Cronobacter spp. – opportunistic food-borne pathogens. A review of their virulence and environmental-adaptive traits

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The genus Cronobacter consists of a diverse group of Gram-negative bacilli and comprises seven species: Cronobacter sakazakii, Cronobacter malonaticus, Cronobacter muytjensii, Cronobacter turicensis, Cronobacter dublinensis, Cronobacter universalis and Cronobacter condimenti (Iversen et al., 2007, 2008a; Joseph et al., 2012b, 2013a, b, c). Recently, Brady et al. (2013) suggested that three non-pathogenic Enterobacter spp. (Enterobacter pulveris, Enterobacter helveticus and Enterobacter turicensis), originally excluded by Iversen et al. (2008b), be included as members

Introduction

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Abbreviations: aw, water activity; BBB, blood–brain barrier; CNS, central nervous system; CSF, cerebrospinal fluid; FHA, filamentous hemagglutination; GIT, gastrointestinal tract; HBMEC, human brain microvascular endothelial cell; iNOS, inducible nitric oxide; MAPK, mitogen-activated protein kinase; MLST, multilocus sequence typing; NEC, necrotizing enterocolitis; PI3K, phosphatidylinositol 3-kinase; PIF, powdered infant formula; PKC, protein kinase C; ST, sequence type; T6SS, type VI secretion system; TGF, transforming growth factor.
of Cronobacter, but the current biological basis for this suggestion does not support further revision of the taxon at this time. As a result of this posited taxonomic uncertainty and the fact that no virulence attributes have been ascribed to these organisms, this review will not treat these Enterobacteriaceae as members of the genus Cronobacter.

All Cronobacter spp., except for the single species epithet C. condimenti, have been associated with human infections (Cruz-Córdova et al., 2012). Historically, Cronobacter have been implicated in newborn and infant infections, causing meningitis, necrotizing enterocolitis (NEC) and bacteraemia or sepsis (Healy et al., 2010). However, not all Cronobacter spp. are linked to infantile infections and it is thought that virulence among strains may vary. C. sakazakii, C. malonaticus and C. turicensis are the three species most often isolated from infantile cases (Joseph & Forsythe, 2011). For an understanding of recent unresolved issues remaining with respect to taxonomy, sources and clinical relevance, and for suggestions on how to safely feed premature neonates, see Holý & Forsythe (2013).

Infections in elderly and immunocompromised adults have also been reported (Healy et al., 2010), and the epidemiology of these cases suggests that other potential sources of contamination exist, such as the home environment (Kandhai et al., 2004; Kilonzo-Nthenge et al., 2008), retail foods (e.g. dried milk powder, dried meats, legumes, nuts, dried flours and spices) (Friedemann, 2007; Hochel et al., 2012) or drinking water (Lui et al., 2013). Although Cronobacter spp. have been detected in this wide assortment of foods, only contaminated powdered infant formula (PIF) has been linked epidemiologically with infant infections and outbreaks caused by Cronobacter (Himelright et al., 2002; Hunter & Bean, 2013). The source of this contamination is thought to be PIF manufactured under poor Good Manufacturing Practice; however, extrinsic contamination of opened cans and human carriage may also be possible. Some physiological traits exhibited by Cronobacter, such as the expression of an extracellular polysaccharide, the ability to produce a yellow pigment and the ability to resist desiccation during long dry periods, suggest that an environmental niche may be the source of these organisms (Schmid et al., 2009). A further understanding of the molecular mechanisms involved in survival and persistence of Cronobacter would contribute significantly towards relating food contamination to its food matrix or environmental food production source, and will mitigate the spread of infectious disease occurring through food vehicles and allow for a reduction of illnesses caused by Cronobacter.

Cronobacter exhibit unusual resistance to heat, dry and acid growth conditions compared with other members of the family Enterobacteriaceae (Nazarowec-White & Farber, 1997; Breeuwer et al., 2003; Edelson-Mammel et al., 2005; Dancer et al., 2009). They also form biofilms, which serve as a physical protective barrier from these environmental stresses as well as host immune surveillance mechanisms.

