Demand for Zn\(^{2+}\) in Acid-Secreting Gastric Mucosa and Its Requirement for Intracellular Ca\(^{2+}\)

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Abstract

**Background and Aims:** Recent work has suggested that Zn\(^{2+}\) plays a critical role in regulating acidity within the secretory compartments of isolated gastric glands. Here, we investigate the content, distribution and demand for Zn\(^{2+}\) in gastric mucosa under baseline conditions and its regulation during secretory stimulation.

**Methods and Findings:** Content and distribution of zinc were evaluated in sections of whole gastric mucosa using X-ray fluorescence microscopy. Significant stores of Zn\(^{2+}\) were identified in neural elements of the muscularis, glandular areas enriched in parietal cells, and apical regions of the surface epithelium. In *in vivo* studies, extraction of the low abundance isotope, \(^{70}\)Zn\(^{2+}\), from the circulation was demonstrated in samples of mucosal tissue 24 hours or 72 hours after infusion (250 \(\mu\)g/kg). In *in vitro* studies, uptake of \(^{70}\)Zn\(^{2+}\) from media was demonstrated in isolated rabbit gastric glands following exposure to concentrations as low as 10 nM. In additional studies, demand of individual gastric parietal cells for Zn\(^{2+}\) was monitored using the fluorescent zinc reporter, fluozin-3, by measuring increases in free intracellular concentrations of Zn\(^{2+}\) ([Zn\(^{2+}\)]) during exposure to standard extracellular concentrations of Zn\(^{2+}\) (10 \(\mu\)M) for standard intervals of time. Under resting conditions, demand for extracellular Zn\(^{2+}\) increased with exposure to secretagogues (forskolin, carbachol/histamine) and under conditions associated with increased intracellular Ca\(^{2+}\) ([Ca\(^{2+}\)]\(_{i}\)). Uptake of Zn\(^{2+}\) was abolished following removal of extracellular Ca\(^{2+}\) or depletion of intracellular Ca\(^{2+}\) stores, suggesting that demand for extracellular Zn\(^{2+}\) increases and is dependent on influx of extracellular Ca\(^{2+}\).

**Conclusions:** This study is the first to characterize the content and distribution of Zn\(^{2+}\) in an organ of the gastrointestinal tract. Our findings offer the novel interpretation, that Ca\(^{2+}\) integrates basolateral demand for Zn\(^{2+}\) with stimulation of secretion of HCl into the lumen of the gastric gland. Similar connections may be detectable in other secretory cells and tissues.

Introduction

For many years, investigation of Zn\(^{2+}\) transport in the gastrointestinal tract has focused on nutritional requirements that maintain body stores and pathologic consequences of inadequate intake [1,2,3]. An overall deficiency of Zn\(^{2+}\) stores within the body has been implicated in the systemic susceptibility to infection [4,5] and in the pathogenesis of some cancers [6,7,8]. Also, an important physiologic role for Zn\(^{2+}\) within the lumen of the alimentary canal has been postulated, based on the observations that supplementation of oral diets with Zn\(^{2+}\) has beneficial effects on diarrhea [9,10] and inflammatory conditions [11,12,13,14] of the gastrointestinal tract.

Recent reports have begun to explore the mechanisms that regulate cellular homeostasis of Zn\(^{2+}\) in mucosal cells of the gastrointestinal tract [15,16,17,18,19] and its potential influence on mucosal integrity and function [20,21]. In gastric mucosa, adequate intracellular stores and luminal content of Zn\(^{2+}\) may regulate integrity of [19] and acid secretion by [18,22] the gastric glands and enhance protection of the mucosa as a whole against acid-peptic injury [23,24]. Little is known, however, of the content and distribution of Zn\(^{2+}\) within the mucosa, or of the mechanisms that regulate the flow of Zn\(^{2+}\) into the parietal cell during secretory stimulation.

In this study, we utilized complimentary approaches to characterize content and distribution, acquisition and demand...
for Zn$^{2+}$ in gastric mucosa of the rabbit and in its individual gastric glands, under resting conditions and during secretory stimulation. Our results indicate that there is variation in content and distribution of Zn$^{2+}$ within the gastric wall and mucosa. We find that, in vivo and in vitro, the mucosa and individual gastric glands are capable of extracting Zn$^{2+}$ from extracellular sources even when its concentration may be in the nanomolar range. In the isolated gastric gland, a multicellular model of epithelial secretion, we find that basolateral uptake of Zn$^{2+}$ is modulated by [Ca$^{2+}$]$_i$ during stimulation with agonists of apical secretion of acid. Our findings thus suggest a novel role for classical second messenger pathways in integrating secretory functions of the apical membrane with supply functions across the basolateral membrane, and may be applicable to a variety of epithelial systems.

**Methods**

**Animals and tissue procurement**

Anesthesia and euthanasia for New Zealand White rabbits were approved according to policies of Harvard Medical School (Harvard Medical Area (HMA) Standing Committee on Animals; Protocol 03359). As described previously [15,18], rabbits (female, ~2 kg) were anesthetized with ketamine and pentobarbital, undergoing midline laparotomy in order to harvest stomach tissues and glands. For studies of fixed tissue, full thickness squares (7 mm to 10 mm each side) of gastric wall from the acid secreting regions (body/fundus) were obtained, then cut into small strips and frozen in liquid nitrogen. For gland isolations, the aorta was perfused retrograde with warmed (37°C) phosphate-buffered saline, as described previously [15]. The gastric mucosa was separated from underlying muscularis. Isolated glands were prepared using published methods [15,25]. Collagenase Type I (Sigma Chemical, St. Louis, MO) was used for ~60 min digestion with BSA in Dulbecco’s Modified Eagle Medium (DMEM, Sigma Chemical, with 100 μM cimetidine, pH 7.4). Glands were used within 8 hr of isolation.

**Micro X-Ray Fluorescence Studies.** To survey the distribution of metals in the gastric mucosa, we utilized micro X-Ray Fluorescence microscopy (μXRF) [26]. In this technique, a micron-size X-ray beam is rastered over the sample. The incident X-rays excite fluorescence from elements in the sample such as Zn provided the incident energy is above the relevant absorption edge. For Zn, the edge is at 9.66 keV and the Ka fluorescence at 8.62 keV. A solid-state energy-resolving detector picks up the fluorescence and the counts in energy regions corresponding to elements of interest are recorded for each pixel. Our samples are thin enough to be transparent to both the incident and fluorescence X-rays from the detected elements. In this regime, the signals are proportional to the column densities (μg/cm$^2$) of each element, with a different sensitivity for each element.

