

Formulas to Quantify the Maximum Theoretical Gas Volumes from Fermentable Carbohydrates in the Human Gut with and Without Lactose

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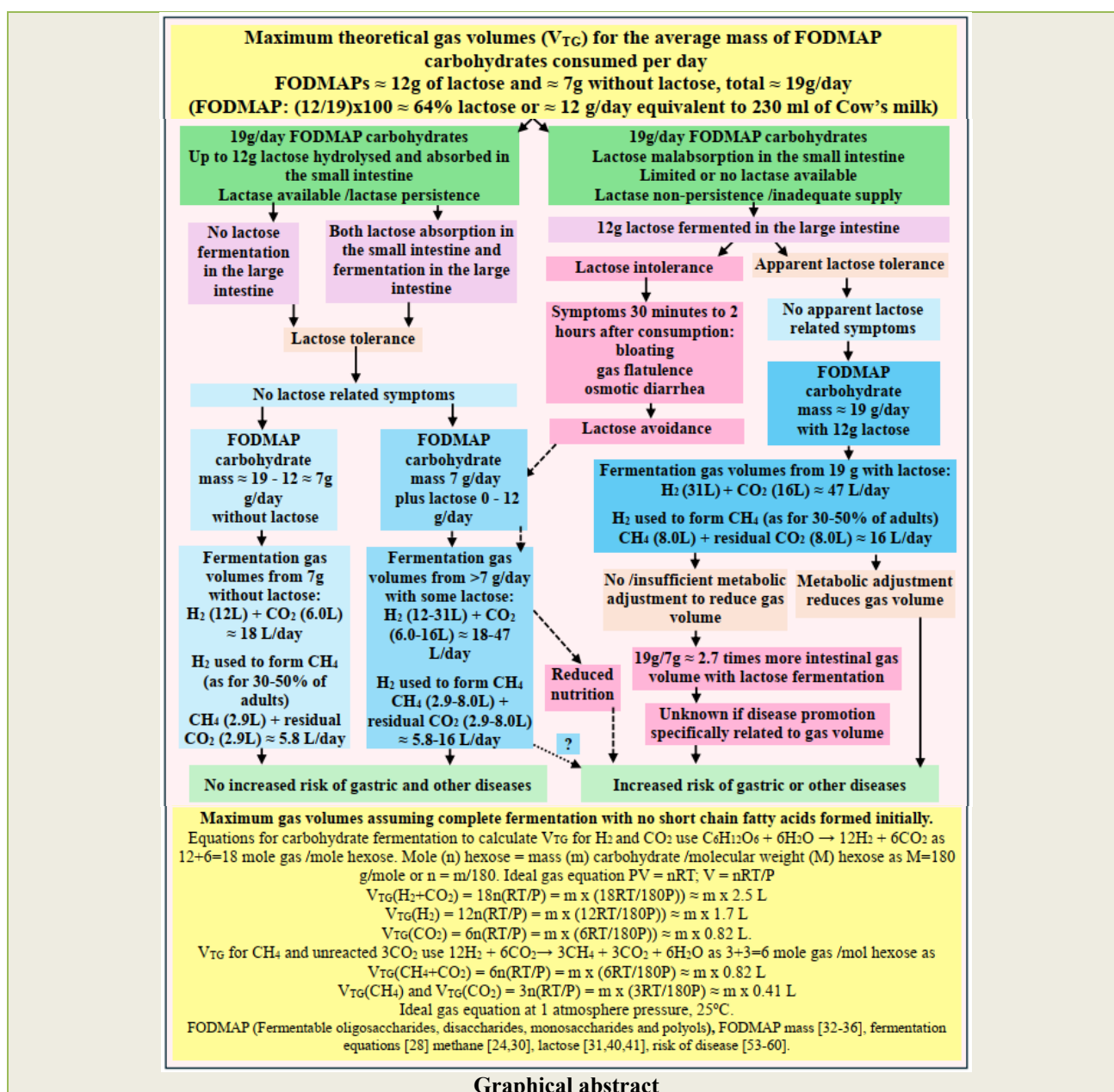
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Abstract

Original Research Article



Bloating, visual abdominal distension, irritable bowel syndrome (IBS), functional dyspepsia (FD) and small intestinal bacterial overgrowth (SIBO) are some of the symptoms that have been associated with the volume of intestinal gas produced. A reduced intake of fermentable carbohydrates as oligosaccharides, disaccharides, monosaccharides and polyols (FODMAP) has been suggested may reduce intestinal gas related symptoms. In this report formulas to quantify the maximum theoretical gas volumes (V_{TG}) that could be produced from fermentable carbohydrates if completely fermented, although not expected to be reached due to substrate depletion on forming new biomass, would allow the possible scale of gas production to be considered. Only the main gases from fermentation as hydrogen (H_2), carbon dioxide (CO_2) and methane (CH_4) were considered. To calculate V_{TG} it was assumed the mass (m) of carbohydrate underwent complete hydrolysis /fermentation to produce hexose ($C_6H_{12}O_6$) which was then further fermented with water to form a maximum possible 12 mole H_2 and 6 mole CO_2 per mole hexose according to the equation $C_6H_{12}O_6 + 6H_2O \rightarrow 12H_2 + 6CO_2$. With these assumptions and the use of the ideal gas equation at 25°C and 1 atmosphere pressure, it was calculated the volume of H_2 and CO_2 was $V_{TG}(H_2 + CO_2) \approx m \times 2.5$ litres (L) or ≈ 2.5 L per gram of fermentable carbohydrate of which 2/3 the volume is H_2 and 1/3 the volume is CO_2 . If all the H_2 and CO_2 were reacted to form methane (CH_4) leaving some residual CO_2 , the new volume becomes $V_{TG}(CH_4 + CO_2) = m \times 0.82$ L or ≈ 0.82 L per gram of fermentable carbohydrate of which 1/2 the volume is CH_4 and 1/2 the volume is CO_2 according to the equation $12H_2 + 6CO_2 \rightarrow 3CH_4 + 3CO_2 + 6H_2O$. For FODMAP carbohydrates consumed at an average 19(16-22) g/day, gas volumes can be calculated as $V_{TG}(H_2 + CO_2) \approx 19 \times 2.5 \approx 47$ L/day with $V_{TG}(H_2) \approx 47 \times 2/3 \approx 31$ L/day and the $V_{TG}(CO_2) \approx 47 \times 1/3 \approx 16$ L/day. If lactose, with consumption $\approx 12(7.7-16)$ g/day was excluded, due to hydrolysis and absorption in the small intestine, then the fermentable mass reduces to $19-12 \approx 7(5-9)$ g/day and $V_{TG}(H_2 + CO_2) \approx 7 \times 2.5 \approx 18$ L/day with $V_{TG}(H_2) \approx 18 \times 2/3 \approx 12$ L/day and the $V_{TG}(CO_2) \approx 18 \times 1/3 \approx 6$ L/day. A ratio of gas volumes was also used to show that if lactose, 64% of FODMAP carbohydrate mass, was fermented rather than hydrolysed and absorbed in the small intestine, gas volumes could increase by ≈ 2.7 times. The role of gas in promoting gastric reflux and other health conditions was considered, finding lactose malabsorption likely to increase the risk.

Keywords: Carbohydrates, FODMAP, gas, GERD, hydrogen, IBS, lactose, LPR, methane, volume.

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1. INTRODUCTION

Bloating, visual abdominal distension, irritable bowel syndrome (IBS), functional dyspepsia (FD) and small intestinal bacterial overgrowth (SIBO) are some of the symptoms that have been associated with the volume of intestinal gas produced [1,2]. A reduced intake of FODMAP (fermentable oligosaccharides, disaccharides, monosaccharides and polyols) carbohydrates has been suggested may reduce internal gas related symptoms and osmotic effects via reduced luminal distension in patients with visceral hypersensitivity [1].

The source of gas in the gut lumen is not only from the fermentation of carbohydrates and protein more so if carbohydrates are lacking, but includes swallowed air at 6.4(0.32-47) litres (L)/24 hours, possible gas release from the blood supply by diffusion, carbonated drinks, food metabolism, antacid tablets or acid neutralisation of acidic stomach contents in the duodenum by bicarbonate ions [3-6].

