Deoxynivalenol in cereal-based baby food production process. A review

Xenia Pascari, Sonia Marín, Antonio J. Ramos, Francisco Molino, Vicente Sanchis*

Applied Mycology Unit, Food Technology Department, University of Lleida, UTPV-XaRTA, Agrotecnio, Av. Rovira Roure 191, 25198 Lleida, Spain

*Corresponding autor: Vicente Sanchis, email: vsanchis@tecal.udl.cat, tel +34 973 702535; fax: +34 973 702596.

Abstract

Deoxynivalenol (DON) is one of the highest occurring mycotoxin of *Fusarium* species. Its presence in cereal-based infant foods is extremely undesirable, especially considering the increased sensitivity of this population group to toxins. There are various studies on the influence of processing operations on DON and its conjugated levels in raw materials, however there is no available publication on baby food production process impact on DON. According to the available studies on the occurrence of DON and its conjugates in cereal-based infant food, it often occurs above the legally allowed limit, thus there is a need to study the influence of production processes on its evolution from raw materials to the final product. The available studies suggest that there are two production steps with a significant impact on DON concentration, namely enzymatic hydrolysis, which leads to its increase due to the release of the toxin from the cereal matrix, and drum drying, which might decrease DON concentration thanks to the high temperatures employed and highly efficient temperature penetration into the product.

Keywords: Deoxynivalenol, cereal-based baby food, processing, deoxynivalenol-3-glucoside, amylases.

Highlights

- DON is the most occurring *Fusarium* mycotoxin in oats, wheat and barley.

- DON levels in several cereal-based baby food exceeding legal limits were found.

- Cereal species and nature of contamination define the efficacy of DON reduction.

- Enzymatic hydrolysis lead to an increase in DON levels.

- Drum drying may result in a decrease in DON concentration.

Contents

1. Introduction

Nowadays, cereals are the most important source of energy worldwide, with approximately 30 % of daily calories being derived from cereals in the developed countries, reaching more than 60 and 80 % in the developing and poor countries, respectively (Awika, 2011). Nevertheless, cereals are not consumed directly, usually being processed to obtain various foodstuff and ingredients (e.g. sweeteners). Cereal-based foods are one of the most important contributors to human exposure to mycotoxins (toxic secondary fungal metabolites inducing both acute and chronic exposure symptoms) (De Boevre, Di Mavungu, Landschoot, et al., 2012; Zinedine, Soriano, Moltó, & Mañes, 2007), deoxynivalenol (DON) being the most common contaminant. DON is produced by *Fusarium graminearum* and *F. culmorum,* both implicated in FHB disease (Fusarium Head Blight) in cereal crops, especially oats, barley, wheat and maize (Tanaka et al., 1988). DON was not classified as carcinogenic by IARC (International Agency for Cancer Research), nevertheless studies in various animal species proved its teratogenicity, cytotoxicity, genotoxicity and immunotoxicity as a results of a chronic exposure, and nausea, vomiting and food rejection in the case of an acute exposure (Sobrova et al., 2010). Besides all, it is highly thermostable, withstanding temperatures between 170 and 350 ºC (no reduction observed after 30 min at 170 ºC treatment) (Wolf & Bullerman, 1998) .

Considering the abovementioned DON toxicity, the concern regarding this toxin has increased with the discovery of its major modified forms, namely deoxynivalenol-3-glucoside (DON-3-Glc) and 3- and 15-acetyldeoxynivalenol (3 and 15Ac-DON) (Rychlik et al., 2014). Each of these metabolites has its source of formation: DON-3-Glc is a result of plant detoxification strategy (Lemmens et al., 2005) and 3- and 15Ac-DON are synthetized by the *fungus* to protect itself from its own toxins (Berthiller et al., 2013). Figure 1 represents the major mechanisms that cereal plants use to protect themselves from the pathogen. The toxicity of the modified forms is lower compared to the parental form, however human and animal digestion may lead to their conversion back into DON or to the formation of other metabolised forms which proves their contribution to the exposure (Berthiller et al., 2011). A co-occurrence of DON and its metabolites was repeatedly identified in cereal commodities (Bryła et al., 2016; De Boevre, Mavungu et al., 2012; Uhlig et al., 2013), however the existing legislation has not yet defined maximum acceptable levels for those mycotoxins in food products. The available studies for cytotoxicity prove that in order of decreasing toxicity DON is followed by 15-Ac-DON, 3-Ac-DON and de-epoxy-deoxynivalenol (DOM-1), nonetheless more investigation is needed to better evaluate the consequences of their metabolism (Dänicke & Brezina, 2013).

Infants and young children´s diet is mainly restricted to cereal-based food. European Commission defines processed cereal baby-food and baby foods as food intended for use by infants (<12 months) when they are weaned and young children (from 1 to 3 years) as a supplement to their diet and/or for their progressive adaptation to ordinary food (European Commission, 2006a). Several recent surveys prove that the mycotoxin problem is also an issue in this product category (Juan, Raiola, Manes, & Ritieni, 2014; Pereira, Fernandes, & Cunha, 2015; Ul Hassan et al., 2018). Considering the increased vulnerability to contaminants of this group of population, European Commission establishes the strictest maximum levels of DON and other mycotoxins allowed in food intended for infants and young children (200 μg/kg), which is 2.5 fold lower than the maximum level in other cereal-based foodstuff and 8.75 times less than the maximum level of DON allowed in unprocessed oats, wheat and maize intended for human consumption (European Commission, 2006b). Although DON is one of the least lethal trichothecenes, its effects in children occur within hours after the intake (Raiola, Tenore, Manyes, Meca, & Ritieni, 2015).

A review of the available surveys regarding the incidence of DON and its metabolites in cereals and cereal-based baby foods will be performed in order to complete the study. Considering the previously published research on the stability of mycotoxins during various food processing operations (Scudamore, Baillie, Patel, & Edwards, 2007), this review is aiming to compile the existing information on the transfer of DON and its metabolites during specific cereal-based baby food production processes, focusing on both chemical and biochemical changes that might be induced.

2. DON occurrence in cereals intended for food production

A market research on cereal-based baby foods available in the European Union (EU) showed that the mainly used commodities in this sector are oats, wheat and barley followed by maize, rye and triticale and, on a lower extent, millet, sorghum and spelt. Very often, these are coming in formulation of three and more cereals (up to eight cereals), in order to provide a more complex spectrum of nutrients needed to ensure a correct infant growth. Table 1 regroups the available information on the occurrence of DON in cereals intended for food production worldwide.

