Impaired Barrier Function and Autoantibody Generation in Malnutrition Enteropathy in Zambia

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Accessibility
Intestinal damage in malnutrition constitutes a threat to the survival of many thousands of children globally. We studied children in Lusaka, Zambia, with severe acute malnutrition (SAM) and persistent diarrhea using endoscopy, biopsy and analysis of markers and protective proteins in blood and intestinal secretions. We carried out parallel investigations in apparently healthy adults, and analyzed biomarkers only in apparently healthy children.

Villus height and crypt depth did not differ in children with SAM and adult controls, but epithelial surface was reduced in children with SAM (median 445, interquartile range (IQR) 388, 562 μm) compared to adults (758, IQR 655, 709; P = 0.004). Histological lesions and disruptions of claudin-4 and E-cadherin were most pronounced in children with SAM. Circulating lipopolysaccharide, a marker of bacterial translocation, was higher in malnourished children (251, IQR 110, 460 EU/ml) than in healthy children (51, IQR 26, 86; P = 0.001). Other translocation markers showed similar patterns. Anti-Deamidated Gliadin Peptide IgG concentrations, although within the normal range, were higher in children with SAM (median 2.7 U/ml, IQR 1.5–4.4) than in adults (1.6, 1.4–2.1; P = 0.005), and were inversely correlated with villus height (r = −0.79, n = 13, P = 0.001). Malnutrition enteropathy is associated with intestinal barrier failure and immune dysregulation.

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specific interventions, together with evidence of increased intestinal permeability related to poor sanitation (Humphrey, 2009), and the impact of enteropathogens (Kosek and the MAL-ED Network Investigators, 2017) suggests that environmental enteropathy contributes to stunting (Prendergast et al., 2014; Prendergast and Kelly, 2012). Children with SAM and persistent diarrhea have a severe enteropathy, with very high burdens of intestinal infection (Amadi et al., 2001; Salazar-Lindo et al., 2003), enteric inflammation (Sullivan et al., 1991), deranged glycosylation (Amadi et al., 2009) and a T-cell activation enteropathy (Campbell et al., 2003; Veitch et al., 2001).

Among children in LMICs, enteropathy is frequently caused by a combination of EE, SAM and HIV infection (Prendergast and Kelly, 2012). A precise understanding of the pathology underlying these conditions is lacking because most studies rely on markers of gut injury as measured in blood and stool, and there have been very few studies informed by small intestinal biopsy. Using confocal laser endomicroscopy in adults (Kelly et al., 2016), we recently reported that the small intestinal mucosa has increased permeability in EE and that diminished barrier integrity is associated with microbial translocation (Brenchley and Douek, 2012; Marchetti et al., 2013). However, no studies have yet directly compared gut structure and function in children with SAM to children with only background EE using small intestinal biopsy and non-invasive biomarkers. Furthermore, the contribution of HIV infection to these enteropathies is unclear.

Here we report a cross-sectional analysis of enteropathy in children hospitalised with complicated SAM, children from a poor community with a high prevalence of stunting but without wasting, and adults from the same community. Its aim was to better understand the pathology of enteropathy in SAM and the contribution, if any, of HIV to its severity.

2. Methods

This study was granted approval by the University of Zambia Biomedical Research Ethics Committee (ref 006-01-13) on 11th April 2013, and was conducted in full compliance with the Declaration of Helsinki. Children hospitalised with SAM in the University Teaching Hospital were enrolled in the study following signed informed caregiver consent, on the basis that small intestinal biopsy was indicated for malnutrition and persistent diarrhea of unknown aetiology (stool parasitology and culture negative). Persistent diarrhea was defined as 3 or more loose or watery stools per day for 14 days or more. These children were all undergoing standard nutritional rehabilitation following WHO guidelines (Ashworth et al., 2003) so they were all receiving milk-based feeds (F75 and F100). HIV testing, following national guidelines, was carried out during the course of a community malnutrition screening programme (Amadi et al., 2016) and caregivers provided written informed consent to join the study. Adults and children from the community were screened for recent episodes of diarrhea (one month), NSAID use (one month), antibiotic use (one month) and excluded and treated if needed. Thus, 20 adults were excluded because of concurrent illness, pregnancy or use of antibiotics or NSAIDs, so 61 adults were studied, and of these 41 adults had satisfactory biopsies for morphometry.