Fermentation in the small intestine can occur from small intestinal bacterial overgrowth (SIBO) with fermentation by bacteria or intestinal methanogen overgrowth (IMO) with fermentation by methanogenic archaea, but mostly occurs in the large intestine [1,7,8].

The types of carbohydrates in the diet include those that can be either absorbed or absorbed after hydrolysis /broken down in the small intestine like mono and di-saccharides and starch (polymer of glucose monomers), unless malabsorption occurs (like lactose

and fructose) [1,9-13]. Carbohydrates that are not absorbed in the small intestine are mostly fermented in the large intestine, which include FODMAP, resistant starch (RS) and non-starch polysaccharide (NSP) that may be either fermented or excreted [1,9-13].

The volume of gas produced using empirical equations for 40g lactulose has been calculated, finding a maximum 12-13.5 L/day of hydrogen (H_2) but included the production of short chain fatty acids (SCFAs) which reduces substrate available to produce gas and results in lower values than V_{TG} [14-16].

In this report formulas are developed to calculate V_{TG} from the mass (m) in grams (g) of fermentable dietary carbohydrates consumed. Values are also determined for the average mass of FODMAP carbohydrates consumed daily, including changes in the gas volume and volume ratio with and without the dominant component, lactose. Only the main gases H_2 , carbon dioxide (CO_2) and methane (CH_4), that make up 99% of fermentation gas were considered [17].

2. RESULTS

2.1 Microbial metabolism and fermentation gas volumes

Microbial fermentation in the gut involves hydrogenase mediated H_2 production and cycling that support fermentative growth of gut bacteria [18]. The complex fermentation process has been described as a “black box” in which catabolism drives the production of products and through energy coupling, drives anabolism

and the production of new biomass [19]. Microbial communities act in competition and mutualism, acting as fermenters and consumers with cross-feeding, sharing metabolites between microbes and the host [20]. Examples of cross-feeding can be demonstrated from fecal samples under isotopically labelled CO₂ showing the short chain fatty acids (SCFAs) acetate was formed from CO₂ fixation at 25-33% of the total acetate produced in two subjects, with propionate also formed by CO₂ fixation pathways [21].

These findings indicate that the volume of gas produced can change during the fermentation process, with excess gases as waste, only a fraction of the overall gas and gas cycling volumes. In this case, the simplest way to estimate V_{TG} was to calculate the total mass of carbohydrate consumed that could be converted to gas as the sum of the actual gas volume produced by fermentation (V_F) plus the volume that had fermentation potential (V_{FP}), that could have been converted into gas;

$$V_{TG} = V_F + V_{FP} \tag{1}$$

where V_F consists of the volume of gas used by both the microbiome (V_M) for anabolism and the volume shared with the host (V_H);

$$V_F = V_M + V_H \tag{2}$$

where V_H consists of the volume of regulatory gases V_{RG} and the volume of unrequired gas as waste V_W;

$$V_H = V_{RG} + V_W \tag{3}$$

as shown in Fig. 1. Regulatory gases include CO₂ used as the bicarbonate ion to balance pH, H₂ for pH and electron transfer/redox reactions which may provide neuroprotective activity against oxidative stress and CH₄ which has an emerging role as a regulatory molecule [5,22-25]. Humans host microbial anabolism by providing fermentable carbohydrate and heat exchange gaining useful metabolites like SCFAs with the gases generally considered waste products.

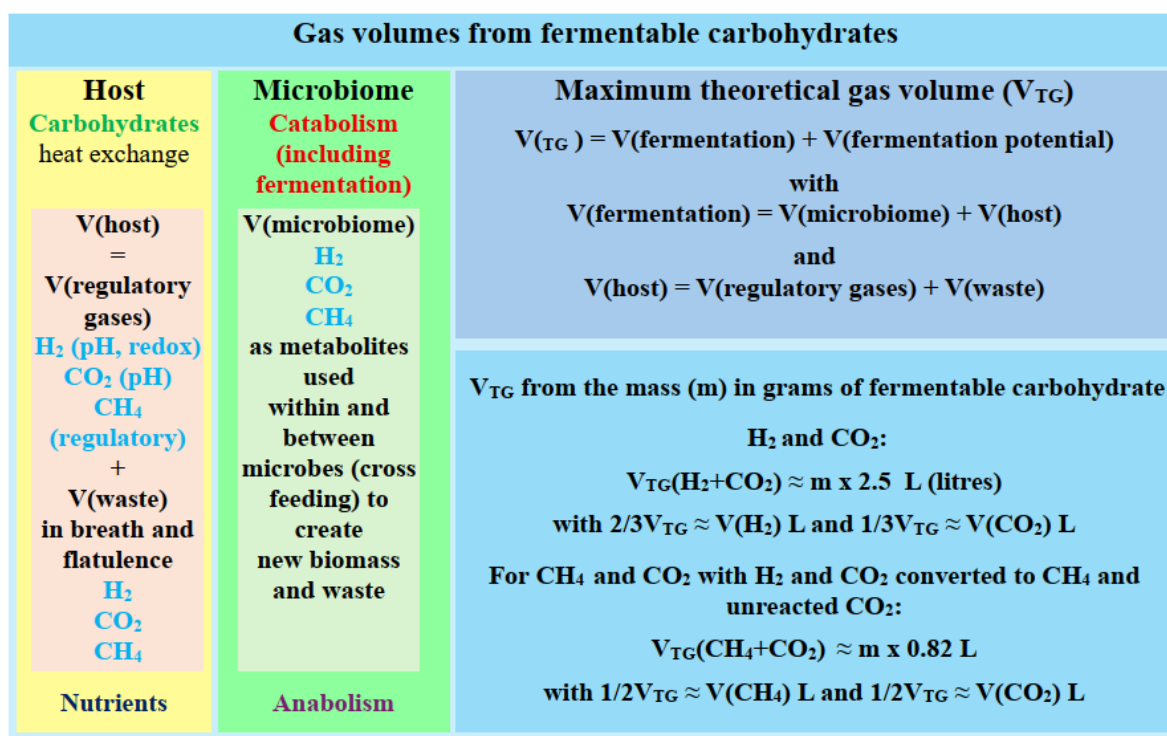


Figure 1: Microbial fermentation with formulas to calculate the maximum theoretical fermentation gas volumes (V_{TG}) from the mass of fermentable carbohydrates consumed. Gas volumes including gas within bacterial cells and free gas in the lumen used to create new biomass, gas used by the host in a regulatory role and that expressed as waste by the host

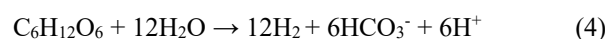
2.2 Calculation method: maximum theoretical gas volume (V_{TG})

To develop equations to determine V_{TG} from the mass of fermentable carbohydrate (eq 1), the following assumptions and steps were undertaken;

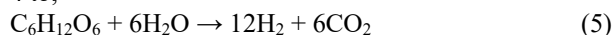
1. Carbohydrates generally have the empirical formula C_x(H₂O)_y [10].
2. Carbohydrates are first hydrated /fermented such that the mass of carbohydrate forms approximately the same mass of hexose,

defined as monosaccharides of the formula C₆H₁₂O₆ like glucose, fructose or galactose [26,27].

3. Hexose can be fermented with the addition of water to form the bicarbonate ion and may not generate any CO₂ [28];



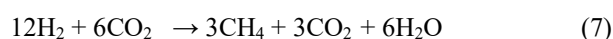
The survival of the bicarbonate ion depends on pH and if acidic enough, generates $6\text{H}_2\text{O}$ and 6CO_2 simplifying eq. 4 to;



resulting in 12 moles of H_2 and 6 moles of CO_2 as $12 + 6 = 18$ moles gas /mol hexose with $2/3\text{H}_2$ and $1/3\text{CO}_2$ [28,29]. Methane can be formed from H_2 and CO_2 as [28-30];



On combining eqs. 5 and 6 and using all the gas available;



Resulting in 6 moles gas /mole hexose composed of 3 moles of CH_4 with 3 moles unreacted CO_2 as $1/2\text{CH}_4$ and $1/2\text{CO}_2$ with the initial 18 moles of gas (eq. 5) reduced by $2/3$ to 6 moles of gas.

