Food Chemistry 182 (2015) 55–63

Contents lists available at ScienceDirect

Food Chemistry

journal homepage: www.elsevier.com/locate/foodchem

In vitro digestion of short-dough biscuits enriched in proteins and/or fibres, using a multi-compartmental and dynamic system (1): Viscosity measurement and prediction

C. Villemejane [a,b,c,*], R. Wahl [d], P. Aymard [d], S. Denis [e], C. Michon [a,b,c]

[a] AgroParisTech, UMR1145 Ingénierie Procédés Aliments, F-91300 Massy, France
[b] INRA, UMR1145 Ingénierie Procédés Aliments, F-91300 Massy, France
[c] CNAM, UMR1145 Ingénierie Procédés Aliments, F-75003 Paris, France
[d] Mondelēz International, F-91400 Saclay, France
[e] Clermont Université, Université d'Auvergne, Centre de Recherche en Nutrition Humaine Auvergne, EA 4678, Conception Ingénierie et Développement de l'Aliment et du Médicament, CS 60032, F-63001 Clermont-Ferrand, France

ARTICLE INFO

Article history:
Received 20 October 2014
Received in revised form 30 January 2015
Accepted 24 February 2015
Available online 3 March 2015

Keywords:
Rheology
Chyme
Biscuits
Fibres

ABSTRACT

The effects of biscuit composition on the viscosity generated during digestion were investigated. A control biscuit, one with proteins, one with fibres, and one with both proteins and fibres were digested under the same conditions, using the TNO intestinal model (TIM-1). The TIM-1 is a multi-compartmental and dynamic *in vitro* system, simulating digestion in the upper tract (stomach and small intestine) of healthy adult humans. Digesta were collected at different times, in the different compartments of the TIM-1 (stomach, duodenum, jejunum and ileum) and viscosity was measured with a dynamic rheometer. Results showed a marked effect of biscuit composition on chyme viscosity. Highest viscosity was obtained with biscuits containing viscous soluble fibres, followed by those enriched in both proteins and fibres, then by protein-enriched and control biscuits. The viscosity was maintained throughout the gut up to the ileal compartment. A prediction of the evolution of the chyme viscosity in each compartment of the TIM-1 was built, based on model curves describing the evolution of the viscosity as a function of biscuit concentration, and on dilution factors measured by spectrophotometry on a blank digestion.

1. Introduction

Biscuits are traditional food products favoured by consumers for their ease of transportation, their sensory properties and their long shelf-life. Biscuits usually contain significant amounts of sugars and fats. Nowadays, consumers request foods with an improved nutritional profile (lower sugar and fat contents) and/or with health benefits. To obtain products with additional health benefits, fibres or proteins are generally incorporated in cereal products such as biscuits (Bajaj, Kaur, & Sidhu, 1991; Kamaljit, Baljeet, & Amarjeet, 2010), bread (Brennan, Blake, Ellis, & Schofield, 1996; Brennan & Cleary, 2007; Kamaljit et al., 2010) or pasta (Rendon-Villalobos, Agama-Acevedo, Islas-Hernandez, Sanchez-Munoz, & Bello-Perez, 2006; Tudorica, Kuri, & Brennan, 2002). Protein enrichment in cereal products is carried out to improve their nutritional properties, to increase protein consumption, or to offset the deficiencies of certain limiting amino acids in cereals such as lysine, methionine, or tryptophan (Bajaj et al., 1991; Kamaljit et al., 2010). Dietary fibres are well-known (and well-documented) for their health benefits: "prevention of constipation, reduction of risk of developing diseases such as coronary heart disease, stroke, hypertension, diabetes, obesity, and certain gastrointestinal disorders (colorectal cancer), promotion of colonic health, stimulation of the growth of beneficial gut microflora (prebiotic effect). Furthermore, increased consumption of dietary fibres improves serum lipid concentrations, lowers blood pressure, improves blood glucose control in diabetes, promotes regularity, aids in weight loss, increases satiety, and appears to improve immune function" (Anderson et al., 2009; Slavin & Green, 2007). Among them, viscous soluble fibres have been shown to modify

Abbreviations: BCS, sodium bicarbonate; BCA, ammonium bicarbonate; SAPP, sodium acid pyrophosphate; TIM-1, TNO intestinal model; TDF, total dietary fibres; C, the control biscuit; P, the biscuit enriched in proteins; F, the biscuit enriched in fibres; P + F, the biscuit enriched in proteins and fibres; DF, dilution factor.