Usually the studies on mycotoxins incidence in commodities are not only focused on a group of cereals from a country or region but also on more than one mycotoxin, yet their co-occurrence was frequently proved (Bryła et al., 2016; De Boevre, Di Mavungu, Landschoot, et al., 2012; Pleadin et al., 2017; Vanheule et al., 2014). The present work was oriented on studying the occurrence of DON and its metabolites, over the last 25 years, in the cereal species which are mainly used in baby food industry. There are very few studies searching for DON metabolites in cereals. The studied metabolites are the ones which are either produced by the mould itself (3Ac-DON and 15Ac-DON) or the ones which are a result of the plants activity against the contamination (DON-3-Glc) (Bryła et al., 2016; De Boevre, Di Mavungu, Landschoot, et al., 2012; Rasmussen et al., 2012; Uhlig et al., 2013; Vanheule et al., 2014).

One of the largest review on DON occurrence in cereals, after Tanaka et al. (1988b), was performed by Placinta et al. (1999), regrouping the available information on DON contamination in oats, wheat, barley, maize and rye from 15 countries over a decade. Its concentration ranged from 4 to 62050 µg/kg, the highest levels being reported in oats from Norway in 1996's harvest year.

According to a report published by Eurostat (2017), France is the main producer of cereals in the EU, accounting for almost a fifth of total EU production in 2016 (18%), followed by Germany (15.1%), Poland (9.9%) and Spain (8%). However, very limited studies are available on DON occurrence in France (Tangni, Pussemier, Schneider, & Larondelle, 2013), wheat presenting the highest DON incidence (145 positive samples from 169 analysed samples) with a maximum of 3280 µg/kg.

FHB infection and DON contamination is a function of several factors such as climatic factors, crop rotation, fungicide application, debris management and tillage practices applied, variety resistance to FHB, etc. (Blandino et al., 2012). All the above mentioned explains the differences in DON contamination among countries, different cereal varieties and among years. In Norway, Finland and Sweden, for example, important spring rainfalls and relatively warm temperatures during this season would promote the propagation of both *F. graminearum* and *F. culmorum* and mycotoxin formation on cereal crops (Hope, Aldred, & Magan, 2005). This explains the high DON accumulation showed in the published studies: maximum 9298 µg/kg of DON in oats in Finland (Hietaniemi et al., 2016), up to 2340 and 22000 µg/kg in oats from Norway and Sweden, respectively (Lindblad, Börjesson, Hietaniemi, & Elen, 2012); 2240 and 16000 µg/kg of DON in wheat in Finland and Norway, respectively (Hietaniemi et al., 2016; Hofgaard et al., 2016); 636 and 4752 µg/kg of DON in barley from Norway and Finland, respectively (Hietaniemi et al., 2016; Uhlig et al., 2013). Nonetheless, no such important DON accumulation was found in other crops such as maize, rye and triticale (Table 1), probably because of the differences in fungal ecology characteristics of these crops (Doohan, Brennan, & Cooke, 2003).

Moreover, differences in DON occurrence and accumulation were observed between organic and conventional agricultural systems. Nevertheless, from the available literature, it results that DON accumulation is crop dependent too: in oats, maize and rye from organic agriculture DON concentration is higher compared to the conventional system but it is the opposite in the case of wheat and barley (Bernhoft, Clasen, Kristoffersen, & Torp, 2010; Pleadin et al., 2017).

Many of the works listed in the Table 1 were focused on more than one mycotoxin, however all of them found DON as the most prevalent product of fungal activity (in almost all the studies over various years DON positive samples were found in more than 50% of the total analysed cereal samples). Studies on DON-3-Glc occurrence in cereals and its fate during food and feed processing are quite recent (Berthiller et al., 2007). Moreover, the concern about DON-3-Glc toxic effects on human and animal health is increasing continuously, which made researchers worldwide to study its occurrence (Bryła et al., 2016; De Boevre, Di Mavungu, Landschoot, et al., 2012; Rasmussen et al., 2012; Uhlig et al., 2013; Vanheule et al., 2014) and synthesis pathways in cereals (Berthiller et al., 2007). The levels of DON-3-Glc found are usually lower or similar to DON: a mean of 18 and 51.2 µg/kg of DON-3-Glc was found in wheat and oats from Belgium, respectively (de Boevre, Mavungu, et al., 2012); 252, 56 and 68 µg/kg in oats, wheat and barley, respectively, from Hungary (Uhlig et al., 2013); 99, 102 and 138 µg/kg of DON-3-Glc in wheat, barley and triticale, respectively, from Poland (Bryła et al., 2016). Two years after the study performed by De Boevre et al. (2012), 250 and 390 µg/kg of DON-3-Glc in wheat and barley from the same region in Belgium (Flanders) were found (Vanheule et al., 2014). Interestingly, during these two years a considerable increase in both average rainfall and average temperature was registered (Statistica, 2018), which would explain the higher amount of both DON and DON-3-Glc accumulated (Table 1).

Considering that oats and wheat are the primarily used cereals in baby food production and that these two commodities, together with barley, are the most susceptible for DON contamination, a transfer to the final product may take place, especially in the case of a high contamination level, which would expose these consumers to an important health risk.

3. DON occurrence in cereal-based baby food and food for young children

In Europe, DON maximum allowed levels were applied in baby food, for the first time, in Soviet Ukraine in 1984 (FAO, 2004; Ministry of Health of the Union of Soviet Socialist Republics, 1989). The first EU harmonized regulation on mycotoxins in foodstuffs came in 1998, which included several limits for aflatoxins, also containing sampling and analytical methods procedures (European Commission, 1998). Only with the European Regulation 1881/2006/EC maximum allowed limits for *Fusarium* toxins in foods were legislated (European Commission, 2006b), with its updates and amendments on the following years.