However, little is known about these virulence properties and antigenic determinants. The outer-membrane protein A (OmpA) is probably the best-characterized virulence marker of Cronobacter (Nair et al., 2009; Mittal et al., 2009a, b; Kim et al., 2010). Furthermore, it was reported that Cronobacter employ phosphatidylinositol 3-kinase (PI3K)/Akt signalling to initiate actin microfilaments’ rearrangement and the subsequent invasion of host cells. Protein kinase c (PKC)-α activation and impairment of the mitogen-activated protein kinase (MAPK) pathway are also important steps involved in the invasion process (Singamsetty et al., 2008; Li et al., 2010; Liu et al., 2012b). The fact that Cronobacter can exploit immature dendritic cells and persist within human macrophages indicates that Cronobacter possess some immune evasion properties that enable them to avoid the host’s immune response, and reach and penetrate the blood–brain barrier (BBB) (Townsend et al., 2007b, 2008; Mittal et al., 2009b; Emami et al., 2011; Joseph & Forsythe, 2011).

Attachment of Cronobacter to certain cell lines and the subsequent invasion were the focus of several reports in an attempt to understand the pathogenicity mechanisms of this pathogen (Mange et al., 2006; Kim & Loessner, 2008; Singamsetty et al., 2008; Townsend et al., 2008; Giri et al., 2012). Therefore, the objective of this review is to address the various virulence characteristics of members of the genus Cronobacter that contribute to its contamination of foods, and survival in the environment and host.

Diseases and outbreaks caused by Cronobacter
Infantile or neonatal infections

These organisms are regarded as opportunistic pathogens linked to life-threatening infections predominantly in neonates (infants <4 weeks old) (Bar-Oz et al., 2001; Mullane et al., 2008). Clinical presentation of Cronobacter infections in infants include NEC, bacteraemia and meningitis, with case fatality rates ranging between 40 and 80% being reported (Bowen & Braden, 2006; Friedemann, 2007). Infections in older infants have also been noted (Bowen & Braden, 2006).

The Food and Agriculture Organization of the United Nations/World Health Organization statistics for 2006 estimated that the annual incidence rate in the USA among low-birth-weight infants who weighed <2500 g and were <1 year old was 8.7 per 100 000 (FAO/WHO, 2006). Globally, there is no active surveillance system for tracking this pathogen; however, in their 2008 report, the WHO Expert Panel tracked cases from 1961 to 2008, and found 120 recorded cases of Cronobacter among infants and children <3 years old (FAO/WHO, 2008). Although only ~120 cases have been reported worldwide, the actual number of cases is considered far higher (CDC, 2009; Friedemann, 2009; Teramoto et al., 2010). Stoll et al. (2004) reported that only one case of sepsis caused by Cronobacter was diagnosed among 10 660 neonates, indicating that outside the epidemic outbreaks, Cronobacter are very rare in...
low-birth-weight infants. Even though septicaemia was the diagnosis in this single case, the infant was breast fed, further emphasizing that other routes of nosocomial transmission may be present. Nonetheless, it is not the number of infections caused by Cronobacter that is the issue; it is rather the 80% fatality rate associated with illness. In addition, it was reported that all patients recovering from central nervous system (CNS) infections develop chronic neurological and developmental disorders (Lai, 2001).

An early hypothesized source of Cronobacter infection was the birth canal. However, this source now seems to be unlikely, as none of the vaginally delivered infants developed signs of infection until several days after birth and it is also unlikely that Cronobacter constitute a part of the vaginal microflora (Yan et al., 2012; Hunter & Bean, 2013). In addition, Biering et al. (1989) observed that infants who showed Cronobacter meningitis had all received reconstituted powdered-milk formula before falling ill. Furthermore, after a review of feeding procedures, a significant association was found between the consumption of certain brands of PIF, the development of NEC in neonates and the isolation of Cronobacter (van Acker et al., 2001). Several Cronobacter outbreaks have occurred in neonatal intensive care units that were linked epidemiologically to contaminated PIF (Himelright et al., 2002; Teramoto et al., 2010). In a recent survey, the majority of the infant formula packages were found completely devoid of any micro-organisms (Jaradat et al., 2009). However, extrinsic contamination of opened PIF cans or formula preparation utensils has also been reported (Noriega et al., 1990; Friedemann, 2009; Jaradat et al., 2009). Table 1 shows a list of the various foods and environments where Cronobacter have been isolated. Accordingly, the risk of infection may rely on different factors, including the number of bacterial cells contaminating the product, the source of Cronobacter, handling after preparation and the health status of the infants (e.g. low birth weight, prematurity, or immunosuppression) (Himelright et al., 2002).