2.1. Clinical Procedures - Adults

In adult participants, following an overnight fast, blood and urine samples were collected and then 100 ml of test solution A was given by mouth. After exactly 3 h, further urine and blood samples were collected. 1 ml of 20% chlorhexidine was added to urine samples. Blood samples were collected into EDTA, plain and trace element-free lithium heparin tubes (Vacutainer, Becton Dickinson; and TekLab respectively). Blood samples were kept in the dark for 20 min then centrifuged (537g, 15 min). Test solution A contained 1 g l-rhamnose (Sigma, Poole, UK), 5 g lactulose (as lactulose syrup USP) per dose, diluted in water to 100 ml.

The next day, after an overnight fast, urine and blood samples were collected as above. After 2–3 min of observation and oxygen saturation recording, intravenous sedation (2.5–10 mg diazepam, 50–100 mg pethidine) was given and endoscopy performed using Pentax EC2990i gastroscopes (Pentax, Slough, UK). 2 ml of gastric contents were aspirated from the stomach for pH measurement, and 0.5–3 ml intestinal fluid was aspirated slowly from the duodenal lumen. Three biopsies were collected into normal saline, orientated under the dissecting microscope (Swift Optical Instruments, Schertz, TX at 10× magnification) in the endoscopy unit, the villus configuration noted, and the biopsies fixed in formal saline. After 3 h, further blood and urine samples were collected, and the exact time noted.

2.2. Endoscopy (Children)

Children were evaluated on the day of endoscopy by an experienced paediatrician (BCA) to confirm fitness for endoscopy, and then fasted from 0600 after a feed of F100, until 1000, the time of the endoscopy. Endoscopy was carried out using a Pentax E2490k paediatric gastroscope (8 mm external diameter) under sedation by an anaesthetist using ketamine-based protocols. Two biopsies were orientated and fixed as above. Lactase deficiency was tested in an additional biopsy for using the Biohit Lactose Intolerance Quick Test kit (Biohit, Ellesmere Port, UK). Test solution C, for children, contained 0.2 g rhamnose and 1 g lactulose per dose, made up to 50 ml, and was instilled down the endoscope as previously described (Kelly et al., 2004).

2.3. Clinical Procedures (Children in the Community)

Absorption and permeability testing was carried out using a very similar protocol to that used in adults, except that the period of fasting was limited to 1 h and that test solution C was taken orally. HIV testing was not carried out on these children.

2.4. Morphometry

Biopsies were processed, paraffin embedded, sectioned into 3 μm sections and stained with haematoxylin and eosin. Morphometry was carried out using NanoZoomer Digital Pathology (Hamamatsu Photonics, Hamamatsu, Japan) as previously described (Kelly et al., 2004, 2016) (Supplementary Fig. S1). The following measurements were made: villus height (VH) and width (VW), crypt depth (CD), villus mucosal perimeter (VP) as a measure of epithelial surface area and related to length of muscularis mucosae, and villus cross-sectional area (VA) as a measure of villus volume. VH/CD and villus surface area/volume ratio (SAVR) (Kelly et al., 2016) were derived from these. Claudin-4 immunostaining was performed on 3 μm sections (see Supplementary material).

2.5. Sugar Analysis

Urine samples were collected at 3 h in adults, and 60 min in children. Lactulose and rhamnose were assayed by mass spectrometry in urine samples as previously described (Faubion et al., 2016).

