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Published in:
Anaerobe

Link to article, DOI:
10.1016/j.anaerobe.2014.05.007

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Molecular biology, genetics and biotechnology

A combined metabolomic and phylogenetic study reveals putatively prebiotic effects of high molecular weight arabino-oligosaccharides when assessed by *in vitro* fermentation in bacterial communities derived from humans

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**A R T I C L E   I N F O**

Article history:
Received 29 April 2013
Received in revised form 27 March 2014
Accepted 19 May 2014
Available online 4 June 2014

Keywords:
Prebiotics
Arabino-oligosaccharides
Intestinal microbial metabolism

**A B S T R A C T**

Prebiotic oligosaccharides are defined by their selective stimulation of growth and/or activity of bacteria in the digestive system in ways claimed to be beneficial for health. However, apart from the short chain fatty acids, little is known about bacterial metabolites created by fermentation of prebiotics, and the significance of the size of the oligosaccharides remains largely unstudied.

By *in vitro* fermentations in human fecal microbial communities (derived from six different individuals), we studied the effects of high-mass (HA, >1 kDa), low-mass (LA, <1 kDa) and mixed (BA) sugar beet arabino-oligosaccharides (AOS) as carbohydrate sources. Fructo-oligosaccharides (FOS) were included as reference. The changes in bacterial communities and the metabolites produced in response to incubation with the different carbohydrates were analyzed by quantitative PCR (qPCR) and Liquid Chromatography–Mass Spectrometry (LC–MS), respectively.

All tested carbohydrate sources resulted in a significant increase of *Bifidobacterium* spp. between 1.79 fold (HA) and 1.64 fold (FOS) in the microbial populations after fermentation, and LC–MS analysis suggested that the bifidobacteria contributed to decomposition of the arabino-oligosaccharide structures, most pronounced in the HA fraction, resulting in release of the essential amino acid phenylalanine. Abundance of *Lactobacillus* spp. correlated with the presence of a compound, most likely a flavonoid, indicating that lactobacilli contribute to release of such health-promoting substances from plant structures.

Additionally, the combination of qPCR and LC–MS revealed a number of other putative interactions between intestinal microbes and the oligosaccharides, which contributes to the understanding of the mechanisms behind prebiotic impact on human health.

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1. Introduction

The human gastrointestinal system produces a large amount of enzymes capable of catalyzing the hydrolysis of various disaccharides and a few specific polysaccharides (starches). However, most complex oligo- and polysaccharides including e.g. arabinan, galactan, and fructo-oligosaccharides cannot be degraded by the human digestive enzymes. These substrates need to be metabolized by the very diverse ecosystem of bacteria inhabiting the human gut [1]. Some of these saccharides are prebiotics, defined as selectively fermented ingredients that result in specific beneficial changes in the composition and/or activity of the
gastrointestinal microbiota, thus conferring benefit(s) upon host health [2].

Inter-bacterial interactions, as well as interactions between bacteria and host are based on a variety of mechanisms. Biochemical messages can be sent e.g. by simple or complex abiotic molecules or by genetic sequences [3]. Previous studies of prebiotic degradation were mainly focused on bacterial production and epithelial absorption of short chain fatty acids (SCFA) [4–6]. A far more exhaustive approach is metabolomic footprinting of the bacterial exo-metabolome, that can be defined as the complete pool of molecules excreted by a bacterial community into the surroundings [7]. Compounds involved in signaling between bacteria or to the host will be present in the metabolomic footprint, and the metabolomics approach has previously been found useful in studies of the intestinal microbial ecosystem [8, 9].

By in vitro fermentation in human fecal slurry, it was recently shown that long-chain arabino-oligosaccharides (AOS) derived from sugar beet pulp had a potentially better bifidogenic effect than shorter-chain AOS, and moreover that the bifidogenic effect of longer chain AOS was as good as the effect exerted by recognized prebiotic fructo-oligosaccharides that were used as control [10, 11]. However, a more detailed evaluation of the microbial response is required to better interpret the overall mechanisms governing the changes in the microbial communities and their potential effects on the host. The present study was thus undertaken to provide a more detailed evaluation. We addressed whether in vitro fermentation of differently sized AOS molecules caused different changes in fecal bacterial communities isolated from six healthy humans. Additionally, the putatively prebiotic (health-promoting) effect of AOS was addressed using a metabolomics-based approach.

2. Materials and methods

2.1. Arabino-oligosaccharide (AOS) substrates

AOS substrates from sugar beet were obtained from Danisco A/S (Nakskov, Denmark). The AOS were derived from a liquid side stream from the ultrafiltration and diafiltration step in the sequential acid extraction of pectin with nitric acid from sugar beet pulp, involving removal of insoluble cellulose, ultrafiltration, and diafiltration with a 50 kDa cutoff [12]. The pulp was dried prior to extraction.

Separation of the base solution of arabino-oligosaccharides (BA) according to size was performed in a 200 mL stirred membrane reactor model 8200 (Millipore, Billerica, MA) equipped with a 1 kDa MWCO regenerated cellulose membrane (Millipore, Billerica, MA) connected to compressed nitrogen for flux regulation. Filtration was performed at room temperature. Filtration was performed at 3 bar until the retentate volume was 30% of the sample volume, and followed by diafiltration in one sample volume of deionized water. The permeates enriched in low molecular weight oligosaccharides (<1 kDa) were denoted LA and the retentate enriched in high molecular weight oligosaccharides (>1 kDa) was denoted HA. Free sugar content and monosaccharide composition was determined by acid hydrolysis and High Performance Anionic Exchange Chromatography (HPAEC) as described previously [11].