There is a limited number of studies available on the occurrence of DON in cereal-based baby food, even considering that the EU regulation of DON in this product category is particularly strict (maximum allowed DON level is 200 µg/kg). Nowadays, available reliable methods for DON analysis using liquid chromatography coupled with diode array detectors (DAD) have relatively high limits of detection and quantification (usually around 100 µg/L) (Sugita-Konishi et al., 2006), and more sensitive techniques are necessary such as mass spectrometry to increase the accuracy of the analysis, particularly for this product category (Habler & Rychlik, 2016; Mats Lindblad et al., 2013; A. Malachova, Varga, Schwartz, Krska, & Berthiller, 2012). Table 2 regroups the available published surveys on DON occurrence in infant foodstuffs. Maize, wheat, barley and oats are the cereals most susceptible for *Fusarium* infestation and DON accumulation in the commodity and the final product (European Food Safety Authority, 2013). In the present review, it was observed that maize and wheat-based cereals show not only higher contamination incidence but also present higher levels of mycotoxins, and in the case of DON incidence, often being close to or overcoming legal limits: mean DON of 260 µg/kg in barley based cereals from Canada (Lombaert et al., 2003), mean DON of 103 µg/kg in wheat based cereals from Italy (Juan et al., 2014); mean DON of 131 µg/kg in cereal-based baby food from Spain (Cano-Sancho, Gauchi, Sanchis, Marín, & Ramos, 2011).

Even considering the abovementioned strict legislation implemented in 2006, there are studies performed on the following years which found DON contaminated commercial products overcoming the stipulated limits (Cano-Sancho et al., 2011; Juan et al., 2014; Pereira et al., 2015; Zhang, Wong, Krynitsky, & Trucksess, 2014). Interestingly, multi-cereal infant and young children foods are the ones most frequently encountered as contaminated above the regulation, moreover in the ones where barley, wheat or maize were the predominant cereal in the formulation, the highest maximum levels were observed (Juan et al., 2014; Lombaert et al., 2003). On the contrary, Lu, Ruiz Leal, Míguez, & Fernández-Franzón (2013) did not found any DON contamination in the 57 analysed baby food samples from the Spanish market. Also, very few surveys encountered or analysed DON-3-Glc, 3- or 15-Ac-DON (Juan et al., 2014; Oueslati, Berrada, Mañes, & Juan, 2018). These studies prove again the heterogeneity in mycotoxins contamination in cereals over different harvest seasons (Doohan et al., 2003), and justify the need for a deeper investigation on the effect of processing on the evolution of grains contamination with DON and its metabolites.

4. Changes of DON levels during cereal-based baby food production process

The production of cereal-based baby foods and food for young children implies the following main process operations: flour roasting, pre-gelatinization, enzymatic hydrolysis, enzymes inactivation, drying and packaging (Figure 2). The objective is to obtain a food product adapted to the particularities of the digestive system of an infant or young child, which has a limited ability to digest starch. The most frequently used cereals are oats, barley, wheat, rice, rye, maize and, on a lower extent, millet, sorghum, triticale and spelt. Also, adjuncts might be added, namely barley or rye malt extracts, maize extracts, quinoa flour, fructo-oligosaccharides (FOS), vitamins and minerals etc., in order to complete or enrich product's nutritional value.

4.1 Flour roasting

Roasting consists in increasing flour temperature to the range of 105-120 ^{0}C and maintaining it from 20 to 40 min. This stage is important in the modulation of organoleptic characteristics of the flour, leading to caramelization and Maillard reactions. Also, it helps improving flour dispersibility in water during the next stage (Fernández-Artigas, Guerra-Hernández, &

García-Villanova, 1999). An important aspect to consider is the change in colour of the flour under this production step, browning being an undesirable result for cereal-based baby food products. It is also crucial not to overcome these physical production conditions, yet that a longer time above 120 ºC might lead to the formation of a carcinogenic compound, acrylamide, which is proven to be particularly dangerous for children under 2 years old (Erkekoğlu & Baydar, 2010).

Only a few studies are available on the occurrence of DON in cereal flour, mainly being focused on wheat or rye flours used in bakery products industry (Malachova et al., 2011; Rasmussen, Ghorbani, & Berg, 2003; Schollenberger, Jara, Suchy, Drochner, & Muller, 2002; Škrbić, Živančev, Durišić-Mladenović, & Godula, 2012). Moreover, those studies are limited in terms of geographical origin of the analysed samples and present a high variability of the results. One of the largest occurrence study in cereal flours was performed by Rasmussen et al. (2003). They collected samples of wheat and rye flour from Denmark over 4 years (1998-2001), finding a high incidence of DON contamination with an average level of 114 (85 % positive samples) and 42.5 µg/kg (59 % positive samples) in wheat and rye flour, respectively. A more recent study in Czech Republic, identified a range of 13 to 320 µg/kg of DON and 11 to 94 µg/kg of DON-3-Glc in wheat flour (Malachova et al., 2011). In the abovementioned studies, very few samples were found exceeding the maximum allowed level of DON in cereal flour (750 µg/kg). Thus, considering the specificity of the contamination with DON mainly in the outer layers of the kernel and the trend in using whole-grain flours for its better nutritional properties compared to the white flour, requires more investigation on mycotoxin occurrence, especially for the products in which flour is used as raw material.

Studies showed a very low DON reduction in roasting cereal flour at temperatures below 180 ºC. Yumbe-Guevara, Imoto, & Yoshizawa (2003) investigated the impact of various temperature levels between 140 and 220 ºC on DON in standard solution and contaminated wheat and barley (whole grains and powder). They found that 8 and 11 min at 220 ºC were necessary to reduce 50 and 90 % of DON in barley powder, respectively. The first significant reduction was observed at 180 ºC. Also, toxin reduction in these conditions was higher in grain powder than in kernels, which led them to the conclusion that heat penetration is an important factor in the effectiveness of thermal treatment. A similar study performed later reached quite controversary results, with only 1.7 to 7.6 % reduction after applying a 230 ºC treatment to wheat flour (Israel-Roming & Avram, 2010). Nonetheless, the authors of the mentioned study did not specify the duration of the treatment. Considering the parameters for flour roasting, there is a chance that although lower temperatures are applied, the longer treatment time could compensate for it, at least, slightly decreasing the level of DON, however there are no available studies that could prove this statement.

Taking into account the risk of acrylamide formation during flour roasting, this stage may not be considered as crucial in the case of adoption of a mitigation strategy against DON contamination, however its possible impact, although small, need to be considered in the evaluation of DON transfer to the final product.