For full thickness samples, a novel fast-freeze method was developed for near instantaneous tissue vitrification. Fixation and mounting of oriented specimens was performed on silicon wafers (Platypus Technologies, Madison, WI). Silicon substrates were used because they exhibit low background signals in XRF) [26]. In this technique, a micron-size X-ray beam is rastered over the sample. The incident X-rays excite fluorescence from elements in the sample such as Zn provided the incident energy is above the relevant absorption edge. For Zn, the edge is at 9.66 keV and the Ka fluorescence at 8.62 keV. A solid-state energy-resolving detector picks up the fluorescence and the counts in energy regions corresponding to elements of interest are recorded for each pixel. Our samples are thin enough to be transparent to both the incident and fluorescence X-rays from the detected elements. In this regime, the signals are proportional to the column densities (μg/cm$^2$) of each element, with a different sensitivity for each element.

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For high-throughput fluorometry, aliquots of glands (200 μl, ~2000 glands/well) were transferred to 96 well plates (total

**High Resolution Magnetic Sector Inductively Coupled Plasma Mass Spectrometry (HR-ICP-MS).** Among the five stable zinc isotopes, $^{64}$Zn, $^{66}$Zn, $^{68}$Zn, $^{69}$Zn and $^{70}$Zn. $^{70}$Zn is the most commonly isotopic tracer due to its low natural abundance and was used for all described experiments. The natural relative abundance for $^{70}$Zn and $^{68}$Zn are 0.6% and 18.8% respectively with an isotopic ratio of 0.0319 and any increase in this isotopic ratio is indicative of $^{70}$Zn uptake in biospecimens. Unless otherwise noted, all reagent and stock solutions were prepared in ultra-trace metal grade nitric acid (Fisher Brand, Fisher Scientific, USA) made from de-ionized water (Millipore, Billerica, MA, USA) in order to match the acid matrix resulting from the sample preparation procedure. Zinc enriched in $^{70}$Zn (99%) was obtained (Cambridge Isotope, MA, USA) and was dissolved in HCl and diluted with de-ionized water to prepare an $^{70}$Zn-enriched spiking solution of 1000 μg/L in 1% HCl/citrate. This stock solution was used to prepare standard and sample solutions for all experiments. Standard-sized tissue samples (~25 mm$^3$) or volumes of isolated glands (0.3 ml or ~2,000 glands, following settling and aspiration of supernatant media) were acid digested in aliquots of concentrated nitric acid and made up to a total volume 2 ml using de-ionized water. Analysis for isotopes $^{68}$Zn and $^{70}$Zn were performed concurrently on 1 ml samples, at the ICP-MS facility of the Institute of Marine and Coastal Sciences, Rutgers the State University, New Brunswick, NJ. An analytical methodology was developed to scan zinc isotopes using a double-focusing, single-collector Thermo Element 2 ICP-MS (Thermo, Waltham, MA, USA). Settings are shown in Table 1. Sample solutions were introduced into a spray chamber by a low-flow nebulizer using argon as a carrier gas. The signal intensity was obtained by integration of the counting signal of the scanning mass over a 2–4 min acquisition period. Sample blanks were taken into account and a natural abundance zinc standard solution was analyzed in between sample runs for quality control purposes [28]. Thus, in each sample the ratio for $^{70}$Zn/$^{68}$Zn was calculated as an index of enrichment [28].

**Fluorescence Microscopy or Plate-Reader Fluorometry for intracellular $^{65}$Zn$^{2+}$ using fluozin-3.** Concentrated preparations of freshly isolated gastric glands were diluted in DMEM to a final concentration 1.875% and loaded for 30 min to 40 min with fluozin-3AM (8 μM) [18,19]. Following transfer to glass coverslips and equilibration in standard Ringer’s solutions, fluorescence imaging of individual glands was performed as described previously [18]. Glands loaded with fluozin-3AM were excited at 488 nm with emission measurement at 520 nm. Fluorescence was monitored concurrently in 4 to 8 individual parietal cells in each isolated gland. Digital images of glands were captured using a CCD camera (Hamamatsu ORCA-ER). In order to take into account variations in starting levels between individual cells, responses were reported as a normalization to starting values ($F/F_0$) [18,19].
Figure 1. Mapping metal divalent cations in rabbit gastric mucosa. Figure 1A visualizes the section of interest with hematoxylin/eosin staining. Figure 2B, 2C and 2D provide maps at low resolution (20 × 20 μm² pixel) of Fe, Cu and Zn. In these images, white and black indicate high and low levels of the metal, respectively.
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Figure 2. Comparisons of the distributions of Zn²⁺ and other abundant cation species in a smaller region of gastric mucosa.
Region of interest is shown in the inset (Figure 2A). The pixel size is 5 × 5 μm². See text for interpretation of the color images.
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Table 1. Typical Element 2 ICP-MS Instrumental parameters for the determination of zinc isotope ratios.

| Parameter                  | Value               |
|----------------------------|---------------------|
| Forward rf power           | 1050 W              |
| Reflected rf power         | <2 W                |
| Coolant gas flow rate      | 16 L/min            |
| Auxiliary gas flow rate    | 1 L/min             |
| Nebulizer gas flow rate    | 0.8–1.2 L/min       |
| Focus lens                 | −700–900 V          |
| Y-Deflection lens          | −1–10 V             |
| Mass range                 | ⁶⁸Zn, ⁷⁰Zn           |
| Dwell time/point           | 0.005 s             |
| Points/peak                | 10                  |
| Scans/measurement          | 1500                |
| Solution uptake rate       | 20–100 μL/min       |
| Scan mode                  | E-scanning, peak-hopping |

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volume 0.50 ml) following loading of dye in media and experimental manipulations in standard (in mM: 145 NaCl, 2.5 KH₂PO₄, 1.0 MgSO₄ or 1.0 MgCl₂, 1.0 CaCl₂, 10 HEPES, and 10 glucose, pH 7.4; concentration of Zn²⁺ measured by atomic absorption is 1.2 µM, kindly determined by Dr. Shannon Kelleher, Pennsylvania State University, University Park, PA) or modified Ringer’s solutions. Readout of fluozin-3 fluorescence was performed (Excitation 485 nm/Emission 590 nm) after correction for background fluorescence of solutions and unlabelled glands [29,30]. Fluorometry was performed using a Synergy™ 2 Multi-Modest Microplate Reader (BioTek Instruments, Inc.). When comparisons to the starting fluorescence levels were required, responses were reported as a normalization to starting values (F/F₀) [18,19]. When comparing responses between groups at a single time point, the responses in total fluorescence are reported.