2.2. Size exclusion

High Performance Size Exclusion chromatography (HPSEC) was performed using a 1580 HPLC pump, an ASI-100 automated sample injector, and an RI-101 refractive index detector (Dionex Corp., Sunnyvale, CA). Samples were separated on a Shodex SB-806HQGPCColumn (300 × 8 mm) with a Shodex SB-G guard column (50 × 6 mm) from Showa Denko K.K. (Tokyo, Japan) with 100 mM sodium acetate pH 6 as mobile phase used with a flow rate of 0.5 mL/min. Temperature was maintained at 40 °C. Data were collected and analyzed with the program Chromelon 6.80 SP4 Build 2361 software (Dionex Corp., Sunnyvale, CA).

2.3. Removal of monosaccharides from the substrates

In order to reduce the amount of monosaccharides present in the AOS-based substrates, we carried out an initial bacterial fermentation using Lactobacillus acidophilus NCFM (ATCC 700396). This strain was kindly provided by Danisco A/S and chosen because we have previously mapped the metabolites consumed and produced by this strain [13], and because its genome sequence [14] does not contain the enzymes needed for AOS degradation.

L. acidophilus NCFM colonies were grown anaerobically at 37 °C overnight in MRS broth (Oxoid Ltd., Basingstoke, Hampshire, England) and diluted 10 fold into Semi Synthetic Medium (SSM) [15] containing 1% glucose. The cultures were incubated for 7 h, resulting in approximately 10^8 CFU/mL of L. acidophilus NCFM, and subsequently further diluted 100 fold into SSM containing either 1% glucose (control), 20 g/L of BA, 20 g/L LA, or 20 g/L HA. After 24 h of anaerobic incubation with the bacteria removing non-arabian monosaccharides from the media, LA and HA were centrifuged at 3000 g for 5 min at 4 °C, where after supernatants were sterile filtered in order to remove remaining L. acidophilus NCFM cells and kept in at 4 °C until further use. Final concentrations of the AOS were calculated to be approximately 10 g/L.

2.4. Subjects and fecal sample collection

Fecal samples were collected from six healthy volunteers (four women and two men). None of the participants had been treated with antibiotics for at least 3 months before enrolment and had no history of gastrointestinal disorder. The mean age of the participants was 41 ± 9 years. The samples were collected in airtight containers at home by the participants and stored at 4 °C (limited storage time was encouraged [16]) until delivery to the laboratory, where the samples were processed immediately. The fecal samples were homogenized in 50% glycerol (1:1 dilution) in an anaerobic cabinet (Macs Work Station, Don Whitley) containing 10% H2, 10% CO2, and 80% N2, and stored at −80 °C until further analysis, as described below.

2.5. In vitro fermentation by human fecal bacterial communities

Fermentation studies were carried out to assess the effect of BA, LA and HA on the microbial composition and activity in human fecal samples, while parallel incubations with the established bifidogenic substrate fructo-oligosaccharide FOS (BENEO-Orafti, Tienen, Belgium) and no carbohydrates, respectively, were used as references. Fecal samples prepared as described above were defrosted in an anaerobic cabinet and 10% (w/v) fecal slurry was prepared by mixing the samples with anoxic PBS (Oxoid, Greve, Denmark) immediately before fermentation.

Sterile SSM supernatants prepared as described above were mixed 1:1 with sterile minimal basal medium containing 2 g/L of peptone water (Oxoid Ltd., Basingstoke, Hampshire, England), 1 g/L of yeast extract (Sigma Chemical co., St. Louis, Missouri, USA), 0.1 g/L of NaCl (Merck KGaA, Darmstadt, Germany), 0.04 g/L of KHPO4 (Merck KGaA, Darmstadt, Germany), 0.04 g/L of KH2PO4 (Merck KGaA, Darmstadt, Germany), 0.01 g/L of CaCl2 · 2H2O (Merck KGaA, Darmstadt, Germany), 2 g/L of NaHCO3 (Merck KGaA, Darmstadt, Germany), 0.5 g/L of i-cysteine hydrochloride (Sigma Chemical co., St. Louis, Missouri, USA), 50 mg/L of hemin (Sigma Chemical co., St.
Louis, Missouri, USA), 10 μL of vitamin K1 (Sigma Chemical co., St. Louis, Missouri, USA), 0.05 g/L manganese sulfate monohydrate (Merck KGaA, Darmstadt, Germany) and 1 mL/L of Tween 80 (VWR, Darmstadt, Germany). The pH of the final solution was adjusted to 7. Estimated concentrations of AOS in the medium were approximately 5 g/L. Positive controls were made by adding 5 g/L of FOS to the SSM supernatant prepared by NCFM fermentation of glucose, and negative controls by adding nothing to the same SSM supernatant. All solutions were reduced over night in an anaerobic cabinet and inoculated with fecal slurry prepared as described