2.6. Biomarkers

To estimate the severity of translocation, we measured plasma lipopolysaccharide (LPS) and carried out PCR for bacterial 16S ribosomal DNA as direct markers of translocation (see Supplementary data), while serum lipopolysaccharide binding protein (LPB), soluble CD14
(sCD14), CD163 and C-reactive protein (CRP) were used as indirect markers of the host response to translocated bacterial molecules (Table 2). Quantification of LPS was by the Pyrochrome Limulus Amoebocyte Lysate (LAL) assay (Associates of Cape Cod, Liverpool, UK). Serum LPS binding protein, CRP, sCD14, CD163, IGF-1 and IGBP3 were measured by ELISA (R&D systems, Abingdon, UK: RRID:SCR_006140). DNA was isolated from plasma using the QIAamp DNA Mini Kit (Qiagen: RRID:SCR_008539), according to the manufacturer’s instructions, then analyzed by PCR (see Supplementary material). Total immunoresponse CLP-2 was measured in fested serum by ELISA (Millipore, St Charles, MO: RRID:SCR_008983). Intestinal FABP was measured by ELISA (Hyctul, Cambridge Bioscience, Cambridge, UK: RRID: SCR_002245). Protein was extracted from duodenal aspirates using a lysis buffer made up of 2-mercaptoethanol and Laemmli buffer, then Western blots were probed for TFF3 using mouse monoclonal antibody to TFF3 (Abcam, Cambridge, UK: RRID: SCR_012931) and detected using VECTASTAIN anti-mouse IgG Biotinylated antibody (Vector laboratories, Peterborough, UK: RRID:SCR_000821). All assays were conducted in duplicate.

2.7. Coeliac Serology

Tissue transglutaminase IgA antibodies were measured in serum using the Orgentech ELISA kit (Launch Diagnostics, Longfield, UK) and the Quanta Lite ELISA kit (Inova Diagnostics, San Diego, USA). Antibodies to deamidated gliadin peptides were measured using the Quanta Lite Gliadin IgGII kit (Inova). The Orgentech ELISAs were run in both the Lusaka and Mayo Clinic laboratories (p = 0.88; p < 0.0001); the Inova TTG and DGP ELISAs were run only in the Mayo Clinic. 2.8. Data Analysis

Data analysis was carried out using Stata 13 (Stata Corp, College Station, TX). Spearman’s rank correlation coefficient and the Kruskal-Wallis test were used for hypothesis testing as most variables were not normally distributed.

2.9. Role of the Funding Source

The funding sources played no role in the decision to publish, data analysis, or in the drafting of the manuscript. The corresponding author had free access to all data.

3. Results

We enrolled 34 children with SAM and persistent diarrhea not responsive to standard treatment (Supplementary Table 1). Three of these children died later during hospitalization. During a programme of screening for malnutrition in Misisi, 101 children who were not acutely malnourished were also evaluated (Supplementary Table 1). Written consent was obtained from caregivers for child participants. Following a 3-stage recruitment and consent process, 81 unselected HIV-seropositive and HIV-seronegative adults from Misisi agreed to participate in the study (Supplementary Table 2).

3.1. Morphological Severity of Enteropathy

Children hospitalised with SAM, and all adults, underwent endoscopy to collect duodenal biopsies. Children from the community did not have endoscopy. All biopsies were examined immediately after endoscopy using a binocular microscope and all demonstrated evidence of villus morphological change, with ridges and convolutions and absence of finger-like villi. This corresponded to histological evidence of villus blunting and infiltration of the mucosa by chronic inflammatory cells (Fig. 1). Villus height (VH), crypt depth (CD), villus width (VW), and VH:CD ratio were measured satisfactorily in biopsies from 41 adults and 22 children; they did not differ significantly between adults with EE and children with SAM, irrespective of HIV status (Table 1). However, two biopsies from children with SAM showed total villus atrophy (Fig. 1); both these children died during their admission. One other child died on the ward; this child had partial villus atrophy with a measured villus height (VH) of 198 μm and a villus height:crypt depth ratio of 1.2. Overall, the three children who died in hospital had lower VH (median 83 μm; IQR 74–198) than those who survived (216 μm; 175–246; P = 0.04) but crypt depth (CD) did not differ (170 vs 156 μm; P = 0.32). SAVR was reduced in HIV-infected children with SAM, but otherwise HIV status had little impact on mucosal morphology (Table 1).

3.2. Claudin 4 and E-Cadherin Immunostaining

To clarify the significance of these breaks, we performed immunostaining for the tight junction protein claudin-4 and the adherens junction protein E-cadherin (Fig. 2). Overall, claudin-4 expression was reduced in all biopsies, compared to previous experience in healthy tissue (Turner, 2009; Gunzel and Yu, 2013), and E-cadherin immunostaining was disrupted at the sites of epithelial breaks. However, claudin-4 immunostaining was markedly increased and disorganised at the villus tip and at sites of epithelial breaks (Fig. 2).

