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Digestion modeling in the small intestine: Impact of dietary fiber

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ABSTRACT

In this work, the modeling of the digestion in the small intestine is developed by investigating specifically the effects of dietary fiber. As our previous model, this new version takes into account the three main phenomena of digestion: transit of the bolus, degradation of feedstuffs and absorption through the intestinal wall. However the two main physiochemical characteristics of dietary fiber, namely viscosity and water holding capacity, lead us to substantially modify our initial model by emphasizing the role of water and its intricated dynamics with dry matter in the bolus. Various numerical simulations given by this new model are qualitatively in agreement with the positive effect of insoluble dietary fiber on the velocity of bolus and on its degradation all along the small intestine. These simulations reproduce the negative effect of soluble dietary fiber on digestion as it has been experimentally observed. Although, this model is generic and contains a large number of parameters but, to the best of our knowledge, it is among the first qualitative dynamical models of fiber influence on intestinal digestion.

1. Introduction

Digestion in the small intestine can be described through three main phenomena: transit of the bolus along the small intestine, degradation of macromolecules into smaller ones and absorption through intestinal wall. Taking into account these phenomena, the authors have presented in [17] a generic model of digestion in which the bolus includes only one category of macromolecules (carbohydrates, proteins or lipids) and water.

However mixing these nutrients influences the digestion process through interactions between molecules. To improve this model, the effects of such interactions have to be incorporated. As a first step, we consider the effect of dietary fiber because of its significant role on digestion. It is known that one of the key properties of dietary fiber is its water holding capacity; this leads us to investigate the role of water in the digestion process. To reach this target, dry matter and water in each substrate are separately accounted for. Then, the kinetic of water is modeled by taking into account its correlation with the kinetic of the dry matter.

Unavoidably, this new model is rather complicated. Consequently to describe and support our modeling approach, we proceed in three main steps mostly written in three sections: firstly, in Section 2, the required biological background on soluble and insoluble dietary fiber, their main physiochemical characteristics and effects on the digestion are introduced. Next, each biological quantity or effect has to be translated into mathematical notations or equations. In Section 3, a list of the main assumptions used to build the mathematical model are described. Obviously these assumptions can be discussed and it is important to have a clear and precise formulation of each of the proposed hypothesis. Finally, the state variables of the model with a brief biologic description for each variable and the associated mathematical equations are given in Section 4.

The aim of this presentation in three steps is to guide the reader all along our modeling process, from the biological background to the final mathematical equations descriptions. Our aim is to have a more readable article in that way, although it may induce a longer paper.

Once the equations of the model are determined, we performed numerical simulations whose aim is to check the behavior of the model according to the proposed biological hypotheses and/or to compare different sets of hypothesis. Specifically, known or assumed biological mechanisms relating dietary fiber and digestion process are simulated. In Section 5 we provided several simulations with comments on the hypothesis. These numerical simulations can be considered as *in silico* experiments. Of course, since our model is generic, it contains a lot of parameters and some of the hypotheses are still to be checked (by biological experiments), we are looking for qualitative behavior with very few attentions on quantitative outputs. This is why no sensitivity on the parameters is checked.

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Finally, in Section 6, the model is discussed and perspectives are proposed.

2. Biological background on water and dietary fiber

Digestion modelling requires the knowledge of the physiochemical properties of macromolecules concerned by this phenomenon as well as mechanical and biochemical reactions observed for their degradation.

Dietary fiber (DF) is usually defined as the sum of plant non-starch polysaccharides and lignin that are not hydrolyzed by the enzymes secreted by the non-ruminant digestive system, but that can be partially digested by microflora in the gut. A main effect of fiber is to regulate intestinal degradation and absorption of nutrients as well as their transit along the gut. Physiochemical characteristics of fiber include viscosity, hydration, fermentability (mostly in the large intestine), adsorption or entrapment of nutrients and bulking effect. Each of these characteristics affects meaningfully the function of the gastrointestinal tract [19,10]. These characteristics depend on the polysaccharides chemistry. One way to classify dietary fiber is based on their water solubility. Insoluble dietary fiber includes cellulose, some hemicelluloses and lignin. The other is soluble dietary fiber such as viscous fiber which includes beta-glucans, pectins, gums and some hemicelluloses [1,18].

For monogastrics, most available nutrients are degraded and absorbed in the small intestine. At the beginning of duodenum the bolus consists of partially degraded feedstuffs and water. Once in the small intestine, mechanical and chemical digestion of feedstuffs make the nutrients available to the organism. Enzymatic hydrolysis is the most important chemical reaction in digestion, which takes place in aqueous solution. Enough water is required for an efficient digestion process even though water/nutrient ratio is not precisely known. Furthermore, classification of dietary fiber through their water solubility and the impact of water holding capacity (WHC) of DF on digestion reveal the key-role of water on digestion. WHC is defined by B.M. Clearly and L. Prasky [10] as the ability of fiber source for water absorption when mixed with water and to hold it within its matrix.