Special Reagents
Thapsigargin and TPEN {tetrakis-(2-pyridylmethyl)ethylenediamine} were obtained from Molecular Probes (Eugene, OR) and were dissolved in Ringer’s solutions directly. Nigericin, DTPA (diethylenetriaminepentaacetic acid) and pyritinone were obtained from Sigma-Aldrich and was dissolved under alkaline conditions, then added to Ringer’s solutions for final dilutions of 1:1000. All solutions were checked for changes in pH and adjusted if necessary to baseline pH. For Ringer’s, calculations of free and bound concentrations of Ca²⁺, Zn²⁺, TPEN, and EGTA were performed using the internet-based WEBMAXSTANDARD program (http://www.stanford.edu/~cpatton/webmaxc/webmaxcS.htm).

Data Summary and Statistical Analysis
In the microscopy imaging system, fluorescence intensities were monitored continuously throughout each experiment (SimplePCI software). At discrete time intervals, measurements were summarized as means ± SE. For comparison between treatments, unless stated otherwise, measurements in individual parietal cells (4 to 8 cells identified in each isolated gland) were combined to provide a single integrated value at each time point for each gland. Unless stated otherwise, comparisons were performed using analysis of variance for sequential or multiple measurements (Kruskal-Wallis and Tukey test for pairwise multiple comparisons), using purchased software (Sigma Stat, Version 3.5).

Results
Metal Maps of Gastric Mucosa using µXRF
Shown in Figure 1 are metal maps for individual divalent metals (Zn, Cu, Fe), demonstrating relative differences in content and distribution in the mucosa. Panel 1A provides a standard tissue frozen section, stained with hematoxylin and eosin, corresponding to a neighboring section that was used to generate metal maps [Panel 1B: Fe; Panel 1C: Cu; Panel 1D: Zn]. In these maps, white represents the maximum intensity while black areas show little or none of the relevant element. Of note, consistently strong signals for the Fe and Zn are detected in region of the surface epithelium, near the luminal interface; signals for Cu are very minimal throughout the section although perhaps more concentrated in the surface epithelium. Relatively homogenous signals for Fe are observed throughout the glandular mucosa, deep to the surface epithelium, in areas known to be populated by mitochondria-rich parietal cells [31,32]. Signal for Zn appears to be distributed within the mucosa much as that for Fe. In contrast, dense content of Zn was detected in the region of the myenteric nerve plexus, lying between the layers of muscle, whereas there was relatively little signal for Cu or Fe. As a control, samples were interrogated for Ni, a metal component of the microtome knife. No Ni was detected (data not shown) indicating that contamination of the specimen with extraneous metals was unlikely.

To further define distribution of Zn within the glandular region of the mucosa (Figure 2), a region 1.8 mm in longest dimension was scanned in more detail, comparing the distribution of Zn with other physiologically relevant elements (K, Ca, Fe). Data for K and Ca are presented in grayscale as in Figure 1, and data for Zn, Fe and K are presented in various combinations as bicolor or tricolor maps. In the bottom-most map (Figure 2D) the red intensity of each pixel represents the relative amount of Fe, the green the amount of Zn and the blue the amount of K. Thus, blue-green colors represent areas containing relatively large amounts of K and Zn together. The surface epithelium is notable for a relatively high content of Zn, compared to the glandular regions deep in the mucosa. Content and distribution of Zn²⁺ is homogeneous throughout the glandular region.

Measurements of ⁷⁰Zn²⁺ uptake in gastric mucosa and isolated gastric glands
To demonstrate that gastric mucosa acquires Zn²⁺ from the circulation, in vivo, three pairs of rabbits were injected intravenously with ⁷⁰Zn²⁺ in sterile saline (ZnSO₄, 250 µg/kg) to one animal and saline alone to the other. Gastric mucosa was harvested 24 hr later, some preserved for analysis and the rest processed for isolation of individual gastric glands. The relative abundance in nature for ⁷⁰Zn and ⁶⁸Zn are 0.6% and 18.8%; and the ratio of ⁷⁰Zn/⁶⁸Zn is 0.0319. Any enrichment of ⁷⁰Zn reflected in a higher ratio would reflect uptake in tissues and individual glands. [33]. As shown in Figure 3, ICP-MS analysis of whole mucosa and isolated glands revealed appropriate ratios of ⁷⁰Zn/⁶⁸Zn in saline injected animals, along with significant uptake of ⁷⁰Zn²⁺ in whole gastric mucosa and isolated gastric glands. Avidity of gastric mucosa for ⁷⁰Zn²⁺ is higher than that of peripheral tissues such as skin, retina, cornea and much higher than the avascular lens.

In in vitro studies, we evaluated potential threshold levels of extracellular [Zn²⁺] which would permit detection of ⁷⁰Zn²⁺ uptake by gastric mucosa. Isolated gastric glands were exposed to increasing concentrations of ⁷⁰Zn²⁺ in Ringer’s solutions (containing EGTA 0.3 mM, with Ca²⁺ adjusted to keep its free concentration 1 mM), with total content of added Zn²⁺ calculated to provide a free [Zn²⁺] of 1 nM, 10 nM or 100 nM. After 1 hour, glands were processed for ICP-MS. In unstimulated glands, evidence of accumulation started to become evident during exposure to extracellular [Zn²⁺] at 10 nM (Figure 3), although accelerated and significant uptake was more consistently observed when [Zn²⁺] reached 100 nM. These data indicate that basolateral uptake processes operate at low threshold concentrations for free extracellular Zn²⁺, consistent with those that have been predicted [34] and measured [35,36] in the circulating plasma.

Fluorescence microscopy in individual parietal cells of isolated gastric glands: dependence of Zn²⁺ uptake on [Ca²⁺]
Flux measurements of ⁷⁰Zn²⁺ reliably measure uptake in relation to small extracellular concentrations; however, they do not allow continuous monitoring of intracellular Zn²⁺ accumulation. To explore the conditions regulating acquisition of Zn²⁺ in real time, glands were loaded with fluozin-3 (Ex 485 nm/Em 520 nm) in order to monitor changes in intracellular concentration of Zn²⁺ ([Zn²⁺]) in individual parietal cells [18]. Following transfer to coverslips on a microscope stage, fluorescence was
monitored during exposure to standard Ringer’s solutions containing free [Zn\(^{2+}\)] of 10 \(\mu\)M to 50 \(\mu\)M. As shown in Figure 4A, exposure to standard Ringer’s containing an additional 10 \(\mu\)M Zn\(^{2+}\) leads immediately to increases in [Zn\(^{2+}\)]\(i\), reaching plateaus within 10 minutes. These responses were abolished during exposure to low concentrations of a membrane-permeable chelator, TPEN (10 \(\mu\)M), indicating that Zn\(^{2+}\) is the source of the fluorescence signal within the cell [37].