2.7. Real-time quantitative PCR (qPCR) assay

Amplification and detection of purified bacterial DNA by qPCR was performed with the ABI Prism 7900 HT from Applied Biosystems using optical grade 384-well plates. Each amplification reaction was done in duplicate for each of the triplicate fermentation samples in a final volume of 11 μL containing: 5.50 μL SYBR® Green Master Mix (Applied Biosystems, Denmark), 200 nM of each of the primers (Eurofins MWG Synthesis GmbH, Ebersberg, Germany), 2 μl template DNA (1 ng/μL), and Nuclease-free water purified for PCR (Qiagen). The amplification program comprised one cycle at 50 °C for 2 min; one cycle at 95 °C for 10 min; 40 cycles at 95 °C for 15 s; 60 °C for 1 min, and finally one cycle of melting curve analysis for amplicon specificity at 95 °C for 15 s, 60 °C for 20 s and increasing ramp rate by 1.92 °C/min until 95 °C for 15 s. The qPCR data was baseline corrected and N0-values, representing initial concentrations of the specified 16S rRNA genes, were calculated using the LinRegPCR software (version 11.1, based on Ruijt et al. [18]). All results were calculated as means of duplicate N0 estimations, equal values required. The relative quantities of gene targets encoding 16S rRNA sequences of the bacterial taxa were calculated using N0 (bacterial target)/N0 (total bacterial population). The applied specific 16S rRNA-targeting primers are listed in Table S1 (supplementary data). Prior to quantification, all primers were tested to confirm sensitivity and specificity using DNA from pure bacterial species [9].

2.8. Metabolism quenching

Time 0 and time 24 h supernatants from the fermentations were quickly quenched by transferring into cold methanol (Fluka, Sigma-Aldrich, Steinheim, Germany, stored at −80 °C in the ratio 1:1 to stop the metabolism. Samples were stored at −80 °C and centrifuged at 15,000g for 5 min at 4 °C just before LC–MS (Liquid Chromatography–Mass Spectrometry) analysis was carried out as described below.

2.9. Metabolite detection by LC–MS

Metabolite profiling was done on a Dionex Ultimate 3000 RS liquid chromatograph (Dionex, Germering, Germany) coupled to a Bruker maXis time of flight mass spectrometer equipped with an electrospray ionsource (ESI-Qtof-MS) (Bruker Daltonics, Bremen, Germany). Analytes were separated on a Kinetex pentafluorophenyl column 50 × 2.10 mm, 2.6 μm, 100A (Phenomenex, USA), using a binary solvent system: 10 mM ammonium formate at pH 3.5 in water (A), and acetonitrile (B). This column was chosen over the typical C-18 columns due to its ability to provide better separation of polar compounds. Solvent programming was: isocratic 0% B at 0 min followed by a linear gradient up to 100% B in 7 min retaining 100% B for 8 min. Flow rate was 0.25 mL/min

Table 1

Relative fold change of bacteria target from samples incubated with either BA, LA, HA or FOS compared to the NC samples (set to 1).

<table>
<thead>
<tr>
<th>ID</th>
<th>Bacterial taxa</th>
<th>Substrates</th>
<th>BA</th>
<th>LA</th>
<th>HA</th>
<th>FOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Firmicutes</td>
<td></td>
<td>0.80 (±0.07)</td>
<td>0.78 (±0.07)</td>
<td>0.80 (±0.08)</td>
<td>0.96 (±0.07)</td>
</tr>
<tr>
<td>Cc</td>
<td>* C. coccoides group</td>
<td></td>
<td>0.59 (±0.11)</td>
<td>0.54 (±0.10)</td>
<td>0.68 (±0.07)</td>
<td>0.85 (±0.08)</td>
</tr>
<tr>
<td>Rs</td>
<td>- Roseburia spp.</td>
<td></td>
<td>0.18 (±0.09)</td>
<td>1.18 (±0.10)</td>
<td>1.07 (±0.12)</td>
<td>1.16 (±0.17)</td>
</tr>
<tr>
<td>Cl</td>
<td>* C. leptum subgroup</td>
<td></td>
<td>0.07 (±0.08)</td>
<td>0.88 (±0.17)</td>
<td>0.85 (±0.11)</td>
<td>0.94 (±0.11)</td>
</tr>
<tr>
<td>Ls</td>
<td>* Lactobacillus spp.</td>
<td></td>
<td>1.17 (±0.12)</td>
<td>0.11 (±0.10)</td>
<td>1.11 (±0.09)</td>
<td>1.14 (±0.11)</td>
</tr>
<tr>
<td>B</td>
<td>Bacteroidetes</td>
<td></td>
<td>0.90 (±0.13)</td>
<td>0.90 (±0.10)</td>
<td>0.80 (±0.15)</td>
<td>0.80 (±0.09)</td>
</tr>
<tr>
<td>Bs</td>
<td>* Bacteroides spp.</td>
<td></td>
<td>0.82 (±0.15)</td>
<td>0.84 (±0.12)</td>
<td>0.74 (±0.13)</td>
<td>0.70 (±0.16)</td>
</tr>
<tr>
<td>BF</td>
<td>- B. fragilis group</td>
<td></td>
<td>0.92 (±0.21)</td>
<td>0.91 (±0.15)</td>
<td>0.85 (±0.21)</td>
<td>0.78 (±0.14)</td>
</tr>
<tr>
<td>Ps</td>
<td>* Prevotella spp.</td>
<td></td>
<td>0.96 (±0.13)</td>
<td>0.95 (±0.10)</td>
<td>0.97 (±0.08)</td>
<td>0.99 (±0.10)</td>
</tr>
<tr>
<td>As</td>
<td>* Alistipes spp.</td>
<td></td>
<td>0.80 (±0.07)</td>
<td>0.74 (±0.06)</td>
<td>0.77 (±0.06)</td>
<td>0.71 (±0.04)</td>
</tr>
<tr>
<td>Actinobacteria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>* Bifidobacterium spp.</td>
<td></td>
<td>1.72 (±0.28)**</td>
<td>1.72 (±0.26)*****</td>
<td>1.79 (±0.24)*****</td>
<td>1.64 (±0.22)*****</td>
</tr>
<tr>
<td>Verrucomicrobia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Am</td>
<td>* Akk. muciniphila</td>
<td></td>
<td>1.26 (±0.09)</td>
<td>1.28 (±0.09)</td>
<td>0.80 (±0.13)</td>
<td>0.96 (±0.04)</td>
</tr>
<tr>
<td>Proteobacteria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Enterobacteriaeae</td>
<td></td>
<td>0.90 (±0.09)</td>
<td>1.14 (±0.09)</td>
<td>1.10 (±0.10)</td>
<td>0.94 (±0.25)</td>
</tr>
<tr>
<td>Ds</td>
<td>* Desulfovibrio spp.</td>
<td></td>
<td>0.81 (±0.05)</td>
<td>0.80 (±0.04)</td>
<td>0.66 (±0.05)**</td>
<td>0.74 (±0.07)**</td>
</tr>
</tbody>
</table>