4.2 Pre-gelatinization and enzymatic hydrolysis

4.2.1 Process description

One of the most important stages in cereal-based baby food production process is enzymatic hydrolysis. It allows a partial break down of the starch contained in the cereals and facilitates its assimilation by infants digestion system (Fernández-Artigas et al., 1999). Starch is the most abundant carbohydrate found in plants, used as source of carbon and energy (Alcázar-Alay & Meireles, 2015). It is formed by two types of polymers: (i) amylose, composed of a linear chain of α-1,4-glucose units representing from 15 to 30 % of the total starch and (ii) amylopectin, composed of α-1,4-glycosidic bonds intensively branched in α-1,6 positions with glucose units (70 to 85% of the starch structure) (Fig. 3) (Martinez & Gómez, 2016).

The arrangement of these two polymers form a matrix of starch granules alternating crystalline (amylopectin) and amorphous (amylose) phases. Cereal starches may have associated other molecules to their structure, such as phospholipids and free fatty acids (0.15 to 0.55%) and proteins (up to 0.6%), which increase the nutritional value of the starch (Alcázar-Alay & Meireles, 2015). Starch granules have microscopic sizes and a great shape variability depending on their biological origin (Tester & Sommerville, 2001). Cereal starches are mainly characterized by the A-type structure (polymerization degree <15), and B1-type structure (polymerization degree between 15 and 25) (Tester, Karkalas, & Qi, 2004).

Starch is not available to the enzymes without undergoing a pre-gelatinization process (loss of swelling and crystallinity phase which result in a formation of a gel) (Tako, Tamaki, Teruya, & Takeda, 2014). The pre-gelatinization would serve two purposes: (i) increase in starch swelling capacity, solubility and cold water dispersion (Alcázar-Alay & Meireles, 2015) and (ii) facilitate the access of α- and β-amylases to the polymer chains (Martinez & Gómez, 2016). The process is determined by transition temperatures (the higher the amount of crystalline structures, the higher the temperatures required for the gelatinization to take place) and gelatinization enthalpies, specific for each botanical source (Tester & Morrison, 1990). Knowing those characteristics together with the temperature for the optimum enzymatic activity allow the producer to identify the best setup of technological conditions in order to minimize energy losses and ensure a more sustainable production. Table 3 regroups the morphology and transition temperatures for native starches from different common cereal sources. In baby food production, pre-gelatinization consists of mixing the roasted cereal flour with a high amount of water (between 60 and 80%, w/w) and heating the mix between 40 and 70 ºC.

When gelatinization is achieved a mix of α- and β- amylases is added, followed by a continuous stirring from 10 to 90 min. Amylases are enzymes hydrolysing starch into smaller molecules to produce dextrins and other small polymers composed of glucose units. They can be synthetized from plants, animals or microorganisms. The last source completely replaced chemical starch hydrolysis in the starch processing industry due to their cost effectiveness, higher stability, great production yields and ease of process modifications (Gupta, Gigras, Mohapatra, Goswami, & Chauhan, 2003). Microbial enzymes include fungal and bacterial amylases. There are two groups of amylases: endoamylases (α-amylase) and exoamylases (β-hydrolases). The α-amylase can be obtained from several bacteria or fungi, bacterial enzyme being preferred due to a larger spectrum of optimum conditions of temperature (30-50 ºC) and pH (2 to 12, most of the α-amylases being active within the neutral range) (Martínez & Gómez, 2016). The mechanism of their action allows to rapidly fragment the poly-glucoside chain and decrease the viscosity of the paste. The products of their activity (mono- and oligo-saccharides) are very numerous, depending on the nature of the α-amylase active site and on the biological origin of the starch (Martínez & Gómez, 2016). There are two types of exo-acting hydrolases: β-amylases and glucoamylases. β-amylase activity leads to the formation of β-maltose and β-limit dextrins of high molecular weight (the distribution of hydrolysation products of amylopectin is half maltose and half limit dextrins). Glucoamylases are able to hydrolyse both α-1,4 and α-1,6 bonds of the starch molecule into D-glucose. β-amylases can be obtained from microbial origins, however the most cost-effective are β-amylases from plant sources (sweet potatoes, soybean, barley and wheat). Glucoamylases can be also derived from animal sources besides plants and microorganisms. Their optimum temperature and pH for activity are 40-60 ºC and 4.9-6.6, respectively (Martínez & Gómez, 2016).

Considering the high diversity and complexity of the product, each producer would establish the technological parameters in accordance to the cereal species used and the desired degree of hydrolysis.

4.2.2 Impact on deoxynivalenol

There are no available studies on the impact of enzymatic hydrolysis on DON during infant food production process, however the addition of enzymes is common in breadmaking and brewing processes. Garda-Buffon, Baraj, & Badiale-Furlong (2010) studied the effect of DON on malt amylase activity (both α- and β-amylases). They found not only an increase in DON content during mashing but also an impact of its concentration by inhibiting the enzymatic activity. While observing those effects, DON concentration varied between 146 and 854 ng/g. Moreover, an increase in the enzymatic activity outside of this range (both below and above) was registered. Simsek, Burgess, Whitney, Gu, & Qian (2012) studied the evolution of DON concentration in wheat flour, dough and bread, with the addition of α-amylase, cellulase, protease and xylanase during breadmaking. The increase of DON level in bread compared to the wheat flour was registered together with the decrease of DON-3-Glc level after baking. Enzymatic activity was found to be the main cause of the increase, especially the protease and xylanase activity, suggesting the release of DON from the grain wall matrix. α -amylase was not found to have a significant impact on DON, probably because of the higher exposure to the toxin of the outer layers of the seed compared to the endosperm, where starch is stored. This result is not confirmed by the work performed by Vidal, Ambrosio, Sanchis, Ramos, & Marín (2016), where they identified a significant increase in DON concentration under amylases activity (10 %), nevertheless confirming that xylanase activity had a slightly higher impact on the increase in DON concentrations during the process (15 % increase). Zachariasova, Vaclavikova, Lacina, Vaclavik, & Hajslova (2012) also suggested a release of DON and its conjugates from starch and dextrins during the hydrolytic enzymatic activity, however the extent of this release depended on wheat variety and the mechanism of *Fusarium* infection.

In conclusion, previous studies show an increase of DON and DON-3-Glc levels due to amylase activity, however these studies are limited to certain cereal species (mainly wheat and barley). Considering the complexity of food matrices and the differences in their composition, which result in differences in *Fusarium* infection and, as a result, DON contamination, more studies are needed in order to complete the knowledge regarding the evolution of DON levels under hydrolases activity, especially taking into account that infant food production usually implies the use of a mix of cereals. Also, an interesting object for study would be identifying if there is a correlation between the progress of starch hydrolysis by amylases and the change of mycotoxins level.