Utilizing fluo-3/3 measurements, previous studies in our laboratory [18] have consistently detected \textit{intracellular} accumulation of labile Zn\(^{2+}\) in isolated gastric glands when extracellular Zn\(^{2+}\) was at least 50 \(\mu\)M, and this was observed in the presence or absence of extracellular Ca\(^{2+}\). We also observed an increase in the rate of Zn\(^{2+}\) uptake when glands were exposed to the secretagogue, forskolin (10 \(\mu\)M), a finding consistent with the idea that stimulation of acid secretion across the apical membrane leads to increased demand for Zn\(^{2+}\) across the basolateral membrane. These observations were corroborated by preliminary studies indicating that exposure to forskolin (10 \(\mu\)M) enhances influx of isotopic Zn\(^{65+}\), more than three-fold over basal influx (extracellular concentration 50 \(\mu\)M, data not shown). In these \textit{in vitro} studies, when extracellular Ca\(^{2+}\) was removed, responses became less consistent, particularly if extracellular Zn\(^{2+}\) concentrations were 10 \(\mu\)M or lower. These observations led us to hypothesize that uptake of Zn\(^{2+}\) into the parietal cell might be connected to intracellular Ca\(^{2+}\) homeostasis.

To assess whether \textit{in vitro} uptake of Zn\(^{2+}\) requires the presence of Ca\(^{2+}\), a protocol was devised to totally deplete Ca\(^{2+}\) from extracellular solutions and intracellular stores. Glands pre-loaded with fluo-3/3 were perfused with Ca\(^{2+}\)-depleted Ringer’s (0.3 mM EGTA) containing 2 \(\mu\)M thapsigargin to deplete the intracellular Ca\(^{2+}\) store, followed by exposure to 10 \(\mu\)M Zn in Ca\(^{2+}\)-depleted Ringer’s. As shown in a representative recording from 5 parietal cells in a single gland in Figure 4B, Zn\(^{2+}\) accumulation was abrogated under these conditions, indicating a requirement for intracellular Ca\(^{2+}\). Exposure to thapsigargin depletes intracellular, membrane-bound stores of Ca\(^{2+}\), but activates store-operated channels at the plasma membrane [38,39]; and exposure to both thapsigargin and physiologic concentrations of extracellular Ca\(^{2+}\) lead to increases in [Ca\(^{2+}\)]\(i\), without any re-filling of stores [40]. We therefore asked whether uptake of extracellular Zn\(^{2+}\) can occur when intracellular, membrane-bound stores are depleted but store-operated entry of Ca\(^{2+}\) is present (Figure 4C). Gastric glands loaded with fluo-3/3 were exposed first to Ringer’s containing thapsigargin (2 \(\mu\)M) and no added Ca\(^{2+}\) to deplete intracellular and extracellular sources of Ca\(^{2+}\). Under these conditions no accumulation was observed in the presence of extracellular Zn\(^{2+}\) (10 \(\mu\)M). When Ca\(^{2+}\) was subsequently restored to the perfusate (1 mM) in the presence of thapsigargin, increases in [Zn\(^{2+}\)]\(i\) were observed (Figure 4C). Thus, the cell’s ability to take up extracellular Zn\(^{2+}\) requires some level of intracellular Ca\(^{2+}\) content, but not necessarily the presence of functionally intact intracellular stores of Ca\(^{2+}\).

Ca\(^{2+}\)-dependent accumulation of intracellular [Zn\(^{2+}\)] is due to influx of Zn\(^{2+}\) from extracellular sources

We next performed studies to confirm that Ca\(^{2+}\)-dependent increases in intracellular Zn\(^{2+}\) is due to influx from extracellular sources rather than release from intracellular pools. Glands loaded with fluo-3/3 were exposed initially to Ringer’s solutions containing thapsigargin (2 \(\mu\)M) and no added Ca\(^{2+}\), in order to deplete intracellular stores. These solutions also contained DTPA (10 \(\mu\)M), a chelator of Zn\(^{2+}\) that is membrane-impermeable and therefore depletes free Zn\(^{2+}\) in the extracellular perfusate but not within the cell. Under these conditions, no increase in [Zn\(^{2+}\)] was observed. Glands were then exposed to solutions containing Zn\(^{2+}\) (10 \(\mu\)M) and Ca\(^{2+}\) (1 mM) and, as expected, increases in intracellular Zn\(^{2+}\) were observed. These increases were, however, arrested when the chelator DTPA (10 \(\mu\)M) was added (Figure 5). These findings indicate that the increases in [Zn\(^{2+}\)]\(i\) are due to influx from extracellular sources and not release from intracellular pools.
Zn\(^{2+}\) demand and Ca\(^{2+}\) in gastric mucosa

In fluorescence microscopy, there is a possibility of inadvertent exchange of intracellular Ca\(^{2+}\) with extracellular Ca\(^{2+}\). These findings indicate that extracellular Ca\(^{2+}\) partially restores Zn\(^{2+}\) uptake and that uptake of Zn\(^{2+}\) across the basolateral membrane of the parietal cell is regulated by Ca\(^{2+}\). doi:10.1371/journal.pone.0019638.g004

Fluorometric measurements of [Zn\(^{2+}\)]\(_i\): evidence for Ca\(^{2+}\)/Zn\(^{2+}\) exchange

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Figure 4. Recordings from imaging studies in individual isolated gastric glands of [Zn\(\text{2+}\)] during deprivation and restoration of Ca\(^{2+}\). Panel 4A: A single gland with 7 parietal cells imaged, exposed first to Ringer’s solution (Ca\(^{2+}\) 1 mM, no added Zn\(^{2+}\)), then Ringer’s solution depleted of Ca\(^{2+}\) but containing Zn\(^{2+}\) 10 \(\mu\)M, then Ringer’s solutions containing both 1 mM Ca\(^{2+}\) and 10 \(\mu\)M Zn\(^{2+}\). Recording is terminated with addition of TPEN to confirm that signals are due to Zn\(^{2+}\). Note variable responses in individual cells. In 15 of 17 studies (88%), loading of Zn\(^{2+}\) was observed in the presence of Ca\(^{2+}\). Among the 15 glands responding, the mean increase over baseline was 157\%+3\% (P<0.0001). Panel 4B: A single gland cell (3 cells), exposed initially to thapsigargin (2 \(\mu\)M) and Ca\(^{2+}\)-depleted Ringer’s solution, then to Ringer’s containing thapsigargin and 10 \(\mu\)M Zn\(^{2+}\) in the absence of Ca\(^{2+}\). In 49 glands (3–8 cell per gland), no loading response to 10 \(\mu\)M Zn\(^{2+}\) was observed in the absence of extracellular Ca\(^{2+}\), more than 3\% above baseline. PANEL 4C. A single gland (12 cells) exposed to initial conditions similar to those in Panel 2B, but with 1 mM Ca\(^{2+}\) present. Among 24 glands, the mean response was 60%+1\% over baseline. In each recording, the experiment is terminated with addition of TPEN to confirm that signals are due to Zn\(^{2+}\). These findings indicate that extracellular Ca\(^{2+}\) partially restores Zn\(^{2+}\) loading and that uptake of Zn\(^{2+}\) across the basolateral membrane of the parietal cell is regulated by Ca\(^{2+}\). doi:10.1371/journal.pone.0019638.g004