- Some gases can re-combine to form SCFAs as cross-feeding or SCFAs can form initially without forming gas, but have the potential to form gas [20,28-30].
- From the ideal gas equation, $PV = nRT$, where pressure (P) is assumed to be 1 atmosphere (atm) or 101,325 pascals, volume (V) in meters (m) as m^3 but requiring multiplication by 10^3 to convert to litres (L), moles (n), gas constant $R = 8.314 \text{ J.K}^{-1}\text{mol}^{-1}$ and temperature in Kelvin as 298.15 K at 25°C . The moles of a substance can be calculated as $n = \text{mass (m)}/\text{molecular weight (M)}$ with M in units g /mole and $n = m/M$.
- The ideal gas equation can be written as;

$$V = n \times (8.314 \times 298.15 / 101325) \times 10^3 = n \times 24.46 \approx n \times 24.5 \text{ L for } n \text{ moles gas at } 1 \text{ atm, } 25^\circ\text{C} \quad (8)$$

Note that only the number of moles of gas influence the volume, not the type of gas, being the same volume for H_2 , CO_2 or CH_4 for the same molar amount.

7. From eq. 5 giving 18 moles of gas /mole hexose consisting of 12H_2 and 6CO_2 and eq. 8 for $n = m/180$ moles of hexose;

$$V_{\text{TG}}(\text{H}_2+\text{CO}_2) = (m/180) \times (12+6) \times 24.5 \approx m \times 2.5 \text{ L with } 2/3 \text{ H}_2 \text{ and } 1/3 \text{ CO}_2 \text{ 1 atm, } 25^\circ\text{C} \quad (9)$$

resulting in;

$$V_{\text{TG}}(\text{H}_2+\text{CO}_2) \approx 2.5\text{m L}, \quad V_{\text{TG}}(\text{H}_2) \approx 2.5 \times 2/3 \approx 1.7\text{m L}, \\ V_{\text{TG}}(\text{CO}_2) \approx 2.5 \times 1/3 \approx 0.82\text{m L} \quad (10)$$

If all the H_2 and CO_2 from eq. 5 are used to form CH_4 as from eq. 7 producing 3CH_4 and 3CO_2 ;

$$V_{\text{TG}} = (m/180) \times (3+3) \times 24.5 = m \times 0.82 \text{ L with } 1/2 \text{ CH}_4 \text{ and } 1/2 \text{ CO}_2 \quad (11)$$

resulting in;

$$V_{\text{TG}}(\text{CH}_4+\text{CO}_2) \approx 0.82\text{m} \quad V_{\text{TG}}(\text{CH}_4) \approx 0.82 \times 1/2 \approx 0.41\text{m L}, \\ V_{\text{TG}}(\text{CO}_2) \approx 0.82 \times 1/2 \approx 0.41\text{m L} \quad (12)$$

8. For example, 19 g of carbohydrate can produce $V_{\text{TG}}(\text{H}_2 + \text{CO}_2)$ from eq. 10;

$$V_{\text{TG}}(\text{H}_2 + \text{CO}_2) \approx 19 \times 2.5 \approx 47 \text{ L}, \quad V_{\text{TG}}(\text{H}_2) \approx 47 \times 2/3 \approx 31 \text{ L}, \\ V_{\text{TG}}(\text{CO}_2) = 47 \times 1/3 \approx 16 \text{ L} \quad (13)$$

and if the H_2 and CO_2 are used to produce CH_4 , from eq. 12;

$$V_{\text{TG}}(\text{CH}_4 + \text{CO}_2) \approx 19 \times 0.82 \approx 16 \text{ L}, \quad V_{\text{TG}}(\text{CH}_4) \approx 16 \times 1/2 \approx 8 \text{ L}, \\ V_{\text{TG}}(\text{CO}_2) = 16 \times 1/2 \approx 8 \text{ L} \quad (14)$$

2.3 Average mass of carbohydrates including FODMAPs consumed per day with and without lactose

Carbohydrates have been differentiated into two broad categories as glycemic carbohydrates including mono and disaccharides digested and absorbed in the small intestine and non-digestible carbohydrates as dietary fibre passing to the large intestine [9]. Carbohydrates can also be classified as sugars and starch absorbed or hydrolysed and absorbed in the small intestine and fibre which includes resistant starch (RS resists digestion in the small intestine) and non-starch polysaccharides (NSP), that may or may not be fermented in the large intestine and can be detected in feces, Table 1 [1,9-13].

Fibre has been defined as non-digestible but possibly fermentable carbohydrates plus lignin and include; RS, NSP as cellulose, inulin (fructans), pectins and hydrocolloids like gums, mucilages and glucans, resistant oligosaccharides like fructooligosaccharide (FOS) and galactooligosaccharide (GOS) and other resistant oligosaccharides and lignin associated with dietary fibre polysaccharides [1,9-13,31].

The low molecular weight (M) carbohydrates with a degree of polymerisation (DP) of less than 10 monomeric sugar /hexose units and polyols have been further classified into FODMAP carbohydrates, based on their rapid rate of fermentation compared to the slower fermentation of higher M hexose polymers like RS and NSP, Table 2 [1,32-36]. FODMAP carbohydrates include mono and disaccharides and polyols that are not classified as fibre but can be fermented and FOS and GOS which are classified as fibre with FOS, $\text{DP} \geq 2$ and GOS, $\text{DP} \geq 3$ fermented in the large intestine [1,31]. The average mass of FODMAP carbohydrates from 5 separate studies was calculated as 19(16-22) g/day but does not include NSP with $\text{DP} > 10$ like RS or inulin, a polymer of fructose monosaccharides generating a fructan polymer with a glucose end group and $\text{DP} > 10$, Table 2 [8,31-36].

The mass and range for the different types of carbohydrates consumed and excreted by 53 volunteers per day for a typical Western diet has been summarised in Table 1 [12]. The mass of carbohydrate consumed was $\approx 253(103-414)$ g/day with 234g (92%) digested in the small intestine and 19(7-46) g/day (8%) fibre of which 12.6 g/day (66%) was fermented in the large intestine and 6.4 g/day (34%) of fibre excreted, Table 1 [12]. For the dietary carbohydrate mass of ≈ 253 g/day surprisingly 97.6% was digested or fermented and only ≈ 6.4 g/day (2.5%) excreted as part of daily fecal output of 127(41-340) g/day wet weight or 33(15-81) g/day dry weight Table 1 [12].

Larger studies with 36,034 volunteers reported the total average and range of carbohydrate consumption re-calculated from the tabulated data was 248(200-300) g/day consisting of 103(71-133)g or 42% sugar, 123(82-151)g or 49% starch (non-resistant and RS) and 22(17-33)g or 9% fibre finding similar values as shown in Table 1 [37].

Resistant starch has been classified into 4 different types that can be potentially fermented in the large intestine of mass $\approx 4.9(2.8-7.9)$ g/day with the main sources, bread 21%, cooked cereals/pastas 19% and vegetables (other than legumes) 19%, similar to the value of 5(2-11)g from Table 1 [11].

The average inulin intake based on dietary recall from over 15,000 Americans was found as 2.6 g/day with 69% from wheat, 23% onions, 3% bananas, 3% garlic and 2% other sources with FOS (a short chain version of inulin) intake 2.5 g/day with 71% from wheat, 24% onions, 2% bananas, 2% garlic and 1% from other sources [38]. GOS is present in human milk as well as in the generative part of plants like beans and legumes with the average mass of GOS and FOS consumed being 3.6 g/day as also shown in Table 2 [31]. This suggests from the values above the mass of GOS consumed is 3.6(mass FOS and GOS) - 2.5(mass of FOS) = 1.1 g/day.