4.3 Enzymes inactivation

Enzymes inactivation is performed by heating the mass until 105-135 ºC, from 2 to 120 s. The applied temperature will depend on the biological origin of the enzymes: bacterial are the most thermostable, then fungal ones and then the enzymes coming from plant sources (Martinez & Gómez, 2016). The heating would take place in a recirculation circuit in order to ensure a minimal exposure of the mass to the high temperature (browning reactions are undesirable at this stage) and to the environmental factors.

According to the studies on the impact of heat operations on DON, this stage might not be of a special concern for toxin reduction, especially because of the time of action: research works suggest the need of at least 180 ºC temperature to be applied in order to observe significant modifications in DON levels (Yumbe-Guevara et al., 2003). Nevertheless, considering the efficient temperature penetration, it has to be considered for further studies.

4.4 Drying and packaging

Drying is performed using a drum drying system which consists of applying the paste as a thin layer (approximately 1.5-2 mm) on the outer face of an internally steam-heated revolving drum. The applied internal steam temperature is up to 200 ºC. The product becomes dry after three quarters of a drum revolution, with a residence time ranging from few seconds to dozens of seconds, being then removed with a static scraper with a final humidity <5%, on a wet basis. The obtained dry material is then ground into flakes or powder and packaged for delivering (Heldman, 2003). Similar to the roasting stage, an important safety factor to control is browning reactions (Maillard or caramelisation reactions), which, as mentioned above, are highly undesirable, and thus the duration of the treatment has to be strictly controlled.

Regarding DON contamination and the impact of drum drying process, there are no studies available in baby-food or flour processing. Nevertheless, a study on cereal kernels drum drying indicates this process as highly efficient, leading to a 25 and 50 % reduction of DON at 160 and 185 ºC, respectively (initial concentration of DON was 15.8±1.5 µg/g (Pronyk, Cenkowski, & Abramson, 2006)). Thus, considering the better potential for heat penetrability in the case of a flour material obtained during cereal-based infant food production process, a greater decrease in DON and its conjugates might be expected, nonetheless experimental studies have to be performed in order to confirm that.

5. Further considerations

Cereals are the most important source of energy worldwide and, thus, might represent an important contributor to mycotoxins exposure through food. DON is the most occurring *Fusarium* mycotoxin within cereal production chain. Nowadays, researchers are concerned about the rates of transfer of these mycotoxins through food production chains. Cereal-based infant food production process includes flour roasting, pre-gelatinization, enzymatic hydrolysis, enzymes inactivation, drying and packaging steps. From the revised scientific literature in the present work two process operations can be highlighted as significantly affecting DON levels, mainly enzymatic hydrolysis (increase in DON level from 10 to 15 % compared to the initial contamination by its release from the food matrix) and drum drying (decrease in DON due to highly effective thermal treatment). Considering the absence of available studies specifically designed in mycotoxin transfer through the production of cereal-based infant foods, a deeper understanding of the production process in combination with the applied physical and biochemical parameters is required to better assess the nature of changes in DON and its conjugates levels while processing. Also, taking into account the strict European regulation concerning the maximum content of DON in infant foods (200 µg/kg), there is an increased need in controlling raw material contamination levels and designing mitigation strategies against the problem. The main limitation that might be encountered while designing these mitigation strategies against mycotoxin contamination is the sensitivity of the raw materials to undergo undesirable chemical changes, mainly browning reactions, which could imply other health risks for the consumer.

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Figure

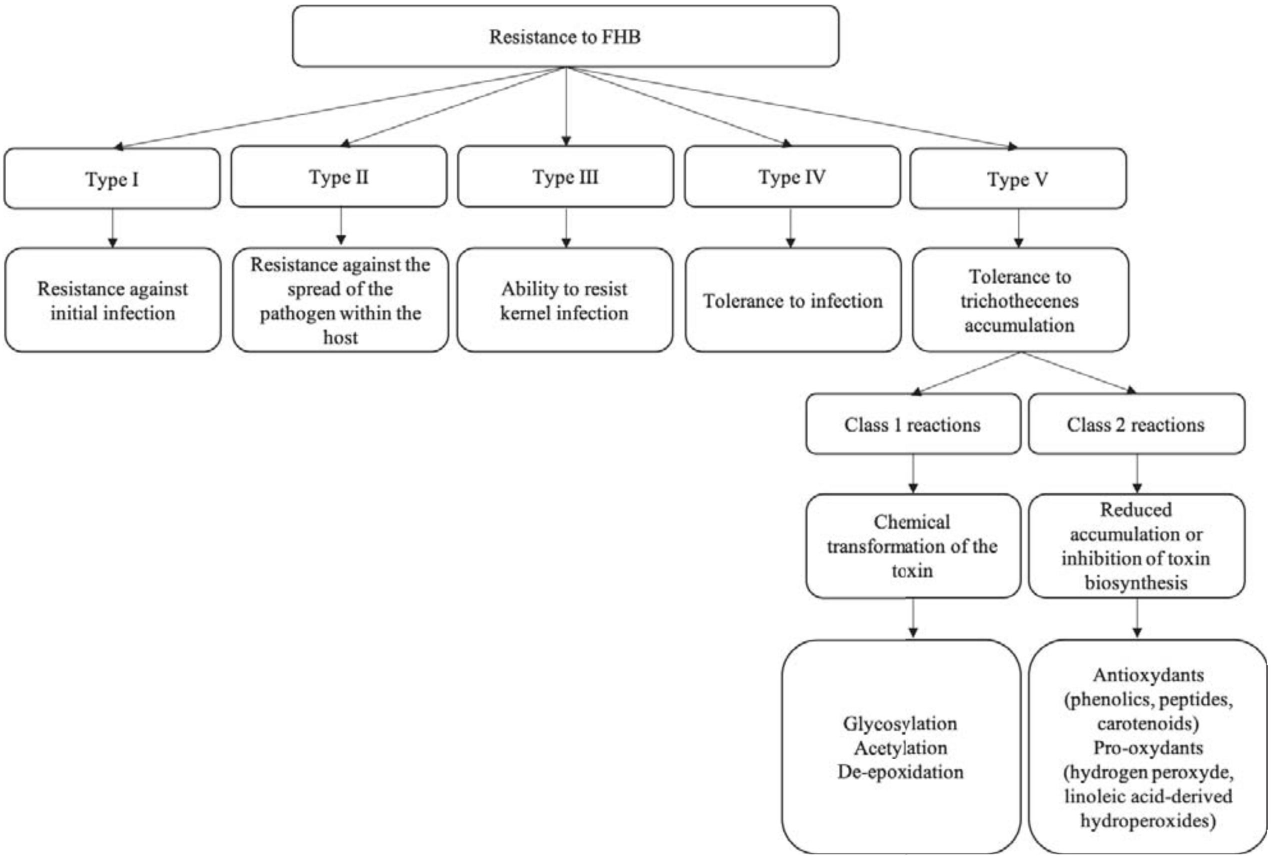

Figure 1: Natural mechanisms for cereal resistance to Fusarium Head Blight (FHB) and trichothecenes accumulation (adapted from Boutigny, Richard-Forget, & Barreau, 2008).