* Corresponding author at: UMR1145 Ingénierie Procédés Aliments, AgroParisTech/Inra/Cnam, AgroParisTech, 1 avenue des Olympiades, F-91300 Massy, France. Tel.: +33 1 69 93 51 58, +33 6 13 72 40 58; fax: +33 1 69 93 50 05.
E-mail address: cindy.villemejane@agroparistech.fr (C. Villemejane).

http://dx.doi.org/10.1016/j.foodchem.2015.02.125
0308-8146/

physiological responses, such as postprandial glycaemic and insulinemic responses. By increasing the consistency of the bolus in the gut, they delay gastric emptying, increase transit time, reduce intestine motility, reduce enzymatic reaction kinetics, prolong the diffusion of nutrients in the intestine and decrease the rate of absorption of macronutrients, and thus reduce metabolic responses (Anderson et al., 2009; Brennan & Cleary, 2007; Brennan et al., 1996; Brownlee, 2011; Ellis, Apling, Leeds, & Bolster, 1981; French & Read, 1994; Lavin & Read, 1995; Wood, Beer, & Butler, 2000). Many studies have been conducted on cereal products enriched in fibres or on products enriched in proteins, but few on products enriched in both proteins and fibres, and even fewer combining an improved nutritional profile (lower sugar and fat content). To develop a satiety product, it is essential to provide highly viscous soluble fibres (Wanders et al., 2011). However, these fibres are generally used as texturizing agents. The literature on cereal products enriched with significant amounts of these types of fibres is still scarce. Highly viscous soluble fibres have a very high affinity for water and thus alter the rheological properties of the dough and, hence the quality of the finished product (Aymard, 2010; Villemejane, Roussel, Berland, Aymard, & Michon, 2013).

Several *in vitro* digestion models or enzymatic *in vitro* procedures exist and differ in complexity (Guerra et al., 2012) by:

- The number and the types of steps in the digestion sequence (mouth, stomach, small intestine, and large intestine).
- The compositions of the digestive fluids used in each step. Enzymatic incubations are either performed with amylases or proteases only or in combination.
- The mechanical stresses and fluid flows in each step.
- The general digestion conditions, such as incubation time or use of dialysis.
- The sample preparations, such as the milling and or/the prior impregnation with natural (Granfeldt, Bjorck, Drews, & Tovar, 1992) or artificial saliva (Htoon et al., 2009).

Most of those systems present a limited number of simulated parameters, a compartmental fragmentation and a lack of dynamism. Very few studies are carried out with a system simulating, more closely, the physiological conditions of digestion, such as gastric and/or intestinal emptying, pH and temperature regulation, peristaltic movements, gastrointestinal secretions (digestive enzymes, mineral solutions, and acid or base solutions), transit time, water and digestion products absorption.

The TNO gastro-intestinal tract model or TIM-1, developed by the Department of Physiology, TNO Nutrition and Food Research Institute (Zeist, The Netherlands), was used in this study, in order to simulate, as closely as possible, the physiological conditions of digestion (Minekus, Marteau, Havenaar, & Huisintveld, 1995).

Indeed, the TIM-1 is certainly one of the most complete and dynamic artificial digestive systems. The TIM-1 is a multi-compartmental and dynamic computer-controlled system that simulates the main physiological digestive functions of the stomach and small intestine.

The objective of this study was to investigate the effects of the enrichment of biscuits in viscous soluble fibres, combined or not with protein-enrichment, on the viscosity of the chyme throughout the different upper digestive compartments (stomach, duodenum, jejunum and ileum), by using the TIM-1 system.