The total mass of fermentable carbohydrates including the FODMAP fibre components of FOS and GOS and other NSP fibre as inulin and RS gives an approximate sum value of $\approx 19 + 4.9 + 2.6 \approx 26-27$ g/day but does not include all NSP like cellulose, gums, mucilages, pectins, et cetera. The mass of carbohydrate fibre consumed may not be the same as the mass fermented as from Table 1, 6.4 g/day or 34% was excreted from the 19 g/day consumed [12]. A more detailed calculation of the mass of all carbohydrate consumed and the rates of consumption, digestion, fermentation and excretion per day requires a dedicated review and is beyond the scope of this article.

Table 1: Results by Birkett *et al.*, [12] from 53 volunteers with some data recalculated and adapted. Results show 97.5% of carbohydrates consumed were either digested or fermented with 2.5% excreted. Of the fibre consumed, 66% was fermented and 33% excreted. For RS, 16% was excreted and for NSP, 40% was excreted. Resistant starch (RS), non-starch polysaccharides (NSP)

Daily carbohydrate consumption, digestion, fermentation and excretion: average mass (range) g/day [12]					
Carbohydrate types	Consumption	Digestion small intestine	Fermentation large intestine	Excretion	% digestion or fermentation
Sugars %	108(32-211) g $\approx 42\%$	$\approx 108(32-211)$ g unless malabsorption	≈ 0 unless FODMAP as lactose or excess fructose present	0	100%
Starch (not resistant) %	126(54-290) g $\approx 50\%$	126(54-290) g	0	0	100%
Fibre %	19(7-46)g $\approx 8\%$ with RS $\approx 5(2-11)$ g NSP $\approx 14(5-35)$ g	0	19-6.4 \approx 12.6g RS: $(5-0.8)/5 \times 100 \approx 84\%$ NSP: $(14-5.6)/14 \times 100 \approx 60\%$	6.4(1.9-23.3)g $(6.4/19) \times 100 \approx 34\%$ RS: 0.8(1.1-5.6)g $(0.8/5) \times 100 \approx 16\%$ NSP: 5.6(1.8-17.4)g $(5.6/14) \times 100 \approx 40\%$	$(12.6/19) \times 100 \approx 66\%$
Total (g)	108+126+19 \approx 253(103-414)g	(253-19) \approx 234g $(234/253) \times 100 \approx 92.5\%$ unless malabsorption	(19-6.4) \approx 12.6g $(12.5/253) \times 100 \approx 5\%$	6.4g $(6.4/258) \times 100 \approx 2.5\%$	(253-6.4) \approx 247g $(247/253) \times 100 \approx 97.5\%$ despite malabsorption

The four types of FODMAP carbohydrates consists of 19% FOS and GOS, 64% the disaccharide

lactose, 8.5% the monosaccharide fructose which when in excess of glucose is not absorbed and available for

fermentation and 8.5% polyols, Table 2, [1,32-36]. FODMAP carbohydrates exert increased osmotic effects in the lumen due to their lower M, increasing molar concentrations in solution (van't Hoff's law) resulting in increased water absorption to a greater extent than for RS and NSP [39]. FODMAP carbohydrates are also fermented more rapidly than RS and NSP and thought to have a greater contribution to the induction of gastrointestinal symptoms of luminal distention and visceral hypersensitivity [1].

The disaccharide lactose can be hydrolysed into glucose and galactose if the persistence of the production of lactase continues into adulthood and then fully absorbed in the small intestine [40]. Lactose malabsorption can result from lactase non-persistence or inadequate supply resulting in lactose fermentation in the distal small intestine or large intestine to produce H₂, CO₂, CH₄ and SCFAs [40]. Lactose malabsorption/fermentation can result in symptoms within 30 minutes to 2 hours include bloating, flatulence, osmotic pressure inducing fluid influx and osmotic diarrhea [40,41]. Cow's milk contains approximately 5g of lactose per 100

ml or for a typical serving size of 250 ml, 12.5 g of lactose, Graphical Abstract [40].

Most individuals with lactose malabsorption tolerate at least 12g without problems, even larger doses if spread over the day and with other food [40]. The colon may adapt to regular lactose ingestion reducing symptoms of lactose intolerance by metabolic adaption, increasing nonhydrogen producing or gas consuming organisms and reducing gas volumes [42].

For 7 healthy Dutch adults who were lactose tolerance, 27.9-47.5% of 1.7g lactose ingested was still detected in the proximal colon, indicating partial absorption in the small intestine resulting in lactose being available for fermentation in the large intestine [31]. As some individuals may fully digest rather than ferment lactose, values excluding lactose were calculated from the average daily intake of FODMAP carbohydrates as ≈ 7(5-9) g/day, Table 2. As FODMAP carbohydrates are likely the greatest and fastest contributors to gas production in the large intestine, V_{TG} using these mass values were calculated, Graphical Abstract.

Table 2: FODMAP carbohydrates consumed over 24 hours based on the data from five studies gave an average daily consumption of ≈ 19(16-22) g/day containing ≈ 64% lactose [32-36]. If lactose was excluded, the average daily consumption reduces to ≈ 7(5-9) g/day. Average mass for each FODMAP carbohydrate type was calculated from the masses of the same component in each group from the row. Average % of each FODMAP component calculated from the mass in each group for the row over the sum of all FODMAP components (96.3g or 33.9g without lactose). Standard deviation (SD) values shown

Four groups of FODMAP carbohydrates in food with "F" in FODMAP for fermentable	2025 [32]	2021 [33]	2020 [34]	2014 [35]	2010 [36]	Average mass (with lactose) ≈ mass per row/5 as g/per day and % mass as mass per row/total mass ≈ 93.6 (5 reports)	Average mass (without lactose) ≈ mass per row/5 as g/day and % mass as mass per row/total mass ≈ 33.9 (5 reports)
"O" in FODMAP for the oligosaccharides FOS and GOS	4.4g	2.61g	3.89g	3.5g	3.62g	18.02/5 ≈ 3.6(3.0-4.3)g 18.02/93.6 ≈ 19%	18.02/5 ≈ 3.6(3.0-4.3)g 18.02/33.9 ≈ 53%
"D" in FODMAP for the disaccharide lactose	6.4g	10.3g	14.2g	11g	17.7g	59.6/5 ≈ 12(7.7-16)g 59.6/93.6 ≈ 64%	weight not included in the % calculation
"M" in FODMAP for the monosaccharide fructose in excess of glucose	3.3g	4.64g	0	0	0	7.94/5 ≈ 1.6(0-3.8)g 7.94/93.6 ≈ 8.5%	7.94/5 ≈ 1.6(0-3.8)g 7.94/33.9 ≈ 23%
"P" in FODMAP for polyols	1.2g	1.93g	1.31g	2.0g	1.54g	7.98/5 ≈ 1.6(1.2-2.0)g 7.98/93.6 ≈ 8.5%	7.98/5 ≈ 1.6(1.2-2.0)g 7.98/33.9 ≈ 24%
Average mass (g) consumed /24 hours with lactose	15.3g	19.5g	19.4g	16.5g	22.9g	15.3+19.5+19.5+16.5+22.9 ≈ 93.6g and 93.6/5 ≈ 19(16-22)g	-
Average mass (g) consumed /24 hours excluding lactose	8.9g	9.18g	5.2g	5.5g	5.16g	-	8.9+9.18+5.2+5.5+5.16 ≈ 33.9g and 33.9/5 ≈ 7(5-9) g

2.4 Factors influencing fermentation rates gas types and volumes

Table 3 lists some of the known factors contributing to the types and volumes of gas resulting from the fermentation of carbohydrates in the gut.