Figure 5. Ca\(^{2+}\)-dependent increases in [Zn\(^{2+}\)], are attributable to influx from extracellular sources. Recording from imaging of a single gland (4 individual parietal cells) loaded with fluozin-3. The recording begins with perfusion in standard Ca-Ringers solution, followed by Ca-Ringer’s containing 2 \(\mu\)M thapsigargin, which depletes intracellular calcium stores. During exposure to 10 \(\mu\)M Zn\(^{2+}\), in the presence of Ca\(^{2+}\), a monotonic increase in [Zn\(^{2+}\)]\(_i\), follows, similar to that observed in Figure 4C. With addition of an excess of DTPA (100 \(\mu\)M), a high affinity and membrane impermeable chelator of heavy metals (but not Ca\(^{2+}\) or Mg\(^{2+}\)), the accumulation of Zn\(^{2+}\) is arrested. In 18 cells monitored in 5 glands, this arrest was always observed, demonstrating that Ca\(^{2+}\)-dependent loading of Zn\(^{2+}\) was due solely to influx from extracellular sources. doi:10.1371/journal.pone.0019638.g005

A first set of studies (Figure 6A) was performed to confirm that accumulation of Zn\(^{2+}\) in a population of glands was impaired in the absence of Ca\(^{2+}\). Glands were exposed, in sequence to: standard Ringer’s solutions containing 1 mM Ca\(^{2+}\) (CaR, 30 min), then Ringer’s depleted of Ca\(^{2+}\) and containing 300 \(\mu\)M EGTA (0CaR TG, 30 min), then 0CaR TG solutions containing 10 \(\mu\)M Zn\(^{2+}\) (0CaR TG 10 \(\mu\)M Zn) for 30 min with replacement by fresh solution at 30 min. As shown, resting levels of [Zn\(^{2+}\)]\(_i\) were decreased and very little uptake was detected when extracellular and intracellular sources of Ca\(^{2+}\) had been depleted.

A second set of studies (Figure 6B) was then performed to confirm that uptake of Zn\(^{2+}\) could be observed despite functional impairment of intracellular Ca\(^{2+}\) stores. To establish baseline conditions with depletion of intracellular stores, glands were exposed to CaR (30 min) and then 0CaR with TG (30 min). Glands were then exposed to solutions in which Ca\(^{2+}\) was restored (CaR, TG and Zn\(^{2+}\) 10 \(\mu\)M) for 30 min, with replacement by fresh solution at 30 min. As in studies of individual glands (Figures 4 and 5), when Ca\(^{2+}\) was restored to the system, uptake of Zn\(^{2+}\) was significantly enhanced and continued to the last period of observation (Figure 6B).

A third set of studies (Figure 6C) was then performed to confirm reversibility of Ca\(^{2+}\)-dependent uptake of Zn\(^{2+}\). Baseline conditions were established with depletion of intracellular stores (CaR for 30 min followed by 0CaR-TG for 30 min). Glands were then exposed to solutions in which Ca\(^{2+}\) had been restored (CaR, TG and Zn\(^{2+}\) 10 \(\mu\)M) for 30 min, followed by exposure to solutions in which Ca\(^{2+}\) was again depleted (0CaR, TG and Zn\(^{2+}\) 10 \(\mu\)M) for 30 min. As previously observed, when Ca\(^{2+}\) was restored to the system, uptake of Zn\(^{2+}\) was significantly enhanced; however, when Ca\(^{2+}\) was again removed accumulation of Zn\(^{2+}\) was impaired and actually decreased. These findings suggest that Zn\(^{2+}\) accumulation is responsive to Ca\(^{2+}\) availability in the cytoplasm, by a mechanism that is consistent with exchange of intracellular Ca\(^{2+}\) for extracellular Zn\(^{2+}\).

Demand for extracellular Zn\(^{2+}\) during secretory stimulation

In a final series of studies, we evaluated demand for extracellular Zn\(^{2+}\) during maximal secretory stimulation, exposing glands to the
Discussion

Work reported previously from our laboratory indicates that the transport of Zn\(^{2+}\) by the parietal cell is a critical feature of its ability to regulate acidity within its secretory compartment, which includes the tubulovesicles of the parietal cell and the lumen of the gland. Chelation of Zn\(^{2+}\) within these compartments led to marked alkalinization, suggesting that the presence of Zn\(^{2+}\) insulates these compartments against leakage of H\(^+\) ions [15]. Recently we have reported evidence that the secretory compartments serve as a reservoir for Zn\(^{2+}\), accumulating it in response to proton gradients and failing to accumulate it when secretion is blocked by proton pump inhibition [18].

The studies reported here provide three sets of observations with respect to utilization of zinc within the gastric mucosa: first, as demonstrated by \(\mu\)XRF, that zinc accumulates differently in distinct micro-anatomic regions of the mucosa; second, as observed following \textit{in vivo} intravenous injection, the non-radioactive isotope \(^{70}\text{Zn}\) accumulates readily within the gastric mucosa. The studies reported here refine and extend the concept that demand for Zn\(^{2+}\) from the circulation and nutrient compartment may be regulated acutely by alterations in H\(^+\) secretion to the lumen.
and pepsinogen; and the surface epithelium, which secretes mucus in different regions [31,47,48]: the gastric glands, which secrete acid. However, interpretation of differences in distribution within tissues depends on unique structural and functional properties of individual cells and resolution of individual isotopes of different metal ions is feasible [26,43,44].

To our knowledge, this is the first report of the use of μXRF to evaluate the distribution of Zn^{2+} and other cations in the mucosa of a specific region of the gastrointestinal tract. The basis of the method is fluorescence produced by synchrotron-derived x-rays, which can be focused to localize elemental content within isolated cells [43,44] or tissues [45,46]. In vitro, quantification within individual cells and resolution of individual isotopes of different metals is feasible [26,43,44]. However, interpretation of differences in distribution within tissues depends on unique structural features [45] or co-localizing markers [46] for cellular or sub-cellular areas of interest.