All calculated data are means ± SEM of the six fecal communities. Asterisks designate a significant difference from samples taken after 24 h of incubation without any added carbon-source (NC samples) (*P < 0.05 (**), **P < 0.01 (**), ***P < 0.001 (****)). No significant difference in the relative density of bacterial taxa after fermentation was obtained when comparing the four substrates.
at 0 min, and increased to 0.4 mL/min at 7 min. Solvent composition and flow were returned to initial conditions at 8.2 min. The total runtime was 10 min, the oven temperature was 40 °C, and injection volumes were 1 μL. The following key mass spec settings were used: Nebulizer pressure 2 bar, drying gas 10 L/min, 200 °C, capillary voltage 4000 V. Data collection range was from 50 to 800 Da/e at 1 Hz. Samples were analyzed in both positive and negative mode. External and internal calibration was done using sodium formate clusters (Sigma–Aldrich, Steinheim, Germany). Lock-mass calibration using hexakis(1H,1H,2H-perfluoroxy)-phosphazene, (Apollo Scientific, Stockport, UK) was applied in order to increase mass accuracy. MSMS fragmentation of the selected masses (Tables 2 and 3) was done using nitrogen as collision gas with collision energy at 14 eV at 0.7 retention time on the chromatogram; MLCMS = m/z (mass to charge) ratio measured; MREF = m/z ratio of metabolites given in the referral data bases; Error = difference between MLCMS and MREF; MMSMS = m/z ratio of the fragment ions after MSMS; NF = no fragmentation or fragments not visible in the given MS settings.

Table 2
Annotated metabolites from LC–MS analysis in positive mode found to separate fermentation samples according to carbohydrate source (Fig. 1).

<table>
<thead>
<tr>
<th>Number</th>
<th>RT [min]</th>
<th>MLCMS [Da]</th>
<th>Adduct</th>
<th>MREF [Da]</th>
<th>Error [mDa]</th>
<th>MMSMS</th>
<th>Metabolite candidate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.7</td>
<td>166.086493</td>
<td>M−H</td>
<td>166.086255</td>
<td>0.2</td>
<td>120.081723</td>
<td>Phenylalanine</td>
</tr>
<tr>
<td>2</td>
<td>0.8</td>
<td>188.175739</td>
<td>M−H</td>
<td>188.175738</td>
<td>0.0</td>
<td>171.150205</td>
<td>N′-Acetylspermidine</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>104.106928</td>
<td>M−NH₄</td>
<td>104.106988</td>
<td>0.1</td>
<td>NF</td>
<td>Iso-Valeraldehyde</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>121.062386</td>
<td>M−NH₄</td>
<td>121.060766</td>
<td>1.6</td>
<td>NF</td>
<td>3-Oxoalanine</td>
</tr>
<tr>
<td>5</td>
<td>1.1</td>
<td>138.091331</td>
<td>M−H</td>
<td>138.091340</td>
<td>0.0</td>
<td>NF</td>
<td>Tyramine</td>
</tr>
<tr>
<td>6</td>
<td>0.9</td>
<td>139.050163</td>
<td>M−NH₄</td>
<td>139.050200</td>
<td>0.0</td>
<td>NF</td>
<td>Cysteine</td>
</tr>
<tr>
<td>7</td>
<td>0.7</td>
<td>156.042329</td>
<td>M−K</td>
<td>156.042137</td>
<td>0.2</td>
<td>NF</td>
<td>Betaine</td>
</tr>
<tr>
<td>8</td>
<td>1.3</td>
<td>155.081504</td>
<td>M−NH₄</td>
<td>155.081516</td>
<td>0.0</td>
<td>NF</td>
<td>N-Methyl-a-aminoisobutyric acid Valine Norvaline</td>
</tr>
<tr>
<td>9</td>
<td>1.0</td>
<td>137.045787</td>
<td>M−H</td>
<td>137.045787</td>
<td>0.0</td>
<td>NF</td>
<td>Hyposaxhine</td>
</tr>
<tr>
<td>10</td>
<td>6.6</td>
<td>282.279062</td>
<td>M−H</td>
<td>282.279141</td>
<td>0.0</td>
<td>NF</td>
<td>Oleamide</td>
</tr>
</tbody>
</table>

Table 3
Annotated metabolites from LC–MS analysis in negative mode found to separate fermentation samples according to carbohydrate source (Fig. 2).