Table 3: Factors influencing fermentation rates, volumes, types of gas and the SCFA produced

Conditions	Factors influencing gas volume and types (H ₂ , CO ₂ and CH ₄)	Date and reference
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Food mixture influences SCFA /gas production	Increasing the amount of lettuce and celery and omitting carrot and applesauce from an in vitro nutrient suspension including human feces increased CH ₄ volume from 10.9 to 18 mmole/L equivalent to ≈ 1L of H ₂ .	1981 [43]
Degrees of fermentation as partial of full	The rate of stirring increased hydrogen production when glucose was added to fecal samples. Comment: the volume of gas produced may be influenced by the degree of mixing and not necessarily directly proportional to the mass of fermentable carbohydrate consumed.	1992 [44]
Co-fermentation influences NADH/NAD ⁺ ratio	Glucose or glycerol fermented separately produce less SCFA, propionic acid, than when fermented together. Comment: although gas volumes were not measured it suggests the mixing of food components may influence gas production volume and type.	2011 [45]
Food mixture glucose /fructose	Fructose is rapidly absorbed in the presence of equimolar concentrations of glucose but if in excess of glucose (free fructose) can still be slowly absorbed in the small intestine but if rapid transit occurs or a low GLUT5 transporter capacity, can be fermented.	2013 [1]
Methanogenic archaea	Methane only detected in 30-50% of healthy adults although methanogenic flora may still be present.	2014 [24]
Age	Quantity of CH ₄ detected in the breath can change with age.	2014 [24]
Inheritance	Methanogens have been detected in meconium.	2014 [24]
Geographical location, socioeconomic status, gender, family clustering	Any of these factors may influence the quantity of CH ₄ detected in the breath. Comment: any factor that changes the choice, type or mixture of food regularly consumed, likely influences gas production volume or type.	2014 [24]
Antibiotics and fermentation	Hydrogen and CH ₄ concentrations, using handheld breath test devices, can measure the response to antibiotics for patients with small intestinal bacterial overgrowth (SIBO).	2024 [46]
Cellular pH and redox status	Formate metabolism can help balance cellular pH, redox status and disproportionate into CO ₂ and H ₂ for <i>Escherichia coli</i> .	2025 [25]
Diurnal pattern of H ₂ and CH ₄ in breath	Handheld test devices show less H ₂ was produced after breakfast (10-11 am) than after dinner (8-11 pm).	2025 [47]

2.5 FODMAP carbohydrate chemistry

Carbohydrates and polysaccharides on fermentation can become hydrated to form hexose [1,26]. Polyols referred to as sugar alcohols like sorbitol found in fruits, vegetables and sugar free sweeteners undergo fermentation in the colon to form hexose and

pentose that then undergo glycolysis to form SCFAs and gases, Table 4 [26].

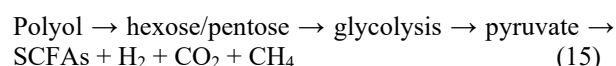
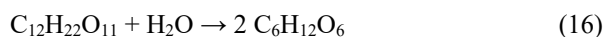


Table 4: The chemical formulas for the FODMAP carbohydrates. Polyols contain multiple hydroxy groups [1,26]

The 4 FODMAP carbohydrate component groups	Formula
Oligosaccharides: including FOS and GOS as low molecular weight polymers containing fructose or galactose	(C ₆ H ₁₀ O ₅) _n
Disaccharide: lactose composed of monosaccharides glucose and galactose	C ₁₂ H ₂₂ O ₁₁
Monosaccharides: Fructose in excess of glucose	C ₆ H ₁₂ O ₆ , (CH ₂ O) ₆
Polyols: sugar alcohols ^a naturally occurring ^b sugar substitute or sweetener	erythritol ^b C ₄ H ₁₀ O ₄ ; xylitol ^b C ₅ H ₁₂ O ₅ ; sorbitol ^a and mannitol ^a both C ₆ H ₁₄ O ₆ ; isomalt ^b , lactitol ^b , maltitol ^b all C ₁₂ H ₂₄ O ₁₁

Lactose found in dairy products can undergo hydrolysis to form the hexoses, glucose and galactose [10];



When 1 mole of lactose is hydrolysed, 2 moles of hexose are formed and the mass of the products increase by the mass of a water molecule. For example, 1 mole of lactose of molecular weight (M) of 342 g /mole on hydrolysis, forms 2 moles of hexose (glucose and galactose) of M 180 g /mole each, with combined mass of 2x180 = 360g (342g + 18g) representing an increase of mass of (360-342/342)x100 = 5.3%. The assumption for example, that 7(5-9)g of FODMAP carbohydrate hydrolyses to the same mass of hexoses can results in a slight increase in gas volume calculations, due to the addition of extra H₂ and O₂ molecules from H₂O but was within the range of the SD and neglected, Table 2.

2.6 The influence of temperature and pressure on gas volumes

From eq. 8, a body temperature of 37° = 310.15 K, has a volume of gas per mole, n = 1, as:

$$V = 1 \times (8.314 \times 310.15 / 101325) \times 10^3 \approx 25.45 \text{ L at 1 atm, } 37^\circ\text{C} \quad (17)$$

which compared to the volume at 25° C (eq. 8) gives (25.45-24.46 /24.46) x 100 ≈ 4% increase in volume when the temperature increasing from 25° to 37° C. Volumes at 25° C can be converted to those at 37° C by multiplication by 25.45/24.46 ≈ 1.04.

Intraluminal pressure in the digestive system includes baseline pressures and those in response to a meal, as pressure waves and part of the propulsive motor pattern, with pressures ranging in amplitude from 5-230 mmHg in the colon [48]. Normal atmospheric pressure is 1 Atm = 760 mmHg = 101,325 pascals such that a

baseline pressure of 5 mmHg, $P = 760 + 5 = 765$ mmHg or $P = 101,325 + 101,325 \times (5/760) = 101,992$ pascals or P (atm) = $1 + 5/760 = 1.0065$ atm, which can be approximated to be close to atmospheric pressure.

For a pressure wave at maximum pressure of 230 mmHg, $P = 101,325 + 101,325 \times (230/760) = 131,989$ pascals or P (atm) = $1 + 30,667/101,325 = 1.30$ atm, a significant increase.

From eq. 8, the change in volume with a pressure wave of 230 mmHg gives $V = n \times (8.314 \times 298.15 / 131,992) \times 10^3 = n \times 18.78$ L at 1.3 atm, 25°C, a significant reduction in volume per mole of $(24.46 - 18.78/24.46) \times 100 = 23\%$. Gas volumes were assumed to be closer to resting pressures and so 1 atm was used as an approximation for the volume calculations.

Pressure has a greater influence on volume than temperature under physiological conditions, with volume increasing as gas can expand from an ambient temperature of 25°C to 37°C by $\approx 4\%$ for example after breathing or swallowing air, while during a maximum pressure wave of 230 mmHg in the colon, volume could reduce by 23%.

2.7 Mass moles and gas volumes

Although the volumes of gases given are often large, the mass (m) of gas can be small. For a mass of 19g of FODMAP carbohydrates as hexose with $M = 180$ or 19/180 moles hexose, from eqs. 5,13 produces 12 moles of H_2 /mole hexose with a volume of 31L. With the number of moles $19/180 \times 12$, the M for $H_2 \approx 2.016$ g/mole and with $m = n \times M$, the mass of H_2 $m(H_2)$;

$$m(H_2) = (19/180) \times 12 \times 2.016 = 2.55g \text{ with } V(H_2) \approx 31L \text{ at } 25^\circ C \text{ and } 1 \text{ atm} \quad (18)$$

showing 31L of H_2 has a mass of 2.55g. Similar calculations using eq. 5,13 with 6 moles of CO_2 /mole hexose and the M for $CO_2 \approx 44$ g/mole give $m(CO_2) \approx (19/180) \times 6 \times 44 \approx 27.8g$ with $V(CO_2) \approx 6$ L. The mass of 6 moles of water /mole hexose used in eq. 5 gives $m(H_2O) \approx (19/180) \times 6 \times 18 \approx 11.40g$. From eq. 5, 19g carbohydrate uses 11.4g water resulting in $19 + 11.4 \approx 30.4g$ of fermentation mass, producing the equivalent mass of gas as $2.55g H_2 + 27.8g CO_2 \approx 30.4g$.