The gastric mucosa is divided into two spatially and functionally distinct regions [31,47,48]: the gastric glands, which secrete acid and pepsinogen; and the surface epithelium, which secretes mucus and bicarbonate and is thought to provide the protective barrier against back-diffusion of luminal H+ ions. Within the gastric gland, the region toward the surface is populated with mucus neck cells; the middle region is dominated by the acid-secreting parietal cells, and the deepest regions harbor pepsinogen-secreting chief cells [47]. The precise localization and quantification of metal signals in the stomach awaits development of co-localizing markers suitable for use in tissues prepared for μXRF. However, the distinct histologic structure of the mucosa permits general conclusions regarding distribution of zinc in the regions of the gastric glands and the surface epithelium. Our μXRF studies thus demonstrate a consistent signal for zinc within the glandular regions. At the same time they do not suggest major variation within different regions of the gastric gland.

Curiously, we find higher levels of Zn^{2+} present at the interface of the lumen and the surface epithelium Figures 1 and 2, more consistently than other metals such as Ca^{2+} and Fe^{2+}, and not in conjunction with other intracellular cations (K+, Ca^{2+}) that are more likely to be free and labile than bound. This observation offers the possibility that Zn^{2+} is secreted with the mucus by the surface epithelium or, possibly, is selectively trapped within the mucus layer after discharge into the gastric lumen with secretion. It is tempting to speculate that associations of Zn^{2+} or other metals with the mucin layer might be important in its structure or ability to resist back-diffusion of H+ ions. The development of a method for evaluating distribution of metal ion species in a complex and highly hydrated mucosal surface provides opportunities to evaluate alterations in content and distribution of metal ion species under pathologically relevant conditions, for example, in response to systemic stress or during infestation with pathogenic organisms such as Helicobacter pylori.

Figure 7. Rapid throughput assay showing influence of Ca^{2+} availability on uptake of Zn^{2+} in populations of isolated gastric glands, during exposure to secretagogues. Aliquots of fluozin-3 loaded glands (n = 8 each group) were incubated in wells for 45 min in Ca-Ringer’s or 0Ca-Ringer’s solutions under control conditions, during exposure to secretagogue combination (carbachol CCh 100 μM, forskolin FSK, 10 μM), or during exposure to secretagogue combination and thapsigargin TG, 10 μM. Glands were then exposed for 10 min to solutions containing Zn^{2+} 10 μM to monitor content. Results reported in total fluorescence units, means ± SEM, t<0.05 compared to Ringer control, *p<0.05 compared to CaR conditions. Designations: a) Ca-Ringer’s 45 min then Ringer’s/Zn^{2+}10 μM 15 min (CaR); b) 0Ca-Ringers 45 min/Zn^{2+}10 μM 15 min (0CaR); c) Ca-Ringer’s, carbachol 100 μM, forskolin 10 μM for 45 min then Ca-Ringer’s, carbachol 100 μM, forskolin 10 μM, Zn^{2+} 10 μM 15 min (CaR-CCh-FSK); d) 0Ca-Ringer’s/2 μM Thapsigargin 45 min then 0Ca-Ringer’s/Thapsigargin 2 μM/Zn^{2+}10 μM 15 min (0CaR-CCh-FSK); e) Ca-Ringer’s, carbachol 100 μM, forskolin 10 μM, Zn^{2+} 10 μM, thapsigargin 2 μM/Zn^{2+}10 μM 15 min (CaR-CCh-FSK/TG); f) 0Ca-Ringer’s/2 μM Thapsigargin 45 min then 0Ca-Ringer’s/Thapsigargin 2 μM/Zn^{2+}10 μM 15 min (0CaR-CCh-FSK/TG).

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Heterogeneous distribution of Zn^{2+} within the gastric mucosa

To our knowledge, the concept of “demand” for any nutrient is based on the need of a cell, tissue or organism to maintain homeostasis. In studies utilizing sector field ICP-MS, following injection of a non-radioactive and naturally scarce isotope, 70Zn^{2+}, uptake is demonstrated within the mucosa as a whole and in individual glands. Such movements can be tracked within hours of injection into the circulation and provide evidence that demands of the tissues are readily replenished by movement of Zn^{2+} from the circulation into the mucosa.

To more precisely characterize the avidity of individual glands, we developed an in vitro assay to monitor uptake of 70Zn^{2+} by isolated glands, observing that it can be detected within minutes when extracellular concentrations are in the 10 nanomolar range and very consistently when concentrations are 100 nM. Moreover, rates of uptake are accelerated during stimulation with a powerful secretory agonist, forskolin. The use of rare, non-radioactive isotopes such as 70Zn^{2+} permits investigation of Zn^{2+} distribution into whole tissues and cell preparations, without the restrictions required when radioactive isotopes (i.e., 65Zn^{2+}) would be used. The specificity of these methods for individual metal species not only permits quantification of rates of entry into cells and tissues, but also increases the confidence in designing studies utilizing potentially less specific reporters of Zn^{2+} movements, such as the fluorescent reporter fluozin-3.

Connection between intracellular Ca^{2+} and uptake of Zn^{2+} across the basolateral membrane of the gastric parietal cell

Based on studies with 70Zn^{2+}, we were able to design experiments to study conditions of uptake under baseline conditions and during exposure to well-recognized secretory agonists, using utilizing relatively inexpensive and rapidly responsive fluorescence imaging and fluorometric methods. Utilizing these methods, we were able to confirm enhanced uptake of Zn^{2+} across the basolateral membrane during secretory stimulation. In addition, we found that manipulation of [Ca^{2+}], homeostasis leads to alterations in the ability of the parietal cell to take up and preserve Zn^{2+}. Thus, intracellular accumulation of Zn^{2+} is nearly abolished when intracellular stores of Ca^{2+} are depleted by exposure to thapsigargin and Ca^{2+}-depleted Ringer’s. Following exposure to thapsigargin, uptake of Zn^{2+} was observed—albeit at a reduced level—if Ca^{2+} is present in the extracellular solution. This uptake was arrested when the chelator DTPA (10 μM) was added. These observations indicate that the increases in [Zn^{2+}], are indeed due to influx from extracellular...
sources and not release from intracellular stores. They argue that, under baseline conditions, uptake of Zn²⁺ across the basolateral membrane depends on adequate stores of intracellular Ca²⁺. With stimulation by powerful agonists such as forskolin and carbachol, demand for extracellular Zn²⁺ increases and depends on influx of extracellular Ca²⁺. In addition, these studies illustrate physiologically relevant approaches for using both real-time imaging of individual glands, which is time-intensive, and 96-well platforms, which would be amenable to rapid through-put approaches for small molecule screens.