<table>
<thead>
<tr>
<th>Number</th>
<th>RT [min]</th>
<th>MLCMS [Da]</th>
<th>Adduct</th>
<th>MREF [Da]</th>
<th>Error [mDa]</th>
<th>MMSMS</th>
<th>Metabolite candidate</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>2.9</td>
<td>195.066074</td>
<td>M−H</td>
<td>195.066283</td>
<td>0.2</td>
<td>151.094347</td>
<td>Homoveratric acid</td>
</tr>
<tr>
<td>14</td>
<td>0.8</td>
<td>133.070545</td>
<td>NF</td>
<td>397.11407</td>
<td>367.102362</td>
<td>325.094322</td>
<td>Fatty acid derivative</td>
</tr>
<tr>
<td>15</td>
<td>3.3</td>
<td>457.135071</td>
<td>NF</td>
<td>397.11407</td>
<td>367.102362</td>
<td>325.094322</td>
<td>Arabinofranosyl structure</td>
</tr>
<tr>
<td>16</td>
<td>3.2</td>
<td>263.073298</td>
<td>M−H</td>
<td>263.071400</td>
<td>1.9</td>
<td>165.073565</td>
<td>Flavonoid</td>
</tr>
<tr>
<td>17</td>
<td>6.3</td>
<td>297.243324</td>
<td>M−H</td>
<td>297.243530</td>
<td>0.2</td>
<td>NF</td>
<td>3-Oxooctadecanoic acid Xanthine</td>
</tr>
<tr>
<td>18</td>
<td>1.0</td>
<td>151.026420</td>
<td>M−H</td>
<td>151.026149</td>
<td>0.2</td>
<td>NF</td>
<td>Phenylactic acid</td>
</tr>
<tr>
<td>19</td>
<td>3.2</td>
<td>165.055711</td>
<td>M−H</td>
<td>165.055718</td>
<td>0.0</td>
<td>NF</td>
<td>Fatty acid derivative</td>
</tr>
<tr>
<td>20</td>
<td>0.6</td>
<td>131.071452</td>
<td>M−H</td>
<td>131.071368</td>
<td>0.0</td>
<td>NF</td>
<td>Linoleic acid</td>
</tr>
<tr>
<td>21</td>
<td>6.6</td>
<td>279.233124</td>
<td>M−H</td>
<td>279.232954</td>
<td>0.1</td>
<td>NF</td>
<td>Derivative of linoleic acid</td>
</tr>
<tr>
<td>22</td>
<td>0.9</td>
<td>175.049132</td>
<td>M−H</td>
<td>175.047272</td>
<td>1.9</td>
<td>157.036324</td>
<td>Allantoic acid</td>
</tr>
</tbody>
</table>
$m/z$ 100 ramped linearly to 20 eV at $m/z$ 500 and to 30 eV at $m/z$ 1000.

### 2.10. Metabolite identification

A putative metabolite identification was based on the exact mass to charge ratio ($m/z$) with a very low measurement error, and MSMS fragments (Tables 2 and 3) using metabolite data from the Human Metabolome Database (HMDB [20]) and the Metabolite Mass Spectral Database (METLIN [21]) where MSMS spectra of selected metabolites are presented, and references to the bacterial metabolism presented in the discussion part of this paper. Metabolites that could not be identified reliably but showed some significance were included in the further data analyses as unknown metabolites given a number.

### 2.11. Statistical analysis of the PCR data

Statistical analysis of the qPCR data was performed with the GraphPad Prism software (version 5.03; GraphPad Software Inc., La Jolla, CA). One-way analysis of variance and Tukey’s multiple comparison tests were used to determine significant differences in the density of selected bacterial taxa in the different fermentations (NC, FOS, BA, LA and HA). Homogeneity of variance was assessed using Bartlett’s test for equal variances. Log-transformations were performed before statistical analysis of qPCR measurements that did not meet this criterion. The nonparametric Kruskal–Wallis test
and Dunn's multiple comparison tests were used for datasets, which did not have homogeneity of variance even after log-transformation. Tests were considered statistically significant when \(P\)-values lower than 0.05 were obtained.

2.12. Principal component analysis (PCA)

The basic data analysis of the LC–MS data were based on the bucketing approach: the centroid data were grouped into buckets of 1 min and 1 m/z differences in the range from 0.5 to 9 min and 50–800 m/z and normalized by the sum of buckets in the analysis by use of Profile Analysis 2.0 (Bruker Daltonics, Bremen, Germany). The typical number of buckets was 6750 per sample. Each bucket was considered as a variable independently of whether the content of the bucket could be attributed to a specific metabolite or not. All variables were exported to Excel for further data analyses.

