. The rate of increase in thickness was higher in the antrum compared with the corpus, although there was no difference in the amount of loosely adherent mucus gel present in the two regions before mucus removal. This increase in mucus thickness was solely a renewal of the loosely adherent mucus layer, because the thickness of the firmly adherent mucus layer was the same after a second mucus removal as that following the initial mucus removal by suction. In another study, using the same experimental setup, the gastric pathogen *Helicobacter pylori* has been shown to reduce the rate of renewal of the mucus layer removed by suction, as well as an acid-induced increase in its renewal rate (7). Unlike the stomach, the small intestine had a continuous increase in basal mucus thickness with the lowest rate in the duodenum and the highest in the ileum. After suction, the remaining mucus layer in the intestine was very thin and discontinuous, but mucus renewal was again observed. Shear forces in vivo therefore might be expected to reduce much of the mucus layer and enhance uptake of nutrients from chyme. However, an increased mucus secretion could occur in response to local factors, e.g., irritation. Sababi et al. (40) have shown that luminal acid in the duodenum increases the rate of mucus accumulation after mucus removal by suction. In the same study, inhibition of nitric oxide (NO) and prostaglandin synthesis reduced basal mucus accumulation by 20% and 35%, respectively, after removal by suction.

In the colon, the mucus gel was thickest and the rate of mucus accumulation both in the basal state and after mucus removal was greatest. Similar to the stomach, only the loosely adherent mucus layer was renewed. This high rate of mucus accumulation in the colon could provide good lubrication, crucial to its function, and be important in providing a suitable environment for the endogenous microflora. Regulation of mucus secretion in the colon has been shown (33) to be mediated by NO, prostaglandins, and a wide range of other neurotransmitters and hormones.

In all regions of the gut, total thickness of the mucus layer was considerably greater than measurements reported for in vitro studies, up to 40-fold in the case of the colon. Standard histological methods employing organic fixatives, extensive dehydration, and paraffin embedding result in severe shrinkage of the adherent mucus layer and frequently its complete loss from the mucosal surface (2, 6). For example, in one study (39) using a modified unfixed section technique, values of 39, 18, and ~20 μm were reported for the rat stomach, cecum, and colon, respectively. However, in another study (44), using celloidin fixation of cryostat sections, approximate values for mucus thickness in the rat duodenum, jejunum, ileum, and proximal colon were 28, 93, 101, and 53 μm, respectively. A recent (25, 43) histological procedure for cryostat sections, which min-
imizes the shrinkage of the adherent mucus gel layer, gives values for mucus thickness in the rat antrum, corpus, and colon of 166, 184, and 45 μm, respectively. These values are reasonably close to those for the firmly adherent gel seen in the present study and compatible with mainly the loosely adherent gel, removable by suction in vivo, being lost during the histological procedures.

Mucus thickness in the rat stomach in vivo has been measured as 118 μm and in the duodenum as 136 μm (1, 45). With a confocal imaging system, rat corpus mucus thickness was found to have a median value in the interval 50–75 μm but with ~23% of the values in the interval 0–25 μm (10). These values are somewhat lower than the values reported here, which may largely be explained by methodological differences, with the former studies (1, 10, 45) using a perfusion system in contrast to the unstirred conditions in the present study.

The relationship of the loosely adherent gel removable by suction to the firmly adherent gel is not clear. The possibilities range from a continuum of the same secretion, which reflects a gradual diluting out of the gel the farther one proceeds from the mucosa, to two different mucus secretions. It is generally accepted that there is one major mucin gene product, MUC2, in the mucus secretion by goblet cells of the colon and small intestine in humans and its equivalent in rats (27, 46). This would tend to argue against two different mucin secretions in colon and small intestine being responsible for the firmly adherent and loosely adherent gels, although the pattern of glycosylation could be different. Interestingly, two different mucin secretions from the goblet and columnar cells of human colonic crypts, with control mechanisms restricting total mucus release, have recently been reported (17). In the stomach, there are two mucin gene products: MUC5AC from the surface epithelia and MUC6 secreted by the neck cells around the pits (19). Therefore, in the stomach, it is possible that the two layers of gel, the firmly adherent and that removed by shear, are two different mucin gene products or different mixtures of two gene products, also perhaps with differing glycosylation patterns. The possibility of a nonblended lamina-ordered gastric gel has been reported for carbohydrate staining (32) and recently for MUC5AC and MUC6 (18).

In summary, this study demonstrates the presence of two types of mucus gel secretion, one that is firmly adherent to the mucosal surface and one that is relatively sloppy and can be removed by suction. The firmly adherent gel, which forms a thick layer over the gastric and colonic mucosal surfaces, would be expected to act as a relatively stable protective barrier, whereas the sloppy mucus, which is rapidly replaced after its removal, might have more lubricative properties in vivo.

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