Additional considerations: technical

The fluorescent reporter utilized here was fluozin-3, which has been utilized in its free acid form for monitoring extracellular secretion of Zn²⁺ from insulin-secreting beta cells [30]. When conjugated to an acetoxyethyl ester group, it has proven useful for monitoring intracellular concentrations of free Zn²⁺ ([Zn²⁺]i) in different cell types [29,49], including epithelial cells of the gastrointestinal tract [16,18]. Importantly, this reporter is unresponsive to Ca²⁺ under a number of experimentally relevant conditions [18,49,50]. However, it is possible for release or sequestration of other divalent cations to influence responses of the reporter [51]. It is for this reason that caution must be used in applying relationships that have been used to calculate free concentration of Zn²⁺ from the reported Ki and from maximum and minimum fluorescence responses, as was originally proposed for Ca²⁺ reporters [52]. Thus, we have refrained from providing direct estimates of [Zn²⁺]i, based on fluozin-3 measurements.

Additional considerations: connection between intracellular Ca²⁺ and movements of Zn²⁺ across the basolateral membrane of the gastric parietal cell

In the current set of studies, we find that Ca²⁺ facilitates optimal uptake of Zn²⁺ across the cell membrane, implying that it is either a counter-ion in exchange or it is acting as a regulatory second-messenger. Membrane proteins that facilitate Zn²⁺ transport constitute the SLC30A (ZnT) and SLC39A (Zip) gene families [53,54]. To date, fourteen proteins that facilitate import of Zn²⁺ into the cytoplasm (either from extracellular sources or possibly intracellular compartments) have been identified in mammals [53,54]. Current information on the mechanisms of Zn²⁺ transport does not implicate Ca²⁺ in the former role and emerging information for ZIP, ZnT and related transporters in yeast suggest that counter exchanging ions are likely to be protons [55]. Based on the well-recognized role of Ca²⁺ as a second messenger in responses to secretagogues [32,38,40,56,57,58,59], our findings offer the novel conclusion that Ca²⁺ is a second messenger that can match the basolateral demand for Zn²⁺ with the secretory response to physiologic stimulation. It seems likely that similar connections will be found in other secretory cells and tissues—neural, endocrine and exocrine.

Additional considerations: pathophysiological implications of Ca²⁺-regulated Zn²⁺ uptake

Compared to levels of free Ca²⁺, the amount of free Zn²⁺ within the cytoplasm is even more tightly controlled. Our studies have suggested that, in different epithelial cells, the baseline concentration of Zn²⁺ is in the nanomolar range [16,18]. This consideration alone suggests tight regulation of the activities of transporters that modulate demand for Zn²⁺ and its disposal from the cytoplasm. Observations in other cell types such as neurons suggest that exposure to elevated levels of Zn²⁺ can be cytotoxic, within minutes [60,61]. Preliminary studies in epithelial cells of the gastrointestinal tract confirm that oxidant stress induces increases in [Zn²⁺]i [16], that can influence pathways of cell death and the balance between necrosis and apoptosis [19,62]. Dysregulation of Ca²⁺ homeostasis is also a consequence of such oxidant-related stress [16,39]. The findings of the current study suggest that oxidative dysregulation of intracellular Zn²⁺ could be amplified by dysregulation of intracellular Ca²⁺ homeostasis. Further studies will help to clarify this potential relationship, not only in gastric mucosa but also in other secretory cell types or tissues.

Author Contributions

Conceived and designed the experiments: JJL AM MAM EB CA EB LEG DIS. Performed the experiments: JJL JEEK ALB MAM CA NC LEG DIS. Analyzed the data: JJL ALB MAM CA NC LEG DIS. Contributed reagents/materials/analysis tools: JAM MAM EAB KAB CA NC LEG DIS. Wrote the paper: JJL JEEK MAM CA NC LEG DIS. Senior authorship and responsibility for this work: LEG DIS.

References

1. Jee MYHA, Philipp AF, Kelleher SL, Lounnerdal B (2009) Tissue-specific alterations in zinc transporter expression in intestine and liver reflect a threshold for homeostatic compensation during dietary zinc deficiency in weanling rats. J Nutr 139: 835–841.
2. Lounnerdal B, Kelleher SL (2009) Micronutrient transfer: infant absorption. Advancements in Experimental Medicine and Biology 639: 29–40.
3. Jee MY, Philipp AF, Kelleher SL, Lounnerdal B (2010) Effects of Zinc Exposure on Zinc Transporter Expression in Human Intestinal Cells of Varying Maturity. Journal of Pediatric Gastroenterology and Nutrition 50: 587–595.
4. Semperelegui F, Diaz M, Mejia R, Rodriguez-Mora OG, Renteria E, et al. (2007) Low concentrations of zinc in gastric mucosa are associated with increased severity of Helicobacter pylori-induced inflammation. Helicobacter 12: 45–48.
5. Movchan J, Kijas K, Vcev A, Bukvoc V (2016) Helicobacter pylori and trefoil elements. Clinical Laboratory 56: 137–142.
6. Carter JV, Lancaster H, Hardman WE, Cameron IL (1997) Zinc deprivation promotes progression of 1,2-dimethylhydrazine-induced colon tumors but reduces malignant invasion in mice. Nutrition and Cancer 27: 217–221.
7. Fong LY, Mancini R, Nakagawa H, Rustgi AK, Huebner K (2003) Combined cyclin D1 overexpression and zinc deficiency disrupts cell cycle and accelerates mouse forestomach carcinogenesis. Cancer Research 63: 4244–4252.
8. Fong LY, Ishi H, Nguyen V-T, Vecchione A, Farber JL, et al. (2003) p53 deficiency accelerates induction and progression of esophageal and forestomach tumors in zinc-deficient mice. Cancer Research 63: 186–195.
9. Hoque KM, Binder HJ (2006) Zinc in the treatment of acute diarrhea: current status and assessment. Gastroenterology 130: 2291–2295.
10. Patel A, Mamtani M, Dibley MJ, Badhoniya N, Kulkarni H (2010) Therapeutic value of zinc supplementation in acute and persistent diarrhea: a systematic review. PLoS One 5: e10356.
11. Frommer DJ (1975) The healing of gastric ulcers by zinc sulphate. Medical Journal of Australia 22: 793–796.
12. Jimenez E, Bosch F, Galmés JL, Batons JE (1992) Meta-analysis of efficacy of zinc in the treatment of peptic ulcer. Digestion 51: 18–26.
13. Sturmiolo GC, Fries W, Mazzon E, Di Leo V, Barollo M, et al. (2002) Effect of zinc supplementation on intestinal permeability in experimental colitis. Journal of Laboratory and Clinical Medicine 139: 311–315.
14. Scrimgeour AG, Goudin ML (2009) Zinc and micromotrient combinations to combat gastrointestinal inflammation. Current Opinion in Clinical Nutrition and Metabolic Care 12: 633–640.
15. Grebino A, Hofer AM, McKay B, Lau BW, Sobyol DI (2004) Divalent cations regulate acetylcholine secretion within the lumen and tubuloveolar compartment of gastric parietal cells. Gastroenterology 126: 102–195.
16. Cima RR, DuBach JM, Wieland AM, Walsh BM, Sobyol DI (2006) Intracellular Ca²⁺ and Zn²⁺ signals during monochloramine-induced oxidative stress in isolated rat colon crypts. American Journal of Physiology-Gastrointestinal and Liver Physiology 290: G250–G261.
17. Yu YW, Kirschke CP, Huang L (2007) Immunohistochemical analysis of ZnT1, 4, 5, 6, and 7 in the mouse gastrointestinal tract. Journal of Histochemistry and Cytochemistry 55: 221–231.
18. Naik HB, Bhashyam M, Walsh BM, Liu J, Sobyol DI (2009) Secretory Stomach regulates Zn²⁺ Transport in the Gastric Parietal Cell of the Rabbit. American Journal of Physiology: Cell and Molecular Physiology 297: C579–C589.
19. Kohler JE, DuBach JM, Naik HB, Tai K, Blass AL, et al. (2010) Monochloramine-induced toxicity and dysregulation of intracellular Zn²⁺ in parietal cells of rabbit gastric glands. American Journal of Physiology: Gastrointestinal and Liver Physiology 299: G170–G178.
20. Hidalgo M, Eckhardt SG (2001) Development of matrix metalloproteinase inhibitors in cancer therapy. Journal of the National Cancer Institute 93: 178–193.