From the ideal gas equation, $V = nRT/P = (m/M)RT/P$ where $n = m/M$ (eq. 8), for a given pure gas or ratio of gases in the same proportion for example, H_2/CO_2 of 12/6 moles (eq. 5) with the same value of M , at the same pressure and temperature that for n_1 and n_2 moles of hexose with masses m_1 and m_2 and gas volumes V_1 and V_2 ;

$$V_2/n_2 = V_1/n_1 \text{ with } P, T \text{ constant} \quad (19)$$

and

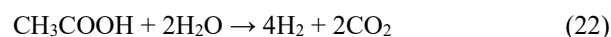
$$V_2 = n_2 V_1 / n_1 = (m_2/M) V_1 / (m_1/M) = (m_2/m_1) V_1 \text{ with } P, T \text{ constant, } M \text{ for } V_1 \text{ and } V_2 \text{ equal} \quad (20)$$

The ratio of moles or masses (M equivalent) can be used to estimate the increase of gas volumes based on moles or mass of hexose. For example, if 7g of FODMAP carbohydrate on fermentation forms $m_1 V_1$ L of gases and 19 g forms $m_2 V_2$ L of the same gases then $V_2 = 19/7 V_1$ or ≈ 2.7 times more gas could be produced when the fermentable mass increases from 7g to 19g, assuming a linear relationship.

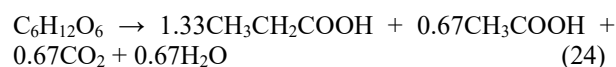
2.8 Gas volumes when carbohydrate fermentation forms SCFA

Four different short chain fatty acids (SCFAs) were detected when lettuce, celery, carrot and applesauce suspension in vitro, including human feces as 1% formate, 69% acetate, 6% propionate and 24% butyrate together with 146 ml of H_2 and 49 ml of CH_4 [43]. Note from eq. 6, the 49 ml CH_4 representing n moles of CH_4 can be converted to a volume for H_2 and CO_2 (CH_4 requiring $4n$ moles of H_2) to give a pre methanogenesis volume of $H_2 = 146 + (4 \times 49) = 342$ ml with an additional 49 ml CO_2 , total $V(H_2 + CO_2) = 342 + 49 = 391$ ml [43].

The most common pathways reported were for acetic acid (including subsequent hydrolysis to form carbon dioxide and water) and for the formation of butyric acid [27,29];

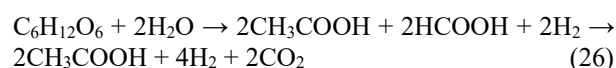


The fermentation of glucose and glycerol has been used industrially to produce propionic acid and CO_2 and if glycerol ($C_3H_8O_3$) was used alone, without the production of gas [45];



Fermentation of either glucose or glycerol alone produced less propionic acid than if co-fermented, with highest yields for a ratio of 1 glycerol: 4 glucoses [45].

Glucose when added to fecal samples generated formic acid initially but reducing over time to 1 % of the SCFAs formed and was possibly an intermediate towards acetic or butyric acid fermentation and not a major end product;

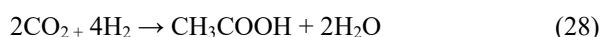


with acetic acid found as 69% of the SCFAs detected [43,50,51]. Formic acid or the formate ion are important in balancing cellular pH and redox status [25,50,51].

Methanogens can convert the H₂ and CO₂ produced by the fermentation of hexoses to methane, but not directly from hexose, reducing gas volumes eq. 6 [30]. Acetogens, bacteria found in anerobic environments, can ferment glucose stoichiometrically into acetic acid or the acetate ions and hydrogen ions (H⁺);



and gases produced by other fermentation processes (cross-feeding) can also be used by acetogens to produce acetic acid;



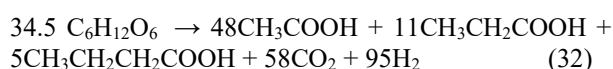
showing a reversal of eq. 22 [52]. A summary of some of the carbohydrate fermentation reactions producing SCFAs and CH₄ are shown in Table 5. If all fermentation occurred by acetogenesis, the minimum fermentation volume for carbohydrates could be 0 L/day.

Table 5: Summary of some of the fermentation pathways forming SCFAs and CH₄ [27,28,43,45,50,51].

Some fermentation equations for hexose forming SCFAs and CH ₄	
Formic acid (intermediate):	$C_6H_{12}O_6 + 2H_2O \rightarrow 2HCOOH + 2CH_3COOH + 2H_2 \rightarrow 2CH_3COOH + 4H_2 + 2CO_2$
Acetic acid:	$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 4H_2 + 2CO_2$
Propionic acid:	$C_6H_{12}O_6 \rightarrow 1.33CH_3CH_2COOH + 0.67CH_3COOH + 0.67CO_2 + 0.67H_2O$
Butyric acid:	$C_6H_{12}O_6 \rightarrow CH_3CH_2CH_2COOH + 2H_2 + 2CO_2$
Acetogenesis shows SCFA production without gas:	$C_6H_{12}O_6 \rightarrow 3CH_3COOH$
Methanogenesis shows 5 moles of gas reduced to 1 mole or by 80%:	$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$

2.9 Fermentation volumes previously reported

Gas volumes calculated for the fermentation of 40g lactulose have reported a maximum 12-13.6 L/day H₂, based on the amount of SCFAs, acetate, propanoate and butyrate produced from fermentation, using a molar quantity of 34.5 mole hexose to create a chemical equation [14-16,51];

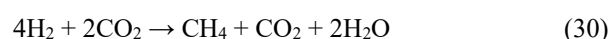


From eq. 32, it was calculated that 95/34.5 = 2.75 mole H₂/mole glucose and 58/34.5 = 1.68 mole CO₂/mole glucose. From Fig. 2, 40g of the carbohydrate lactulose would form 10-12 L of H₂ and 10-12 L of CO₂ if fermentation occurred mostly via the butyric acid pathway, with increasing volumes if more acetic acid was formed. It is recognised that fermentation stoichiometry and the production of SCFAs can vary depending on the food consumed, composition of the gut

Gas volumes using the acetic acid (V_{AA}) pathway from eqs. 8 and 21 produce 6 moles of gas as 4 moles H₂ and 2 moles CO₂;

$$V_{AA}(H_2 + CO_2) = (m/180) \times (4+2) \times 24.5 \approx m \times 0.82 \text{ L as } 2/3 H_2 \text{ and } 1/3 CO_2 \quad (29)$$

and for CH₄ volumes, combining with the methanogenic pathway from eqs. 6, 8 and 21;



with 1 mole CH₄ and 1 mole CO₂;

$$V_{AA}(CH_4 + CO_2) = (m/180) \times 2 \times 24.5 \approx m \times 0.27 \text{ L as } 1/2 CH_4 \text{ and } 1/2 CO_2 \quad (31)$$

Similar equations can be used to calculate gas volumes for the butyric acid pathway from eqs. 6,8,23 with the formic acid (eq. 26) and propionic acid (eq. 24) pathways of low gas volumes and so not shown, Fig. 2. Calculated gas volumes for the acetic and butyric acid pathways, including methane formation and FODMAP carbohydrates with lactose as 19g and without lactose as 7g, Fig. 2.

microbiota, cross-feeding and the gut general environment including pH with butyrate ions favoured under acidic conditions, Table 3 [49].

The maximum yield of H₂ from the fermentation of glucose for use as a source of industrial fuel, under anerobic conditions was reported as 2.68 mole H₂ /mole glucose but under microaerobic conditions could reach 6.68 mole /mole glucose, over half of the value of V_{TG} of 12 mole H₂/mole glucose from eq. 5, indicating significant fermentation volumes per mole glucose are possible, depending on conditions [27].

2.10 Gas volume and disease

Symptoms of bloating, visual abdominal distention, IBS and functional dyspepsia (FD) have been associated with an increase in intestinal gas volume and a low FODMAP diet associated with reduced gas production, could be beneficial [1,2]. Abdominal

symptoms could be induced following a challenge with lactose, fructose, sorbitol or FOS and attributed in part to the rapid production of gas and subsequent luminal distension as well as increased water retention from osmotic activity for patients with visceral hypersensitivity [1].