Figure

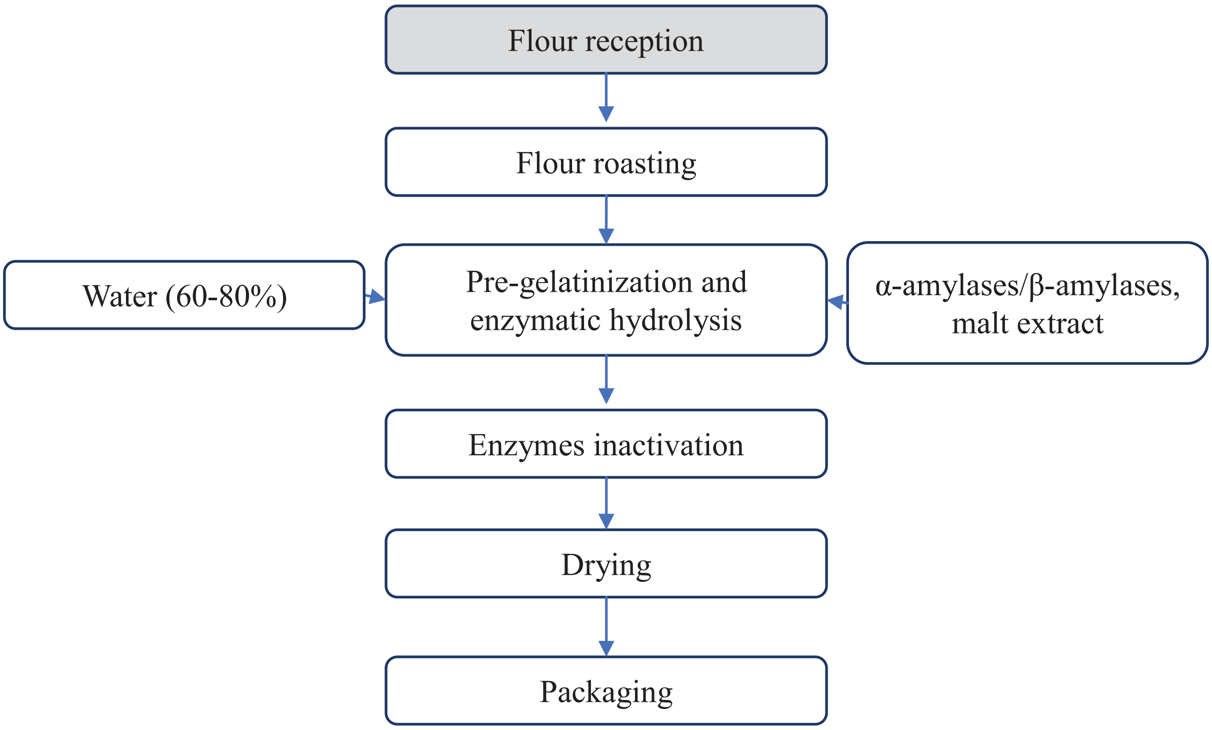

Figure 2: Infant and young children food production scheme

Figure

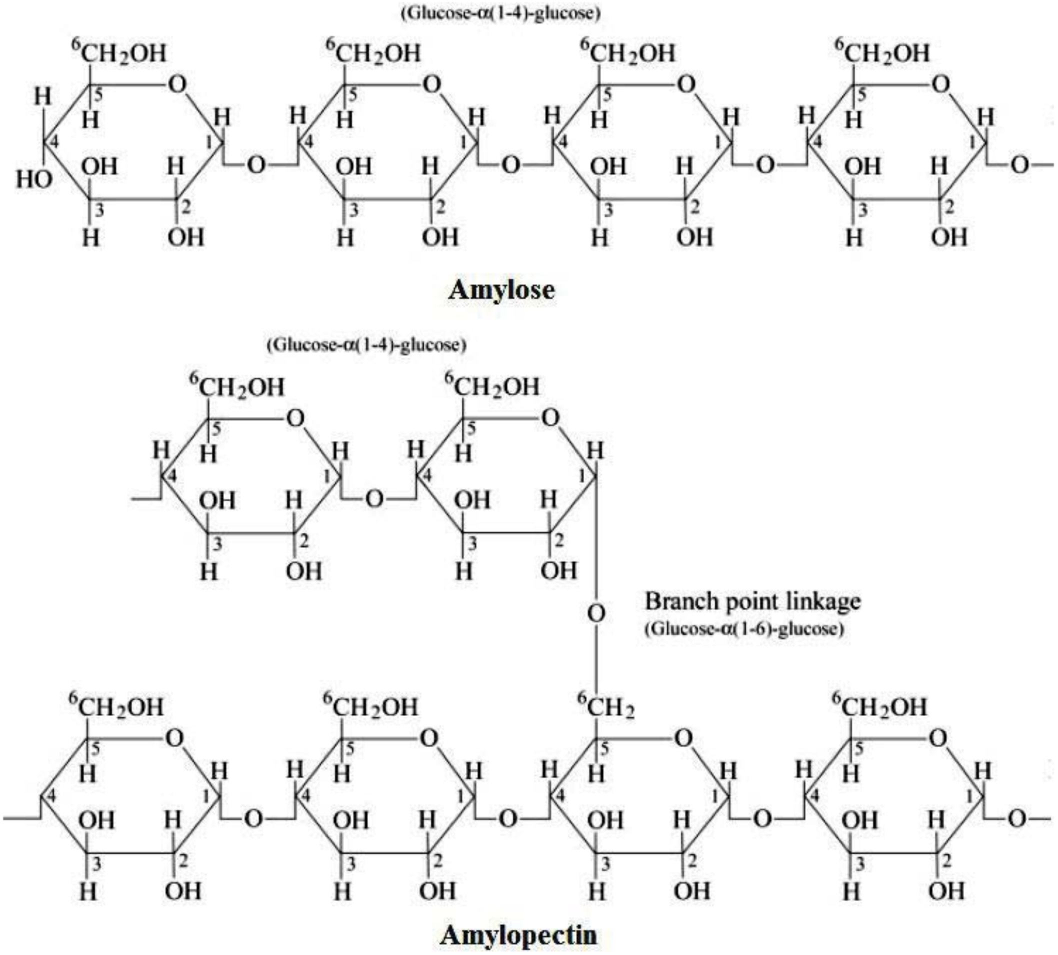

Figure 3: Chemical structure of amylose and amylopectin (Ghanbarzadeh & Almasi, 2013)

Table

Cereal	Country/region	Positive/total samples analysed	Concentration (µg/kg)		Reference
			Mean	Range	
Oats	Belgium	1/6	46	-	(De Boevre et al., 2012)
		9/11	810.1	62-2216	(Rasmussen et al., 2012)
	Canada	34/73	330	<100-1200	(Campbell, Choo, Vigier, & Underhill, 2000)
		63/82	190	-	(Clear, Patrick, & Gaba, 2000)
		6/10	42.5	22-71	(Martos, Thompson, & Diaz, 2010)
		4/4	700	200-1200	(Tamburic-Ilincic, 2010)
	Croatia	7/33	145	34-201	(Pleadin et al., 2013)
		8/13 8/14	O: 119 C: 207	O: 32-377 C: 33-546	(Pleadin et al., 2017)
	Denmark	-/22	44	-	(Nielsen et al., 2011)
	Finland	ND	-	1300-2600	(Placinta, D'Mello, & MacDonald, 1999)
		35/51	154.8	25-896	(Hietaniemi et al., 2004)
		-/470	237.4	Max:8800	(M. Lindblad, Börjesson, Hietaniemi, & Elen, 2012)
		129/137	618	0-9298	(Hietaniemi et al., 2016)
	Hungary	8/29	272	222-359	(Tima, Brückner, Mohácsi-Farkas, & Kiskó, 2016)
	Norway	ND	-	7200-62500	(Placinta et al., 1999)
		-/101	O: 111 C: 404	O: <20-447 C:<20-2056	(Bernhoft, Clasen, Kristoffersen, & Torp, 2010)
		-/171	476.4	Max: 22000	(M. Lindblad et al., 2012)
		28/28	M: 2070	Max: 7230	(Uhlig et al., 2013)
		260/289	-	50-30000	(Hofgaard et al., 2016)
	Poland	6/6	28	1-48	(Krysinska-Traczyk, Perkowski, & Dutkiewicz, 2007)
		34/35 14/18	O: 636 C: 697	O:250-1700 C:220-2150	(Kuzdraliński, Solarska, & Mazurkiewicz, 2013)
		7/34 20/24	O: 33.1 C: 28.7	O: 5-107 C: 5-189	(Twaruzek, Błajet-Kosicka, Wenda-Piesik, Pałubicki, & Grajewski, 2013)
		4/4	113	67-149	(Bryła et al., 2016)
	Russia	2/8	92	90-94	(Tutelyan et al., 2013)
	Scandinavia	4/4	628	-	(Scudamore, Baillie, Patel, & Edwards, 2007)
	Sweden	-/33	199.5	Max: 2340	(M. Lindblad et al., 2012)
		93/93	M: 172	Max: 5544	(Mats Lindblad et al., 2013)
	UK and Ireland	8/8	13	-	(Scudamore et al., 2007)
	UK	147/458	11	0-282	(Edwards, 2009)

Wheat	Argentina	ND	-	100-9250	(Placinta et al., 1999)
	Belgium	4/6	58.5	16-150	(De Boevre et al., 2012)