21. Azriel-Tamir H, Sharir H, Schwartz B, Hershfeld M (2004) Extracellular zinc triggers ERK-dependent activation of Na+/H+ exchange in colonocytes mediated by the zinc-sensing receptor. Journal of Biological Chemistry 279: 51084–51086.

22. Kirchhoff P, Socrates T, Sidani S, Duffy A, Breidttdthart T, et al. (2010) Zinc Sulfate Provides a Novel, Polyspecific Inhibitor of Gastric Acid Secretion. American Journal of Gastroenterology Aug 24 [Epub ahead of print].

23. Joseph RM, Varela V, Kanji VK, Subramony C, Mihas AA (1999) Protective effects of zinc in indomethacin-induced gastric mucosal injury: evidence for a dual mechanism involving lipid peroxidation and nitric oxide. Alimentary Pharmacology and Therapeutics 14: 203–208.

24. Mahmood A, FitzGerald AJ, Marchbank T, Ntatsaki E, Murray D, et al. (2007) Zinc carnosine, a health food supplement that stabilizes small bowel integrity in ethanol-induced mucosal injury in rats. Molecular Medicine Reports 2: 793–799.

25. Berglind T, Helander HF, Obrink KJ (1976) Effects of secretagogues on oxygen consumption, amplyzyme accumulation and morphology in isolated gastric glands. Acta Physiologica Scandinnavia 97: 401–414.

26. Hunter DB, Bertich PM (2001) Applications of Synchrontron-Based X-ray Microprobes. Chemical Reviews 101: 1809–1842.

27. Marcus MA, MacDowell AA, Celestre R, Manceau A, Miller T, et al. (2004) Inductively Coupled Plasma Mass Spectrometric Determination of 70Zn and 70Zn in human blood in reference to the study of zinc metabolism. Journal of Analytical Atomic Spectrometry 7: 915–921.

28. Mahmood A, FitzGeral P, Marchbank T, Ntatsaki E, Murray D, et al. (2007) Zinc carnosine, a health food supplement that stabilizes small bowel integrity in ethanol-induced mucosal injury in rats. Molecular Medicine Reports 2: 793–799.

29. Devinney II MJ, Reynolds IJ, Dineley KE (2005) Simultaneous detection of 

30. Gee KR, Zhou ZL, Qian WJ, Kennedy R (2002) Detection and imaging of zinc 

31. Guerinot ML (2000) The ZIP family of metal transporters. Biochimica et Biophysica Acta 1465: 190–198.

32. Grynkiewicz G, Poenie M, Tsien RY (1985) A new generation of Ca2+ indicators with greatly improved fluorescence properties. Journal of Biological Chemistry 260: 3447–3455.

33. Arslan P, Di Virgilio F, Beltrame M, Tsien RY, Pozzan T (1985) Cytosolic Ca2+ in intact 

34. D.G. Foneska A, Kazmirotz JD (2010) Gastroduodenal mucosal defense. Curr Opin Gastroenterol 26: 604–610.

35. Finney L, Mandava S, Cross L, Zhang W, Rodi D, et al. (2007) X-ray fluorescence microscopy reveals large-scale relocation and extracellular translocation of cellular copper during angiogenesis. Proc Natl Acad Sci U S A 104: 2247–2252.

36. McCormick N, Velasquez V, Fanney L, Vogt S, Kelleher SL (2010) X-ray fluorescence microscopy reveals accumulation and secretion of discrete intracellular zinc pools in the lactating mouse mammary gland. PLoS One 5: e11078.

37. Ito S (1967) Anatomic structure of the gastric mucosa. In: Code CF, ed. Alimentary Canal: Secretion. Washington, D.C.: American Physiological Society. pp 705–741.

38. Caroppo R, Gerbino A, Debellis L, Kifor O, Soybel DI, et al. (2001) Asymmetrical, agonist-induced fluctuations in local extracellular [Ca2+] in intact polarized epithelia. EMBO Journal 20: 6316–6326.

39. Guerinot ML (2000) The ZIP family of metal transporters. Biochimica et Biophysica Acta 1465: 190–198.

40. Geielp JP, Wagner CA, Caroppo R, Qureshi I, Gloeckner J, et al. (2001) The stomach dvalent ion-sensing receptor SCAR is a modulator of gastric acid secretion. Journal of Biological Chemistry 276: 2719–2727.

41. Yokoyama M, Koh JY, Choi DW (1986) Brief exposure to zinc is toxic to cortical neurons. Neuroscience Letters 71: 351–355.

42. Koh JY, Choi DW (1994) Zinc toxicity on cultured cortical neurons: involvement of N-methyl-D-aspartate receptors. Neuroscience 69: 1049–1057.

43. Kohler JE, Mathew J, Tai K, Blay AL, Kelly E, et al. (2009) Monochloramine impairs caspase-3 through thiol oxidation and Zn2+ release. Journal of Surgical Research 153: 121–127.