**NEC**

It is generally thought that Cronobacter gain entrance to the human body through the gastrointestinal tract (GIT) where they may cause NEC (Liu et al., 2012b). Grishin et al. (2013) point out that the development of NEC requires a susceptible host, typically a premature infant with physiological impairment (i.e. hypoxia, hypothermia, intestinal ischaemia), administration of enteral formula feeds (which lack the beneficial protective components normally found in breast milk) and uncontrolled bacterial colonization. These conditions lead to an increased degree of mucosal inflammation, which subsequently results in the production of high levels of host inflammatory factors, including cytokines, nitric oxide, platelet-activating factor and prostanooids, which further damage the apical GIT epithelium. These authors and others also suggest that the virulence of Cronobacter spp. is dose-dependent, but not due to a property of a particular bacterial species as a whole, rather a characteristic(s) of certain strains, which may be innocuous in a full-term, yet pathogenic in a pre-term infant (Hamby et al., 2011; Gürkan et al., 2013). *In vitro* models of infection also suggest that the organism may also gain entrance into the systemic circulation through transcytosis of the GIT epithelium (Giri et al., 2012).

**CNS infections**

Once the organism has entered the systemic circulation, it has a tropism toward the CNS, thus increasing the propensity to cause meningitis among low-birth-weight neonates and infants, whilst causing bacteraemia or sepsis among slightly higher-birth-weight infants (Yan et al., 2012) or adults. Once the pathogen crosses the BBB and enters the brain, it might cause ventriculitis and form cysts or brain abscesses, which later may develop into hydrocephalus – a condition where excessive accumulation of cerebrospinal fluid (CSF) in the brain occurs (Bowen & Braden, 2006; Chenu & Cox, 2009). The disproportionate accumulation of CSF results in an abnormal enlargement of the spaces in the brain called ventricles. The enlarged CSF-filled ventricles create a situation where the balance between CSF production and absorption is disturbed, which potentially leads to an increase of cranial pressure on the tissues of the brain.

**Infections associated with adults**

Compared with infant cases, Cronobacter are more commonly detected in adults, with most case reports describing infections related to elderly patients who were previously ill or immunocompromised. Up to 50% of adults with Cronobacter infection had an underlying malignancy (Lai, 2001; See et al., 2007). Interestingly, Cronobacter have been linked to or should be considered as a pathogen that may cause sepsis, conjunctivitis, aspiration pneumonia in stroke patients, osteomyelitis, diarrhoea, acute cholecystitis, wound infections, abscesses associated with indwelling catheters and urinary tract infections (Gosney et al., 2006; Friedemann, 2009; Flores et al., 2011; Yan et al., 2012; Tsai et al., 2013). Nosocomial infections by Cronobacter, such as aspiration pneumonia, urinary tract infections and conjunctivitis, are unlikely to be related to contaminated PIF, so medical equipment surfaces, water outlets and intrapersonal contacts may serve as possible sources of these infections (Friedemann, 2009; Flores et al., 2011). However, other environmental sources of contamination are also possible. Jaradat et al. (2009) isolated Cronobacter from household vacuum dust in addition to isolating it from spices, indicating the strong association of the pathogen with a variety of dried food products and environmental factors. See et al. (2007) described a case of Cronobacter bacteraemia with multiple splenic abscesses in a 75-year-old institutionalized woman. It was the first reported case of Cronobacter with splenic abscesses and was the first case in a non-immunocompromised adult.
Table 1. Foods of animal and plant origin and environments where Cronobacter was isolated