Of 104 patients referred for anti-reflux surgery, 39.4% had SIBO and 35.6% had IMO and in another report, for 41 patients, 46.3% tested positive for SIBO with higher self-reported laryngopharyngeal reflux

(LPR) symptoms with both reports suggesting a gas volume relationship, Table 6 [7,8].

For patients with refractory gastroesophageal reflux (GERD) who underwent fundoplication, 29/31 (95.5%) had food intolerances /malabsorption including lactose and fructose, Table 6 [53]. Lactose intolerance may be a significant factor contributing towards H₂ respiration possibly aiding *H. pylori* and *E. coli* survival in the gut, but an association specifically with gas volume was not discussed, Table 6 [53-56].

Table 6: The influence of gas from the fermentation of carbohydrates when in the gut or distributed systemically. The association of SIBO and lactose (64% of daily FODMAPs) or fructose (8.5% of daily FODMAPs Table 2) malabsorption with gut diseases and infections suggest excessive gas volume from fermentation may be a factor in disease promotion

Gas in the gut or systemically	Influence /association with a health detriment or benefit	Date and reference
Gut: Thermodynamics of hydrogen as an energy source	$O_2 + 2H_2 \rightarrow H_2O$; $\Delta G^\circ = -474.5$ KJ. Comment: The large negative Gibbs free energy (ΔG°) indicates a very favourable energy source to drive chemical reactions which bacteria like <i>H. pylori</i> and <i>E. coli</i> utilising H ₂ in aerobic environments like the stomach [55,56].	1977 [28]
Gut: H ₂ could promote the survival of <i>H. pylori</i> and <i>H. hepaticus</i>	Ample amounts of H ₂ found in the mucus lining of the stomach and lobes of the liver from a microelectrode study in mice concluding Helicobacter hydrogenases are saturated with H ₂ in the host and coupled to H ₂ /O ₂ respiration, oxidizing hydrogen as an energy source. H ₂ significantly increases <i>H. pylori</i> colonization ability.	2003 [55]
Gut: TLESRs, GERD from carbohydrate	Fermentation of oligosaccharides in the large intestine increase transient lower esophageal sphincter relaxations (TLESRs) and GERD. Comment: gas volume was not discussed as a factor for symptom promotion.	2003 [57]
Gut: Colonic transit time and CH ₄ in breath	Breath tests indicate the median total colonic transit time for children with constipation was 80.5 hours in CH ₄ producers and 61.0 in non CH ₄ producers.	2005 [58]
Gut: H ₂ promoting gut inflammation	<i>E. coli</i> metabolises H ₂ and was in part dependent on respiration of inflammation-derived electron acceptors in the context of non-infectious colitis in mouse models.	2021 [56]
Gut: <i>H. pylori</i> infection lactose intolerance and H ₂ production	For 293 patients with <i>H. pylori</i> , 58 had lactose intolerance, 23 had lactose intolerance with fructose malabsorption, 46 had lactose intolerance with histamine intolerance and 13 had all 3 conditions and suggested high expiratory H ₂ in lactose breath tests may indicate <i>H. pylori</i> infection.	2022 [54]
GUT: Small intestinal bacterial overgrowth (SIBO)	Of 104 patients referred for anti-reflux surgery, 39.4% had SIBO and 35.6% had IMO and more likely to report bloating and belching with H ₂ gas production significantly greater for regurgitation.	2022 [8]
Gut: SIBO	Patients who tested positive for SIBO had higher self-reported LPR symptoms than those who test negative. Suggested mechanisms included fermentation, distension and inducing TLESR.	2023 [7]
Gut: Carbonated drinks; non-fermented gas	Significant dose-response association between carbonated beverages and LPR possibly promoting gastric reflux by increasing acid and decreasing the lower esophageal sphincter pressure. Comment: gas volumes not discussed specifically as a possible significant factor.	2024 [4]
Gut: Lactose, fructose and histamine intolerances /malabsorption	For 31 patients with refractory GERD who underwent fundoplication 29/31 (93.5%) were found to have food intolerances /malabsorption as lactose intolerance only (8/31=25.8%), histamine intolerant only (8/31=25.8%), fructose malabsorption only (2/31= 6.5%), combinations including lactose and histamine intolerance, fructose malabsorption and one <i>H. pylori</i> infection (10/31 = 32%), fructose and histamine intolerant (1/31 = 3.2%) and none (2/31 = 6.5%).	2025 [53]
Systemic: lactose intolerance associated with multiple diseases	From 6758 data records, lactose intolerance considered a trigger for further disease including osteoporosis (reduced nutrition), heartburn, indigestion, stomach /duodenal ulcers, gastrointestinal infections, additional food intolerances including fructose malabsorption for IBS.	2016 [59]
Systemic: Neuroprotective	Neuroprotective effects of H ₂ therapy demonstrated in stroke, neurodegenerative diseases, neurotrauma and global brain injury attributed to reactivity towards hydroxy and peroxy-nitric radicals responsible for oxidative stress and disease process.	2023 [23]
Systemic: Type 2 diabetes	Causal relationship between decreased H ₂ production and increased CH ₄ production and more severe postprandial glycemia for type 2 diabetes.	2025 [60]