3.3. Biomarkers of Mucosal Integrity

Lactulose and rhamnose, measured as percentage excretion of the oral dose given and as a urinary ratio, were used to measure intestinal permeability (Faubion et al., 2016). Failed tests occurred in 65% of the children with SAM and 30% of the children in the community; this was largely due to inability to pass urine in the 60 min specified in the protocol. Lactulose recovery and the lactulose:rhamnose (LR) recovery ratio were greater in malnourished children than in adults or community children (Table 2). The LR ratio was inversely correlated with villus surface area:volume ratio (p = −0.40, P = 0.005; n = 47) but not with other morphometric parameters. Intestinal type fatty acid binding protein (FABP) was increased in all three groups of children, especially children with SAM, compared to adults (Table 2).

3.4. Markers of Microbial Translocation

Lipopolysaccharide (LPS) concentrations were higher in plasma which was also positive for bacterial 16S rRNA gene DNA (median 137, IQR 61–257 EU/ml) compared to plasma in which no bacterial DNA was detected (median 79, IQR 0–191 EU/ml; P = 0.01). Direct markers of translocation (16S DNA and LPS) were markedly higher in adults and malnourished children than in healthy children (Table 2). Indirect markers of bacterial translocation (LBP and CD163, markers of the host response to pathogen associated molecular patterns) were elevated in malnourished children compared to other groups (Table 2). In all children combined, irrespective of nutritional status, IGF-1 was modestly and inversely correlated with LPS (ρ = −0.23, P = 0.02; n = 100), consistent with translocation of microbes or their components being
Fig. 1. Mucosal histology in severe acute malnutrition (SAM) showing moderate villus blunting (villus height 247 μm). A shows a higher magnification of A at the point of the arrow, an early epithelial discontinuity measuring 62.5 μm. C and D, detachment of pale and irregular epithelial cells in biopsies from two adults with EE; at the site of these more extensive discontinuities or microerosions (black arrows) the basement membrane is exposed to the luminal stream. E, a biopsy from a child with SAM showing subtotal villus atrophy.

3.5. Mucosal Repair Peptides

We measured two proteins which promote epithelial restitution: the hormone glucagon-like peptide 2 (GLP-2) (Mutanan and Pakarinen, 2016) in intestinal secretions. Serum GLP-2 concentrations were higher in children than adults (Table 2), and lower than the reference range (Mutanan and Pakarinen, 2016) in all our participants. LPS was inversely correlated with GLP-2 (ρ = -0.35, P = 0.01; n = 54) and this association was stronger in HIV negative adults (ρ = -0.51; P = 0.001; n = 37; Fig. 3). In children with SAM, translocation was associated with reduced TFF3: LPS was undetectable in 3 of 4 children with detectable TFF3 dimer in duodenal aspirates (P = 0.03; Fig. 3).

3.6. Anti-Tissue Transglamininase (TTC) and Related Antibodies

In view of the extensive structural change seen in some biopsies, and most notably in two children with subtotal villus atrophy who expired before discharge, testing for coeliac disease serology was explored in children with SAM and in adults, even though the therapeutic as well as the staple diets of children with SAM contain minimal gluten. Tissue transglamininase (TTG) IgA antibody concentrations, by two different