Enrichments in proteins on the one hand, and in dietary fibres (more particularly soluble ones) on the other, were compared with an enrichment combining both proteins and fibres in order to identify synergies or antagonisms.

As experiments done with the TIM-1 are tedious and time-consuming, it would be interesting to be able to predict the evolution of the chyme viscosity upon digestion in the different compartments of the upper tract (stomach and small intestine), which was also attempted here.

2. Materials and methods

2.1. Biscuit composition

The macronutrient composition of biscuits is shown in Table 1. Sucrose, canola oil, wheat flour, salt, leavening powders, such as sodium bicarbonate (BCS), ammonium bicarbonate (BCA) and sodium acid pyrophosphate (SAPP), and an emulsifier, soy lecithin, were used to produce the biscuits. All products had low fat (15% w/w) and low sugar (15% w/w) contents. The process was described in a previous work (Villemejane et al., 2013). Four biscuits were digested: a control biscuit (C), a proteins-enriched biscuit (P), a fibres-enriched biscuit (F) and a proteins- and fibres-enriched biscuit (P + F). They contained, respectively 9%, 23%, 10% and 23% w/w of proteins and 5%, 4%, 12% and 12% w/w of total dietary fibres (TDF). Enrichments were done by substituting flour by proteins (pea protein concentrate (Nutralys F85 M, Roquette) and whey protein concentrate (Prolacta 80, Lactalis Ingredients)) and/or oat bran (OatWell 22, DSM).

Oat bran contained, on a wet basis, 44.0% of total fibres (with 21.6% of soluble fibres (beta-glucans with a molecular weight of 1500 kg/mol) and 22.4% of insoluble fibres), 24.4%, of carbohydrates (with sugars content below 1.5%), 4.0% of lipids, 20.0% of proteins and 5.3% of water. The rest was ash. Pea protein concentrate and whey protein concentrate contained, on a wet basis, respectively 4.0% and 17.0% of carbohydrates, 7.0% and 0.4% of lipids; 81.0% and 75.0% of proteins and 7.0% and 6.0% of water. The rest was ash.

2.2. In vitro digestion

2.2.1. In vitro digestion model: TIM-1

The TIM-1, TNO gastro-intestinal model, is a multi-compartmental, dynamic and computer-controlled system developed at TNO Nutrition and Food Research (Zeist, the Netherlands) which has already been described in detail elsewhere (Anson, van den Berg, Havenaar, Bast, & Haenen, 2009; Blanquet-Diot, Soufi, Rambeau, Rock, & Alric, 2009; Minekus et al., 1995). The *in vitro* digestion was performed for 240 min at 37 °C. The model consists of 4 successive serial glass compartments simulating stomach, duodenum, jejunum and ileum, respectively. Each compartment is formed by glass units with a flexible wall inside. The system is kept at a constant temperature of 37 °C by pumping water into the space between the glass jacket and the flexible walls. Peristaltic movements are simulated by alternate compression and relaxation of the flexible walls following changes in the water pressure. The mixture of food and digestive juices is referred to as digesta or chyme. To control the transit of the chyme, the equation described by Elashoff, Reedy, and Meyer (1982) was used: $f = 1-2^{-(t/t1/2)\beta}$, where f, t, $t1/2$, and β represent, respectively, the fraction of chyme delivered, the time of delivery, the half-life of delivery, and a coefficient describing the shape of the curve. The TIM-1 was programmed to reproduce postprandial gastrointestinal conditions of a human adult after intake of a solid meal (Blanquet-Diot et al., 2012). The values set for $t1/2$ and β to reproduce gastric delivery, were, respectively, 85 min and 1.8. The half-life of ileal delivery of the meal was fixed at 250 min and β was fixed at 2.5. Chyme transit was regulated by opening or closing the peristaltic valves that connect the compartments. The volume and pH were computer-monitored and continuously controlled in each compartment. Gastric content was progressively acidified using HCl