		6/6	910.5	46-2638	(Rasmussen et al., 2012)
		81/93	1053	-	(Vanheule et al., 2014)
	Brazil	ND	-	470-590	(Placinta et al., 1999)
	Bulgaria	ND	-	<1800	
	Canada	ND	-	10-10500	(Placinta et al., 1999)
		40/40	2732	54-8792	(Martos et al., 2010)
	Croatia	O: 14/25 C: 16/27	O: 256 C: 252	O: 62.4-678 C: 27-1220	(Pleadin et al., 2017)
	Finland	28/61	420	Max: 2224	(Hietaniemi et al., 2016)
	Germany	ND	-	4-20500	(Placinta et al., 1999)
	Hungary	2/2	383	<1400	(Uhlig et al., 2013)
		21/29	478	230-1880	(Tima et al., 2016)
	Japan	ND	-	30-1280	(Placinta et al., 1999)
	Netherlands	ND	-	20-231	(Placinta et al., 1999)
	Norway	ND	-	450-4300	(Placinta et al., 1999)
		92/92	O: 91.7 C: 180	O: <20-358 C: <20-797	(Bernhoft et al., 2010)
		163/178	-	Max: 16000	(Hofgaard et al., 2016)
	Poland	ND	-	2000-40000	(Placinta et al., 1999)
		45/45	770.7	82-2975	(Bryła et al., 2016)
	USA	ND	-	<9300	(Placinta et al., 1999)
Barley	Belgium	64/65	2029	-	(Vanheule et al., 2014)
	Canada	84/116	1370	Max: 9110	(Campbell et al., 2000)
		20/20	816.4	78-2449	(Martos et al., 2010)
	Croatia	18/34	342	74-228	(Pleadin et al., 2013)
		O: 6/11 C: 8/13	O: 71.8 C: 140	O: 32.3-157 C: 42.6-389	(Pleadin et al., 2017)
	Finland	59/86	308.8	Max: 4752	(Hietaniemi et al., 2016)
	Hungary	14/29	339	240-429	(Tima et al., 2016)
	Korea	ND	-	5-361	(Placinta et al., 1999)
	Netherlands	ND	-	4-152	(Placinta et al., 1999)
	Norway	ND	-	2200-13300	(Placinta et al., 1999)
		108	O: 43.7 C: 44	O: <20-154 C: <20-207	(Bernhoft et al., 2010)
		20/20	M: 150	Max: 636	(Uhlig et al., 2013)
	Poland	5/5	22	Max: 40	(Krysinska-Traczyk et al., 2007)
		20/24	370	54-1602	(Bryła et al., 2016)
	Russia	10/214	370.2	60-1280	(Tutelyan et al., 2013)
	USA	ND	-	<500-26000	(Placinta et al., 1999)
Maize	Belgium	6/6	2036	411-5245	(Boevre, Mavungu, Maene, & Audenaert, 2012)
	Canada	ND	-	20-4090	(Placinta et al., 1999)
		14/15	1513.5	574-4865	(Martos et al., 2010)
	China	ND	-	490-3100	(Placinta et al., 1999)
	Croatia	45/63	1565	215-1942	(Pleadin et al., 2013)
		O: 31/33 C: 30/37	O: 564 C: 350	O: 35-2260 C: 28-1430	(Pleadin et al., 2017)
	Hungary	25/29	1872	225-2963	(Tima et al., 2016)