### Table 1

<table>
<thead>
<tr>
<th>Measurement</th>
<th>HIV negative SAM (n = 14)</th>
<th>HIV positive SAM (n = 8)</th>
<th>HIV negative adults (n = 31)</th>
<th>HIV positive adults (n = 10)</th>
<th>P (all groups)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Villus height (μm)</td>
<td>211 (164–246)</td>
<td>206 (180–239)</td>
<td>217 (196–248)</td>
<td>242 (204–280)</td>
<td>0.12</td>
</tr>
<tr>
<td>Crypt depth (μm)</td>
<td>155 (144–170)</td>
<td>173 (144–200)</td>
<td>161 (144–174)</td>
<td>170 (136–195)</td>
<td>0.80</td>
</tr>
<tr>
<td>Villus width (μm)</td>
<td>143 (129–166)</td>
<td>175 (163–247)</td>
<td>171 (147–195)</td>
<td>189 (145–227)</td>
<td>0.58</td>
</tr>
<tr>
<td>Villus epithelial surface (μm²)</td>
<td>467 (367–614)</td>
<td>425 (407–499)</td>
<td>634 (465–714)</td>
<td>512 (462–562)</td>
<td>0.005</td>
</tr>
<tr>
<td>Villus cross-sectional area (μm²) per 100 μm muscularis mucosae</td>
<td>15,006 (11,008–18,111)</td>
<td>16,305 (13,909–19,363)</td>
<td>18,726 (16,489–25,083)</td>
<td>19,371 (14,679–21,437)</td>
<td>0.02</td>
</tr>
<tr>
<td>VH:CD</td>
<td>1.37 (0.96–1.56)</td>
<td>1.30 (1.12–1.46)</td>
<td>1.35 (1.22–1.51)</td>
<td>1.44 (1.35–1.57)</td>
<td>0.35</td>
</tr>
<tr>
<td>Villus SA:volume ratio</td>
<td>0.033 (0.029–0.035)</td>
<td>0.028 (0.021–0.039)</td>
<td>0.031 (0.027–0.035)</td>
<td>0.028 (0.026–0.031)</td>
<td>0.61</td>
</tr>
<tr>
<td>Gastric pH</td>
<td>3.5 (2.0–5.5)</td>
<td>4.8 (3.0–6.0)</td>
<td>1.5 (1.0–2.5)</td>
<td>4.0 (1.5–5.5)</td>
<td>0.0007</td>
</tr>
<tr>
<td>Hypochlorhydria (fasting pH &gt; 4.0)</td>
<td>7/15 (47%)</td>
<td>6/10 (60%)</td>
<td>5/35 (14%)</td>
<td>10/21 (48%)</td>
<td>0.05</td>
</tr>
<tr>
<td>Lactase deficiency</td>
<td>6/13 (46%)</td>
<td>7/10 (60%)</td>
<td>nt</td>
<td>nt</td>
<td></td>
</tr>
</tbody>
</table>

Values given are median with interquartile range in parentheses (()) and range in brackets [ ]. SAM, severe acute malnutrition; VH, villus height; CD, crypt depth; SA, surface area; nt, not tested.
ELISAs, were normal in sera from all adults and children, and the results of both ELISAs correlated closely ($\rho = 0.81$, $P < 0.0001; n = 20$). However, anti-TTG antibodies, even within the normal range, were higher in HIV infected children (median 2.4 U/ml, IQR 2.3–2.7) than in HIV-uninfected children (2.1 U/ml, 2.0–2.2; $P = 0.01$). This difference was not seen in adults. IgG anti-deamidated gliadin peptide (DGP) antibodies were negative in adults, but positive in 3 children, one of whom died in hospital and one of whom died after discharge. Although TTG IgA concentrations were within the normal range, the two children who died in hospital had higher TTG IgA (Inova Quant) concentrations (0.72 and 1.09 U/ml) than children who survived (median 0.55; IQR 0.52–0.6); this was statistically significant ($P = 0.04$) even though the number of events was very small. Anti-DGP IgG concentrations were higher in children with SAM (median 2.7 U/ml, IQR 1.5–8.6) than in adults (1.6, 1.4–2.1; $P = 0.005$), and were inversely correlated with villus height ($\rho = -0.79$, $n = 13$, $P = 0.001$; Fig. 4). Anti-DGP IgG concentrations were also higher in children who died (median 55 U/ml; IQR 8.6–102) than in those who did not (2.7; 1.5–5.1; $P = 0.04$). All three serological tests were strongly correlated with LBP ($\rho = 0.71$, $P = 0.006$ for TTG IgA (Orgentech); $\rho = 0.83$, $P < 0.0001$ for TTG IgA (Inova; Fig. 4); and $\rho = 0.57$, $P = 0.006$ for anti-DGP IgG).