2.1. Soluble dietary fiber

Soluble DF are believed to impact meaningfully digestion and absorption as well as bolus transport in the small intestine. The main physiochemical properties of soluble DF are viscosity, water holding capacity (WHC) and organic compound entrapment [7]. Soluble DF, because of its high viscosity, is generally associated with slow transit through the stomach and increasing of the small intestinal transit time [14]. In the presence of soluble DF, this delay in transit time may also be related to the jelly consistency of the bolus which causes a resistance to the propulsive contractions of small intestine [5]. Viscosity and organic compound entrapment capacities of DF, slow down digestion and absorption of substrates. This effect on digestion is associated with (*i*) the reduction of the nutrient diffusion through the small intestine because of the viscosity and (*ii*) dilution of bolus compounds with the addition of non-digestible material [12].

2.2. Insoluble dietary fiber

Insoluble fiber does not dissolve in water but retains it in its structure. In fact, insoluble DF add a bulk to the bolus which speeds up the motion of food through the gut. Insoluble DF acts primarily in the large intestine where, due to its WHC, it increases fecal bulk, dilutes colonic contents and decreases mouth-to-anus transit time [7]. Wilfart et al. [20] proposed that adding the insoluble DF reduces the transit time in the small intestine. On the other hand, insoluble DF has a positive impact on digestion. In fact, the insoluble DF improves the access of the enzymes to the substrates by enhancing the effects of

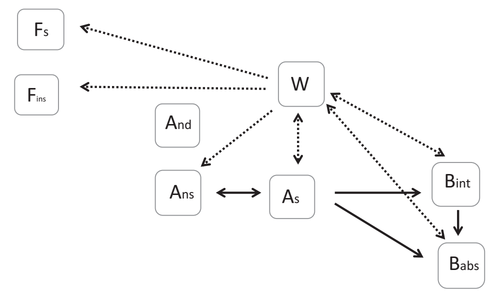

Fig. 1. Feedstuffs degradation inside the bolus ($A_{ns}, A_s, B_{int}, B_{abs}$) and water exchanges ($W$ to other components) conceptual chart. The arrows → and ↔ represent the feedstuffs transformations. The pointed arrows represent water exchanges.

propulsive contractions [4]. Another reason may be the delays in the gastric emptying because of the presence of insoluble DF in the bolus [20,11]. Recent studies have shown that the inclusion of a moderate level of dietary fiber improves the dige stibility in chicks [9]. Therefore to obtain an optimal efficiency in nutrient utilization, Burhalter et al. [3] proposed to increase the ratio of insoluble to soluble DF. Moreover, the use of insoluble fiber in commercial broiler chicks improves the intestine morphological parameters and result in a better performance assumed to be connected to more efficient digestion and absorption processes [11]. Two hypotheses are proposed in order to study the influence of insoluble DF on nutrients digestibility in the small intestine: (*i*) insoluble DF increases the retention time in the stomach changing the nutrient profile of the bolus at the entry of the small intestine which could lead to a higher digestion and absorption. (*ii*) Physical characteristics of insoluble DF change the digestion process mostly through their capacity for absorption of water and nutrients. These both hypotheses are either tested in the *in silico* experiments (cf. Section 5.1) or included in the equations (cf. Section 4).

2.3. Water

To have a better understanding of the role of dietary fiber, it is therefore required to study more precisely the evolution of water during digestion in the small intestine. Water is needed for most of digestion functions, including, in particular, feedstuffs degradation by enzyme hydrolysis, nutrients absorption as well as bolus transit by peristaltic waves. We have assumed that total water in the small intestine has three principal sources: drunk water, water included in the foods and water in the endogenous secretions. Bolus composition on dry matter regulates the quantity of water required for digestion. Thus, the evolution of water amount in the small intestine depends on other substrates' kinetics within the bolus.

Fig. 1 illustrates the exchanges between water and feedstuffs compartments.

3. Key model assumptions

In this section, the key assumptions for the model are presented.

H1: *Each component of the bolus (macromolecules,*[2] *partially degraded macromolecules, nutrients*[3] *and fiber) is represented mathematically as a portion of dry matter and a characteristic proportion of water.*

For example, "starch in a bolus" includes both dry starch and water used to maintain starch molecules in aqueous solution. The same is observed for the "disaccharides in a bolus" and "glucose in a bolus"

[2] The macromolecules are supposed to be the large molecules that cannot penetrate intestinal wall.

[3] The nutrients are the very small molecules which can go through the intestinal wall.