The next step of the data analysis was done in Excel, using a set of criteria, presented below, to select metabolites present in the medium after 24 h and produced exclusively due to the addition of the given carbohydrate:

**First**, the metabolites which were present already before the fermentation (\(CH_0\)), were subtracted from the metabolites present after 24 h of fermentation (\(CH_{24}\)), and the remaining metabolites were represented as an average value \(CH(A)\) of intensities of the given bucket in three independent fermentations (I, II and III):

\[
CH_{24}(I) - CH_0(I) = CH(I); \text{ if } CH(I) \leq 0, \text{ then } CH(I) = 0; \\
(CH(I) + CH(II) + CH(III))/3 = CH(A)
\]

Fig. 2. PCA bi-plots (scores and loadings present on the same plot) of the fermentation samples with different arabino-oligosaccharides BA, LA and HA and the established prebiotic FOS. Data from LC–MS analyses in negative mode for tested bacterial floras separately (B1–B6). Numbers refer to metabolite candidates as listed in Table 3.
with one peak at 24.7 min corresponding to monomers and a larger broader peak around 1.0 kDa corresponding to the oligosaccharides. The low molecular weight fraction (LA) showed a similar profile, but with a tendency towards a lower content of oligosaccharides below 1.0 kDa. The high molecular weight fraction (HA) showed one homogeneous peak around 1.0 kDa with only a minor peak at 24.7 min indicating that the content of monosaccharides was significantly reduced, but not removed completely. The monosaccharides in the BA fraction constituted about 30% of the dry matter and were mainly glucose (13.3% w/w), arabinose (10.1% w/w) and fructose (8.0% w/w). Other pectin derived free sugars like rhamnose, galacturonic acid, galactose, and fructose were found in small amounts (2.3% w/w in total). Acid hydrolysis revealed that 66.3% of the substrate was comprised of arabinose-oligosaccharide moieties. The relatively high content of monosaccharides compared to similar substrates [11] might be due to the drying of the pulp prior to the acidic extraction. LC–MS analysis of the BA fraction revealed several peaks besides those identified by comparison to linear AOS, which indicated that, in accordance with previous data obtained for sugar beet derived AOS [11,22] the AOS applied in this study contained a mixture of linear and branched AOS (data not shown). Initial fermentation with L. acidophilus NCFM removed basically all of the non-arabanin monosaccharides present in the AOS fractions, as detected by LC–MS (data not shown).

### 3.2. Quantitative PCR studies of bacterial community composition

After fermentation in fecal slurries obtained from six different healthy subjects, quantitative PCR was applied to measure the density of gene targets encoding 16S rRNA of selected bacterial taxonomic units. The ability of the substrates to selectively stimulate the growth of a given bacterial taxon was compared to that of the NC (No added Carbohydrate) fermentations (Table 1 and Figure S2). The fecal communities fermented on BA, LA and HA selectively increased the relative abundance of *Bifidobacterium* spp. significantly (*P* < 0.01, *P* < 0.001, and *P* < 0.001, respectively) as compared to the NC fermentations. The densities of bifidobacteria after fermentation of BA, LA and HA were not significantly different from the densities obtained by fermentation of FOS, which has a well established prebiotic effect [23]. Also the densities of *Lactobacillus* spp. appeared to be higher in the BA, LA, HA and FOS fermentations than in the NC samples, although this was not statistically significant (*P* = 0.18, *P* = 0.21, *P* = 0.16 and *P* = 0.23, respectively). The relative abundances of the *C. coccoides* group and *Alistipes* spp. were significantly lower in fecal communities fermented on LA than in the NC fermentations (*P* < 0.05 and *P* < 0.05, respectively). FOS fermentation resulted in a significantly lower relative abundance of *Alistipes* spp. and *Desulfovibrio* spp. than the NC fermentations (*P* < 0.05 and *P* < 0.05, respectively). A significantly lower density of *Desulfovibrio* spp. was additionally observed in the fecal communities fermented on HA (*P* < 0.01). No statistical difference in bacterial density after fermentation of the four different substrates was seen for the remaining investigated bacterial taxa.

In line with previous studies [11,24], major individual differences between intestinal bacterial ecosystems derived from different subjects were observed. The density of 16S rRNA genes of four different bacterial taxonomic units, showing alteration after fermentation (*Bifidobacterium* spp., *C. coccoides* group, *Alistipes* spp. and *Desulfovibrio* spp.), were thus determined for each of the six individual fecal communities (Table S2). Substantial individual differences were observed depending on substrate and bacterial target. However, fermentations in all six intestinal communities resulted in significantly higher increases of bifidobacteria than measured in the NC samples. When comparing the increase caused

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**Fig. 3.** PCA loading plot of selected metabolites (numbers corresponding to Tables 2 and 3) combined with microbial abundance data (Abbreviations corresponding to Table 1).

**Equation:**

\[
\text{NC}_2(I) - \text{NC}_0(I) = \text{NC}(I); \text{if } \text{NC}(I) < 0, \text{then } \text{NC}(I) = 0; \\
(\text{NC}(I) + \text{NC}(II) + \text{NC}(III))/3 = \text{NC}(A)
\]

**Equation:**

- **Finally,** the metabolite values M(A) to be included in the Principal Component Analysis (PCA) were calculated as: CH(A)–NC(A) = M(A); If M(A) < 0, then M(A) = 0.
- **P-values** describing differences between the experiments carried out with different substrates were calculated as: \( \frac{\text{CH(A)} - \text{NC(A)}}{\text{NC}(A)} \).
- **Secondly,** the average amount of specific metabolites NC(A) produced only due to metabolism of the basal medium were identified by analysis of the control incubations (NC) carried out without addition of a carbohydrate source:

\[
\text{NC}_2(I) - \text{NC}_0(I) = \text{NC}(I); \text{if } \text{NC}(I) < 0, \text{then } \text{NC}(I) = 0; \\
(\text{NC}(I) + \text{NC}(II) + \text{NC}(III))/3 = \text{NC}(A)
\]
HA fermentation fractions (but not FOS) were positively correlated to the presence of a metabolite corresponding to: 3-oxoalanine (Fig. 1; No. 4; B1, B2, B3, B5, B6), tyramine (Fig. 1; No. 5; B1, B2; B3, B5, B6), homoveratic acid (Fig. 2; No. 13; B1, B2; B3, B5, B6); and arabionofuranosyl structures (Fig. 2; No. 15; B1, B2, B3, B4 and B5).