4. Discussion

Children living in LMICs may have one or more enteropathies, with or without a contribution from HIV infection. Together they are believed to contribute substantially to child morbidity and mortality. Here we report a comparison of the pathology and severity of enteropathy in children with severe acute malnutrition and well children and adults living in a community where the prevalence of stunting is high and from which, historically, many admissions to the hospital malnutrition ward have originated. Using histopathology and other biomarkers of enteropathy, we found that the principal difference between these different groups was one of degree: severe malnutrition is associated with severe enteropathy, intense microbial translocation and severe systemic inflammation. No biopsy was normal: almost all biopsies demonstrated villus remodeling and epithelial breaks with disorganization of claudin 4 and E-cadherin. The most severe enteropathy (total villus

![Fig. 2. Epithelial histology and disruption of claudin 4 and E-cadherin. Epithelial breaks imaged in pairs in nearby sections from three children with severe acute malnutrition, each in a separate column. Top row: haematoxylin/eosin (H&E) stains with scale bar representing 50 μm. Second row, magnified H&E images of boxes from the first row with scale bars representing 20 μm. Third row, images of same sections shown in first row, with E-cadherin immunostaining in green, claudin-4 immunostaining in red, and nuclei (DAPI) in blue; scale bars at 50 μm. Fourth row, further magnification of boxes from third row, using the same colour code, and scale bars at 20 μm.](image-url)
Table 2
Biomarkers of microbial translocation and mucosal dysfunction in environmental, HIV and malnutrition enteropathy.

<table>
<thead>
<tr>
<th>Biomarker</th>
<th>Normal rangea</th>
<th>HIV negative children with SAM (n = 20)</th>
<th>HIV positive children with SAM (n = 14)</th>
<th>HIV negative adults (n = 39)</th>
<th>HIV positive adults (n = 22)</th>
<th>Community children (n = 101)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>16S rDNA PCR positive</td>
<td>Not established</td>
<td>8/14 (57%)</td>
<td>4/6 (67%)</td>
<td>19/34 (56%)</td>
<td>14/20 (70%)</td>
<td>13/82 (16%)</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>LPS (EU/ml)</td>
<td>Not established</td>
<td>272 (142–600)</td>
<td>120 (0–223)</td>
<td>187 (92–374)</td>
<td>122 (66–202)</td>
<td>50.9 (0–111)</td>
<td>0.0001</td>
</tr>
<tr>
<td>LBP (ng/ml)</td>
<td>Not established</td>
<td>150 (148–190)</td>
<td>253 (170–356)</td>
<td>22.9 (18.285)</td>
<td>28.9 (26.372)</td>
<td>40.3 (32.8–48.2)</td>
<td>0.0001</td>
</tr>
<tr>
<td>sCD14 (mg/l)</td>
<td>0.8–3.2</td>
<td>2.53 (2.19–3.31)</td>
<td>2.84 (1.50–3.72)</td>
<td>1.62 (1.34–1.84)</td>
<td>1.84 (1.40–2.41)</td>
<td>1.78 (1.54–2.14)</td>
<td>0.0001</td>
</tr>
<tr>
<td>CD163 (µg/l)</td>
<td>88–902</td>
<td>1226</td>
<td>1482 (661–3147)</td>
<td>618 (408–804)</td>
<td>684 (453–1068)</td>
<td>874 (686–1305)</td>
<td>0.0001</td>
</tr>
<tr>
<td>CRP (mg/l)</td>
<td>0–5.0</td>
<td>1.75 (0.63–5.09)</td>
<td>3.67 (0.50–10.31)</td>
<td>0.95 (0.47–2.45)</td>
<td>2.31 (0.64–10.33)</td>
<td>nt</td>
<td>ns</td>
</tr>
<tr>
<td>FABP (ng/ml)</td>
<td>Not established</td>
<td>3.14 (2.5–4.8)</td>
<td>4.52 (2.76–13.47)</td>
<td>0.65 (0.44–0.86)</td>
<td>0.64 (0.49–1.4)</td>
<td>2.01 (1.33,3.04)</td>
<td>0.0001</td>
</tr>
<tr>
<td>GLP-2 (ng/ml)</td>
<td>Median</td>
<td>1.8 (1.0–2.3)</td>
<td>4.21 (2.6–5.2)</td>
<td>1.0 (0.8–2.1)</td>
<td>2.1 (1.0–2.7)</td>
<td>nt</td>
<td>0.007</td>
</tr>
<tr>
<td>IGF-1 (ng/ml)</td>
<td>43–182</td>
<td>11.7 (9.8–20.2)</td>
<td>93.3 (10.1)</td>
<td>nt</td>
<td>nt</td>
<td>26.1 (19.4–36.4)</td>
<td>0.0001</td>
</tr>
<tr>
<td>IGFBP-3 (µg/ml)</td>
<td>1.53–3.09</td>
<td>0.89 (0.35–1.67)</td>
<td>0.70 (0.49–0.89)</td>
<td>nt</td>
<td>nt</td>
<td>0.34 (0.93–1.43)</td>
<td>0.02</td>
</tr>
<tr>
<td>Lactate release (% of administered dose)</td>
<td>Children: median 0.01 (range 0–0.07)</td>
<td>0.29 (0.023–2.25)</td>
<td>0.0287</td>
<td>0.10 (0.017–0.474)</td>
<td>0.0823</td>
<td>0.0597</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Adults: mean 0.281 (sd 0.004)</td>
<td>0.0008</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Rhamnose release (% of dose)</td>
<td>Children: median 0.38 (range 0.1–1.84)</td>
<td>0.087</td>
<td>0.072 (0.027–0.273)</td>
<td>0.15 (0.068–0.46)</td>
<td>0.70 (0.877–2.62)</td>
<td>0.35 (0.2–1.85)</td>
<td>0.0007</td>
</tr>
<tr>
<td></td>
<td>Adults: mean 1.11 (sd 0.4)</td>
<td>0.031-16</td>
<td>0.03-72</td>
<td>0.03-72</td>
<td>0.35-66</td>
<td>0.03-16</td>
<td>0.0007</td>
</tr>
<tr>
<td>L/R recovery ratio</td>
<td>Children: median 0.14 (range 0.06–1.00)</td>
<td>0.213</td>
<td>0.762 (0.357–1.00)</td>
<td>0.055</td>
<td>0.069</td>
<td>0.071</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Adults: mean 0.026 (sd 0.0001)</td>
<td>0.0008</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Anti-TTG IgA (Inova) (U/ml)</td>
<td>Below 10 0.54 (0.51–0.59)</td>
<td>0.61 (0.56–1.09)</td>
<td>0.555</td>
<td>0.057</td>
<td>0.062</td>
<td>0.071</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Below 10 2.12 (2.03–2.21)</td>
<td>2.44 (2.30–2.68)</td>
<td>2.39 (2.18–2.36)</td>
<td>0.29 (0.218–2.65)</td>
<td>0.29 (0.218–2.36)</td>
<td>0.29 (0.0–0.0)</td>
<td>0.0001</td>
</tr>
<tr>
<td>Anti-DGP IgG (U/ml)</td>
<td>Below 30 1.6 (1.4–3.6)</td>
<td>15.7 (4.0–45.7)</td>
<td>1.48 (1.41–2.04)</td>
<td>1.51 (1.42–1.96)</td>
<td>nt</td>
<td>0.0007</td>
<td></td>
</tr>
</tbody>
</table>