	New Zeeland	ND	-	3400-8500	(Placinta et al., 1999)
	Poland	1/2	180	180	(Krysinska-Traczyk et al., 2007)
	Russia	1/53	70	-	(Tutelyan et al., 2013)
	South Africa	ND	-	Max: 1830	(Placinta et al., 1999)
Rye	Canada	15/15	269.8	87-500	(Martos et al., 2010)
	Croatia	O: 4/7 C: 2/9	O: 68.6 C: 35.4	O: 34-113 C: 31-40.2	(Pleadin et al., 2017)
	Denmark	17/17	56	-	(Nielsen et al., 2011)
	Finland	38/43	-	5-100	(Eskola, Parikka, & Rizzo, 2001)
		2/13	25	12-40	(Hietaniemi et al., 2016)
	Netherlands	ND	-	8-384	(Placinta et al., 1999)
	Poland	5/5	19	-	(Krysinska-Traczyk et al., 2007)
	Russia	1/63	60	-	(Tutelyan et al., 2013)
Triticale	Denmark	4/5	306	43-737	(Rasmussen et al., 2012)
	Poland	15/20	573	196-1326	(Bryła et al., 2016)

O=organic; C=conventional, M=median; ND= not defined

Table 2: Occurrence of deoxynivalenol (DON) in cereal-based baby food and food for young children

Baby and young children foods	**Country**	**DON, µg/kg**		**Reference**
		Mean (+ve/total samples)	**Range**	
Cereal-based food	Germany	61(15/25)	15-314	(Schollenberger, Suchy, Jara, Drochner, & Müller, 1999)
Biscuits and pasta	Italy	35 (7/12)	7-166	(Cirillo, Ritieni, Galvano, & Cocchieri, 2003)
Oat based cereals	Canada	52 (33/53)	Max: 90	(Lombaert et al., 2003)
Barley based cereals		260 (29/50)	Max: 980	
Soy based cereals		116 (8/8)	Max: 240	
Rice based		(0/9)	-	
Multigrain cereals		116 (62/86)	Max: 400	
Cereal-based food	Italy	(16/44)	ND	(Romagnoli, Ferrari, & Bergamini, 2010)
Barley based cereals	USA	63.5 (10/11)	ND	(DOMBRINK-KURTZMAN, POLING, & KENDRA, 2010)
Oat based cereals		13 (8/18)		
Mixed cereals		35.1 (15/23)		
Cereal-based food	Spain	131 (12/30)	Max: 286	(Cano-Sancho et al., 2011)
Wheat-based cereals	Italy	(11/11)	Max: 245	(Juan et al., 2014)
3 cereals (rice >70 %)		(1/2)	Max: 40.2	
3 cereals (maize > 65%)		(2/2)	Max: 103.8	
4-5 cereals (wheat >50%)		(3/7)	Max: 268	
5 cereals (barley >50%)		(2/3)	Max: 108	
Rice/corn-based meals	ND	(4/7)	46-877	(Zhang et al., 2014)
Cereal-based food	Portugal	160.6(4/9)	29-271	(Pereira et al., 2015)
Breakfast cereals	Tunisia	13 (5/10)	5-47	(Oueslati et al., 2018)
Infant cereals		46 (6/6)	10-110	
Baby mix		61 (7/9)	12-109	

ND=not defined.

Table 3: Morphology and transition temperatures for native starches from different cereal sources

Species	Granule shape	Diameter (µm)	Amylose (%, w/w)	Crystalline type	Gelatinization temperatures[1]			Reference
					T_o (ºC)	T_p (ºC)	T_c (ºC)	
Wheat	Spherical and lenticular*	<30*	25.6±1*	A*	52**	57**	63**	*Alcázar-Alay & Meireles, 2015 **Sasaki & Matsuki, 1998
Barley	Lenticular (A-type), spherical (B-type)*	15-25, 2-5*	19-22.1*	A, B*	46.7**	56.5**	73.7**	*Tester et al., 2004 **Tester & Morrison, 1990
Oats	Polyhedral*	3-10 (single) 80 (compound)*	28.4±0.8**	Do not fall into discrete size distribution***	45**	57**	72**	*Tester et al., 2004 **Tester & Karkalas, 1996 ***Zhou, Robards, Glennie-Holmes, & Helliwell, 1998
Maize	Angular*	11.5±0.3*	23-28*	A*	67.3**	72.9**	82.7**	*Alcázar-Alay & Meireles, 2015 **Chung, Liu, & Hoover, 2009
Rye	Lenticular (A-type), spherical (B-type)*	10-40 5-10*	29.7**	A**	51**	56**	62**	*Tester et al., 2004 **Verwimp, Vandeputte, Marrant, & Delcour, 2004
Sorghum	Polygonal, dented, round*	0.8*	23.7-27.6*	A*	67.9**	70.7**	75.7**	*Alcázar-Alay & Meireles, 2015 **Sang, Bean, Seib, Pedersen, & Shi, 2008
Triticale	Disc-shaped, Spherical*	1-30*	26.9**	A, B**	43.8**	53.6**	60.1**	*Tester et al., 2004 **Ao & Jane, 2007
Rice	Angular, polygonal*	<20*	21-25*		72**	76.6**	89.2**	*Alcázar-Alay & Meireles, 2015 **Lii, Shao, & Tseng, 1995

[1] T_o, T_p and T_c are onset, peak and conclusion temperatures, respectively; the stars in a line correspond to the references the data was cited from.