Presence of the remaining metabolite candidates listed in Tables 2 and 3 depended highly on the bacterial community.

3.4. Combined data analysis of qPCR and LC–MS data

A PCA analysis was conducted for combined LC–MS and qPCR data. A loading plot combining selected metabolites (Tables 2 and 3) with all targeted bacteria taxa (Table 1) was created (Fig. 3) in order to reveal correlations between the presence of specific bacteria and specific metabolites.

The analysis indicated that abundance of the clostridial taxa (CI and CC), and a fatty acid derivative (14) was likely to co-occur. Additionally, a positive correlation was seen between the bacterial taxons Bifidobacterium spp. (Bis), Roseburia spp. (Rs), Bacteroides spp. (Bs) and the two metabolites corresponding to flavonoid C25H24O7 (15) and linoleic acid (21). Lactobacillus spp. (Ls) was seen to correlate with what could be 3-oxo-27-dodecanedioic acid (11 and 17), xanthine (18), flavonoid C15H14O3 (16), phenylactic acid (19) and a fatty acid derivative (20). Interestingly, the outcomes also included a negative correlation between the possible metabolites: 3-oxo-27-dodecanedioic acid (11, 17) and (R)-3-hydroxy-octadecanoic acid (12) as well as between two different fatty acid derivatives (20 and 14).

4. Discussion

Previous in vitro studies of sugar beet arabinono-oligosaccharides (AOS) have shown their bifidogenic effect and influence on the gastrointestinal microbiota, and have indicated that the prebiotic potential of high molecular weight AOS may be slightly better than that of the shorter ones [10,11,24]. Our present results confirm that AOS, whether it was high molecular weight (HA, > 1 kDa), low molecular weight (LA < 1 kDa), or a mix of these (BA) selectively stimulated the growth of bifidobacterial species (Table 1 and S2), which are associated with positive effects on the host health [25–27]. One of the health promoting properties of bifidobacteria is known to be the production of conjugated linoleic acid [28], which is produced from linoleic acid available in the GIT, originating (among other sources) from consumed plant tissues. In line with this, a positive correlation between the linoleic acid (No. 21) and several bacterial taxa including bifidobacteria (Bis), was found in the present study (Fig. 3).

Metabolites corresponding to phenylalanine (1), xanthine (18), linoleic acid or its derivatives (21) (based on accurate mass data) were all produced by AOS fermentation to a larger extent than seen for FOS (Fig. 5). A possible source of phenylalanine is bacterial degradation of arabionofuranosyl structures, present in the AOS [11]. The HA fermentation fraction, which was enriched for high-mass carbohydrates, was also enriched in feruloylated AOS, and in line with this, arabionofuranosyl structures (15) were partly explaining the observed difference between HA and LA or BA, respectively (Fig. 2). Higher amounts of feruloylated AOS in the HA fraction may lead to a higher probability of the non-digestible carbohydrate to reach the distal colon, potentially preventing the accumulation of toxic by-products of proteolysis and amino acid fermentation, which typically takes place in the absence of carbohydrates [29,30]. Phenylalanine produced by decomposition of the feruloylated AOS by the intestinal microbiota is an essential amino acid, and acts as precursor for tyrosine, signaling molecules such as

by the three substrates (BA, LA and HA), it varied significantly among the six fecal communities. FOS fermentation resulted in significantly lower fold changes of bifidobacteria in three out of the six fecal communities than seen for the AOS based substrates. Only one fecal community (derived from individual 2) showed no significant difference in bifidobacterial increase caused by the tested substrates. The densities of the C. coccoides group were either unaltered or significantly lower after fermentation of the four substrates. However, fermentation of FOS generally caused a smaller decrease of C. coccoides than observed for BA, LA and HA. In all six bacterial communities, densities of Alstipes spp. and Desulfovibrio spp. were either unaltered or significantly lower after fermentation of the four substrates, however the extent of the reduction varied between communities.

3.3. Metabolomic studies

After quenching the metabolism, LC–MS analysis of samples taken before and after fermentation was performed using electrospray ionization in both positive and negative mode. After grouping of the LC–MS data in time-mass buckets, only buckets with significant differences between at least 2 substrates were included in the further analysis, which significantly reduced the number of variables (metabolites). PCA analysis of the reduced metabolite (bucket) profile data (Figs. S3 and S4) from positive mode did not show a clear clustering, indicating that none of the selected profile data explain a differentiation caused by the different fermentation substrates. However, in the negative mode, the selected profile data from FOS-fermentation samples clustered separately from all three types of AOS (Fig. S4). For each of the bacterial communities, we observed that BA and LA metabolite profiles were typically very similar to each other, but different from the profiles measured after fermentation of HA or FOS.