P is the result of Kruskal-Wallis test or Fisher’s exact test across all groups. n is shown where it is less than the number of participants shown at the head of the column. nt, not tested; ns, not significant; LPS, lipopolysaccharide; LBP, LPS binding protein; sCD14, soluble cluster of differentiation 14; CD163, cluster of differentiation 163; CRP, C-reactive protein; FABP, fatty acid binding protein; GLP-2, glucagon-like peptide 2; IGF-1, insulin-like growth factor-1; IGFBP-3, IGF binding protein-3; TTG, tissue transglutaminase; DGP, deamidated gliadin peptides.

a Reference ranges are obtained from package inserts in ELISA kits, except for: mono- and disaccharide excretion in children (Faubion et al., 2016), mono- and disaccharide excretion in adults (Menzies et al., 1999); GLP-2 (Hoffmann, 2009); normal values for some molecules are not established. In the study by Menzies et al. (1999) a 4-hour collection was used so recoveries would be expected to be higher; the LR ratio remains unchanged over 3 or 5 h.

Microbial translocation was associated with subsequent death in both children in whom it was found. Children with malnutrition and persistent diarrhea had the most abnormal markers of microbial translocation and inflammation. However, the severity of the villus blunting did not explain the translocation observed, as the differences in translocation and inflammation greatly outweighed the modest morphometric differences. A comparison of our data with previous morphometric studies is provided in Supplemental material. We readily acknowledge the difficulties of interpretation imposed by being unable to justify (ethically) taking biopsies from apparently healthy children with presumed environmental enteropathy. Our understanding would be greatly enhanced if well-orientated biopsy material from healthy children were available for formal morphometric analysis.