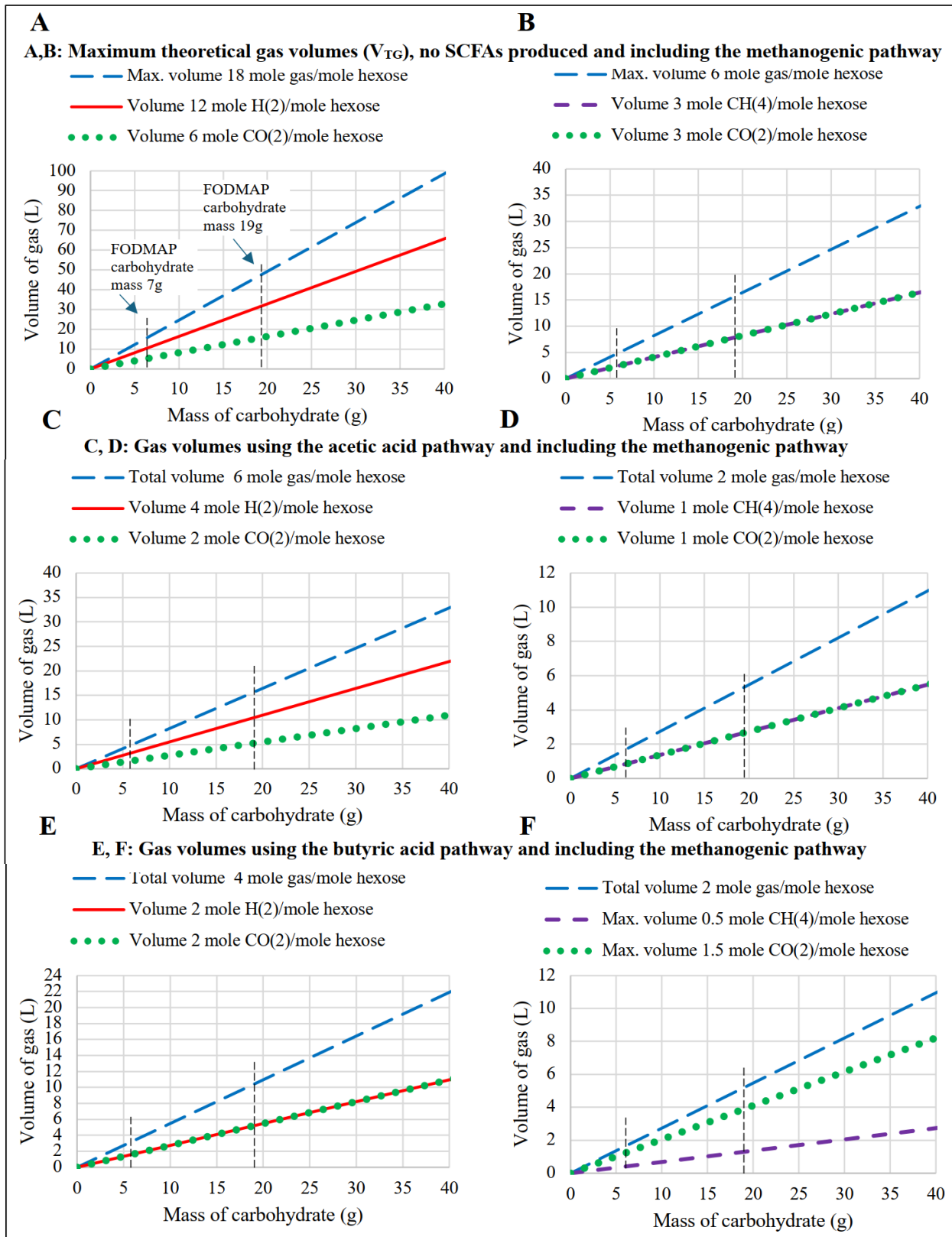


Figure 2: A, B. Maximum theoretical volume V_{TG} for H_2 and CO_2 (eqs. 5,8) and for the methanogenic pathway (eqs. 5, 6, 8) if all H_2 and CO_2 was converted into CH_4 including unreacted CO_2 without forming SCFA. C, D. Maximum volumes of H_2 and CO_2 using the acetic acid pathway (eqs. 8,21) and for the methanogenic pathway if all H_2 and CO_2 was converted into CH_4 and CO_2 (eqs. 6,8,21). E, F. Maximum volumes of H_2 and CO_2 using the butyric acid pathway (eqs. 8,23) and for the methanogenic pathway if all H_2 and CO_2 was converted into CH_4 and CO_2 (eq. 6,8,23). The volumes of gas produced from the average mass of FODMAP carbohydrates per day as 19g and without lactose as 7g for these pathways can be determined from the graphs

3. DISCUSSION

In the present study V_{TG} was calculated assuming the mass (grams) of fermentable carbohydrate consumed could be entirely converted to gas (eqs. 1,5) to provide a maximum value on the scale of possible gas volume production, Fig. 1. As a result, the scale for gas production could range from $V(H_2+CO_2) \approx 0$ L/day if carbohydrate fermentation occurred entirely by acetogenesis (eq. 27) converting all hexose to acetic acid to the maximum value of $V_{TG}(H_2+CO_2) \approx m \times 2.5$ L (eqs. 5,9) converting all hexose to 12 mole H_2 and 6 mole CO_2 /mole hexose.

The maximum yield of H_2 gas from the fermentation of glucose under microaerobic conditions was found could reach 6.68 mole /mole glucose, over half of the value of $V_{TG}(H_2)$ of 12 mole H_2 /mole glucose from eq. 5, indicating large volumes of gas are possible. A lower and more realistic value of actual gas production rather than the theoretical maximum could be $V(H_2+CO_2) \approx m/2 \times 2.5$ L to accommodate substrate depletion to form new biomass [27]. Gas production as part of catabolism and anabolism occurs over several hours and due to cross-feeding, gas could be produced and consumed in a cyclical manner, indicating the gas that can be measured from breath tests and from flatulence as waste gas, may be significantly less than that produced [18-20].

If all the H_2 reacted with the CO_2 available to produce CH_4 , a lower volume of $V_{TG}(CH_4+CO_2) \approx m \times 0.82$ L as $1/2CH_4$ and $1/2CO_2$ (eqs. 7,12) equivalent to 3 mole CH_4 and 3 mole CO_2 /mole glucose was produced, Fig. 1. As H_2 and CH_4 can be present at the same time in the large intestine, volumes between these values could also occur.

Gas volumes for fermentable carbohydrate that also produced SCFAs via the acetic acid pathway (eq. 21) were calculated and gave lower volumes $V_{AA}(H_2 + CO_2) \approx m \times 0.82$ L or for $V_{AA}(CH_4 + CO_2) \approx m \times 0.27$ L (eqs. 29,31) as expected, with reduced substrate when SCFAs are formed to produce gas, with values for both acetic and butyric acid (eq. 23) fermentation pathways shown in Fig.2.

Numerous factors are likely involved in hexose catabolism and anabolism and a linear increase in gas volumes with carbohydrate mass, as suggested, is a significant assumption, particularly given gas volume in vitro were found to increase with stirring rate for glucose /fecal samples, suggesting partial and not necessarily full fermentation can occur, Table 3 [44].

As FODMAPs form a significant part of fermentable carbohydrate consumption and can likely be converted to gas faster than RS and NSP and have be associated with digestive symptoms, V_{TG} values for the average mass was calculated. Lactose was found to represent 64% of FODMAP components and if

fermentation occurred in the large intestine, rather than hydrolysis and absorption in the small intestine, could increase gas volumes by ≈ 2.7 times, Graphical Abstract.

Individuals with both lactose malabsorption and apparent lactose tolerance, by showing no troublesome symptoms could potentially be the greatest gas volume producers per day with increased H_2 and possibly CH_4 in the lumen and systemically, Graphical Abstract. An increased risk of several diseases including refractory symptoms of GERD, *H. pylori* infection, heartburn, indigestion and stomach /duodenal ulcers have been associated with lactose and fructose malabsorption, Table 6 [53-56]. Higher respiratory H_2 from breath tests in patients with lactose and fructose malabsorption was considered a possible indicator for *H. pylori* infection and suggests the volume of H_2 produced, that enters the system, may have a role in promoting disease [54,55]. Fructose represents 8.5% of average FODMAP consumption and may have a lesser role than lactose at 64%, Table 2. Lactose avoidance has been associated with calcium deficiency and osteoporosis [59].

A decreased H_2 production and increased CH_4 has been linked to more severe postprandial glycemia for type 2 diabetes [59]. Gas from carbonated beverages (not from fermentation) has been reported to show a significant dose response for LPR although not specifically attributed to CO_2 gas volume, Table 6 [4].

Gas from fermentation may also have beneficial effects with therapy using H_2 showing neuroprotective effects, Table 6 [23]. It is possible the volume of gas (H_2 , CO_2 and CH_4) produced by fermentation may have a role in promoting gastric and other diseases as well as providing potential benefits and requires further research including determining the significance of dietary choices.

4. Assumptions and limitations

The main assumptions were that the mass of fermentable carbohydrate can be converted to moles of hexose according to eq. 5 to allow V_{TG} to be determined and that V_{TG} increases linearly with the mass of carbohydrate consumed. The rate of gas production from fermentation can be estimated for 19 g/day of carbohydrate as $V_{TG} / \text{min} \approx (2.5 \times 19) / (60 \times 24) \approx 0.033$ L/min or 33 ml/minute but a evaluation of the kinetics of fermentation was not considered but may be important in that a fast rate may overwhelm normal tolerance mechanisms and contribute to digestive symptoms. The influence of protein fermentation, which can increase in the absence of sufficient carbohydrate was not considered [6].

5. CONCLUSION

Formulas were developed to allow the maximum theoretical gas volume to be determined from the mass (grams) of fermentable carbohydrate consumed as $V_{TG}(H_2+CO_2) \approx 2.5m$ L composed of $2/3H_2$ and

1/3CO₂. If all the H₂ was used to form CH₄, V_{TG}(CH₄+CO₂) ≈ 0.82m L composed of 1/2CH₄ and 1/2CO₂. These values provide the upper limit to the scale of possible gas production from carbohydrate fermentation in the human gut.

A ratio of gas volumes was also used to show that if lactose, 64% of FODMAP carbohydrate consumption, was fermented rather than hydrolysed and absorbed in the small intestine, gas volumes could increase by ≈ 2.7 times.

It is likely the volume of H₂, CO₂ and CH₄ produced from the fermentation of dietary carbohydrates in the small intestine via SIBO and in the large intestine via FODMAP malabsorption (lactose, fructose) have a role in promoting numerous gut disorders including GERD, LPR, FD, *H. pylori* infection, heartburn, indigestion, stomach /duodenal ulcers, gastrointestinal infections and IBS. Malabsorption of lactose and possibly to a lesser extent, fructose (8.5% of daily FODMAPs) can increase gas production which likely increases the risk of disease promotion for some individuals.

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