In order to identify effects of the fermentation substrates on the metabolite profiles and avoid missing caused by the differences between the individual bacterial communities, PCA analysis was carried out for each community separately and presented as bi-plots (Figs. 1 and 2). Based on this, metabolites that may contribute to the differences observed between samples fermented on the four substrates were selected as shown in Tables 2 and 3, and Fig. S5. As described above, the profiles obtained after BA and LA fermentation were typically quite similar to each other, but different from those from HA and FOS fermentation. This was also seen in the PCA plots based on the metabolite profiles from the individual bacterial communities. Based on the accurate mass data, phenylalanine (Fig. 1; No. 1; all individuals), xanthine (Fig. 2; No. 18; B2, B3, B5 and B6) and linoleic acid or its derivative (Fig. 2; No. 21; B1, B4 and B6) are likely candidates that contribute significantly to differentiate between AOS and FOS-fermented samples. In all six microbial communities, the metabolite corresponding to phenylalanine (1) was present in higher amounts in one or more of the AOS-fermented samples than in FOS-fermented samples (Fig. S5).

A metabolite corresponding to N-acyetylserine (Fig. 1; No. 2; B1, B2, B3, B5 and B6) was present in high levels in FOS and LA fermentation samples, but separated these from BA and LA fermentation, and although a significant increase of N-acyetylserine was observed in all bacterial communities after fermentation of one or more of the 4 oligosaccharides (Fig. S5), the highest increase of this metabolite candidate was observed in HA and FOS.

Oppositely, BA and LA fractions typically had a higher content of the metabolite candidates: cysteine (Fig. 1; No. 6; B1, B3, B5 and B6), aminobenzoic acid (Fig. 1; No. 8; B1, B4 and B5), hypoxanthine (Fig. 1; No. 9; B2, B3, B4 and B6) and 3-oxo-27-dodecanedioic acid (Fig. 1; No. 11; B3, B5, B6 and Fig. 2; No. 17; B2, B3, B5, B6).
A metabolite corresponding to N'-acetylspermidine (as determined by accurate mass) was typically increased in HA as well as FOS fermentations. N'-acetylspermidine has significant roles in many biological systems found in mammals, plants, and microbes [20]. Whether bacterially-produced N'-acetylspermidines affect epithelial cell growth and proliferation remains to be addressed.

Generally, we observed that BA and LA metabolite profiles were similar to each other, but different from the profiles measured after fermentation of HA or FOS. In fact, no major differences in the metabolite profiles were observed between the BA and LA fractions (Figs. 1 and 2 and S5). We speculate that intestinal bacteria were more prone to metabolize the carbohydrates with lower mass, which were present in rather high amounts in BA (Fig. S1). Metabolites typically correlated with the BA and LA fractions corresponded to cysteine (6) and aminobenzoic acid (8). Cysteine, which may arise from bacterial metabolism of plant structures [31], and contributes to the maintenance of anaerobic conditions by binding free oxygen [40], is known to increase the pH during fermentation by buffering the environment [41]. This may explain the higher number of Desulfovibrio spp. observed in the BA and LA fermentations (Table S2), as previous reports show that cysteine supports the growth of Desulfovibrio [42]. Aminobenzoic acid may originate from degradation of phytochemicals or ferulic structures by the microbial communities [31].

A significant increase of a putative flavonoid (16) was observed in five out of six subjects for all of the tested carbohydrates (Fig. S5). Flavonoids may be released by microbial fermentation of plant structures present in the fecal matter, and are shown to have a number of biological effects on the human body, including antioxidative ramification of polyphenolic compounds active against cancer, atherosclerosis and chronic inflammation [43,44]. They are known to inhibit and induce a large number of mammalian enzymes [43] involved in cell division, proliferation and detoxification [45]. Absorption of flavonoids from the diet was long considered to be negligible, as they are present in foods bound to sugars as glycosides [46]. However, it has now been shown that the final biological activity of flavonoids depends on the intestinal bacterial metabolism, which breaks the glycosidic bonds and leads to biotransformation of flavonoic compounds, thereby changing their bioactivity [47]. Many lactic acid bacteria (LAB) are able to break the glycosidic bonds, and the observed increase in the number of bifidobacteria observed for all fermentation substrates may have caused a higher amount of free flavonoids to be released. A correlation between the abundance of Lactobacillus spp (Ls) and the candidate flavonoid compound (16) was found (Fig. 3), indicating that also these species contributed to release of flavonoids.

In conclusion, we find that the present investigation shows that combining PCR techniques with metabolic profiling provides a strong tool to study complex microbiotas and their interactions with given substrates. We have shown that the response to high-mass arabino-oligosaccharides (HA) resembled that of FOS more than seen for mixed and low-mass arabino-oligosaccharides (BA and LA), supporting that the high-mass arabinans were the most promising prebiotic candidates. The proposed list of metabolite candidates enhanced by the arabino-oligosaccharide substrates constitutes a new and substantial contribution to the understanding of the mechanisms behind prebiotic interaction with the host.

Acknowledgments

The authors thank Kate Vina Vibefeldt and Bodil Madsen for excellent technical support. This work was supported by a grant from the Øresund Food Network (co-financed by The European Regional Development Fund and Vækstforum Hovedstaden; grant no.09198-02 “Bacterial Impact on the Gut Metabolome”) and by the Danish Strategic Research Council’s Committee on Food and Health (FaSu; project no. 2101-06-0067 “Biological Production of Dietary Fibres and Prebiotics”). AOS substrates were kindly provided by Danisco A/S (Nakskov, Denmark).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.anaerobe.2014.05.007.

References