Mucosal atrophy was associated with subsequent death in both children in whom it was found. Children with malnutrition and persistent diarrhea had the most abnormal markers of microbial translocation and inflammation. However, the severity of the villus blunting did not explain the translocation observed, as the differences in translocation and inflammation greatly outweighed the modest morphometric differences. A comparison of our data with previous morphometric studies is provided in Supplemental material. We readily acknowledge the difficulties of interpretation imposed by being unable to justify (ethically) taking biopsies from apparently healthy children with presumed environmental enteropathy. Our understanding would be greatly enhanced if well-orientated biopsy material from healthy children were available for formal morphometric analysis.
Having found very severe mucosal damage in two children with SAM, we were concerned to exclude coeliac disease, and conducted three different assays for coeliac disease serology in two laboratories in Zambia and the USA. While the great majority of these serological results were within the normal range, closer scrutiny revealed that in children with severe acute malnutrition, concentrations of antibodies to tissue transglutaminase and deamidated gliadin peptides were very strongly correlated with LBP (a marker of the host response to bacterial translocation), inversely correlated with villus height, and were highest in the children who subsequently died. We postulate that in the presence of mucosal T cell activation (Campbell et al., 2003; Veitch et al., 2001) and epithelial leakiness the cells of the lamina propria can generate autoantibodies, and that this autoreactivity exacerbates mucosal pathology. Autoantibody generation has been reported in Crohn’s disease (Ribeiro-Cabral et al., 2011) and in olmesartan-induced enteropathy (Esteve et al., 2016) where it was reversible. Exposure to gluten and gliadin peptides is thought to be essential for development of the autoantibodies which characterize coeliac disease (Sollid and Jabri, 2013), but in Zambia the staple diet is maize, and children being treated for SAM have a therapeutic feed which includes no gluten (Ashworth et al., 2003). We have previously reported that elemental feeds enhance weight gain during nutritional rehabilitation in children with SAM (Amadi et al., 2005). These serological data suggest that coeliac antibodies, even within the clinically normal range, may be a useful biomarker of the severity of enteropathy; further work is needed in other settings to confirm or refine this hypothesis. It does not mean that these children have coeliac disease: the concentrations were within the normal range, the children were exposed to minimal gluten. There are few data on the prevalence of those HLA alleles which mediate coeliac disease in Africa (Kang et al., 2013). We have considered whether the increased anti-TTG and anti-DGP antibodies may be due to hypergammaglobulinaemia. There is good evidence that IgA concentrations are increased in SAM, particularly in the presence of oedema (Rytter et al., 2014). Unfortunately, insufficient serum was available to measure total immunoglobulins, as blood sampling volumes from these children are limited. The consistency between IgA anti-TTG and IgG anti-DGP suggests that this is not merely a reflection of increased circulating IgA concentrations, and we observed no correlation between severity of edema and antibody concentrations (data not shown).

Claudin-4 is a structural protein of the tight junction that augments epithelial barrier function in vitro (Turner, 2009; Gunzel and Yu, 2013) and has been characterized in vivo as a paracellular anion channel (Hou et al., 2010). Maintenance of tight junctions requires the physical apposition of adjacent cells which are held together, in part, by adherens
HIV enteropathy is a malabsorption syndrome. In populations where EE is also prevalent, the microbiota is thought to contribute to the development of this syndrome. The principal adherens junction adhesive protein E-cadherin is an important regulator of intestinal permeability, and mutations in the gene encoding E-cadherin have been associated with a variety of gastrointestinal disorders. E-cadherin mediates the formation of tight junctions, which are critical for maintaining the integrity of the intestinal barrier. The principal adherens junction adhesive protein E-cadherin, together with the transmembrane protein catenin, forms the catenin complex, which regulates the activity of the Wnt signaling pathway. The catenin complex is thought to play a key role in the regulation of cell adhesion and polarity, and alterations in the expression or function of this complex may contribute to the development of intestinal disorders.

References