<table>
<thead>
<tr>
<th>Food/environment</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Infant food, beverages and processed foods</td>
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<tr>
<td>Infant food</td>
<td>Jaradat et al. (2009); Chap et al. (2009)</td>
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<tr>
<td>Follow-up formula</td>
<td>Chap et al. (2009)</td>
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<tr>
<td>Rice flour</td>
<td>Lampel &amp; Chen (2009)</td>
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<tr>
<td>Chocolate and cakes, vanilla cream bars</td>
<td>Baumgartner et al. (2009)</td>
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<tr>
<td>Herbal tea, iced tea</td>
<td>Chap et al. (2009); Osalli &amp; Forsythe (2009)</td>
</tr>
<tr>
<td>Weaning foods</td>
<td>Osalli &amp; Forsythe (2009)</td>
</tr>
<tr>
<td>Rice, corn, soy, grain, starches, potato flour, pasta, cereals</td>
<td>Osalli &amp; Forsythe (2009)</td>
</tr>
<tr>
<td>Tofu, sodium casinate</td>
<td></td>
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<tr>
<td>Plants and spices</td>
<td></td>
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<tr>
<td>Liquorice, thyme, anise, chamomile, fennel, sage</td>
<td>Jaradat et al. (2009)</td>
</tr>
<tr>
<td>Mixed spices</td>
<td>Jaradat et al. (2009)</td>
</tr>
<tr>
<td>Attieke, barley, biscuits, cereals, cowpea paste, dry nuts, grains, herbs and spices, red algae, sorghum, peas</td>
<td>Beuchat et al. (2009)</td>
</tr>
<tr>
<td>Dried herbs</td>
<td>Molley et al. (2009)</td>
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<tr>
<td>Mixed spices, black pepper and white pepper, curry and mixed herbs</td>
<td>Baumgartner et al. (2009)</td>
</tr>
<tr>
<td>Oats, barley, wheat</td>
<td>Molley et al. (2009)</td>
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<tr>
<td>Dried vegetables</td>
<td>Osalli &amp; Forsythe (2009)</td>
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<tr>
<td>Fresh produce</td>
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<tr>
<td>Salads, and herbs</td>
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<tr>
<td>Mixed vegetables, salad</td>
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<tr>
<td>Sprouts, fresh herbs and salads, parsley, dill, coriander, celery, basil</td>
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<tr>
<td>Animal products</td>
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<tr>
<td>Camel, eggs, cheese, milk, pork, fish and products, poultry, sausages, shellfish, shrimp</td>
<td>Beuchat et al. (2009)</td>
</tr>
<tr>
<td>Beef and products, pork, burgers, minced meat from beef and pork</td>
<td>Molley et al. (2009)</td>
</tr>
<tr>
<td>Environment</td>
<td></td>
</tr>
<tr>
<td>Milk powder and environment</td>
<td>Lampel &amp; Chen (2009)</td>
</tr>
<tr>
<td>Water, soil and grass</td>
<td>Lampel &amp; Chen (2009); Molly et al. (2009)</td>
</tr>
<tr>
<td>Household vacuum dust</td>
<td>Jaradat et al. (2009); Molley et al. (2009)</td>
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</table>

Molecular characterization of strains

Multilocus sequence typing (MLST) sequence types (STs)

The reclassification scheme described by Iversen et al. (2007, 2008a) was supported subsequently by both optical mapping and genome sequencing data, which confirmed the revision of the taxonomic positions of the seven species (Yan et al., 2012; Kotevitz & Tall, 2009; Kucerova et al., 2010; Stephan et al., 2011; Joseph et al., 2012; Grim et al., 2013). Although C. sakazakii and C. malonaticus were found to be closely related and difficult to distinguish by 16S rDNA gene sequence analysis, a MLST scheme reported by Baldwin et al. (2009) was shown to support the separation of these two species (Yan et al., 2012). Other supporting evidence which suggested that C. malonaticus and C. sakazakii are separate species were the single nucleotide polymorphisms identified for two genes, rpoB and cgca, as reported by Stoop et al. (2009) and Carter et al. (2013). Their work led to the development of two species-specific end-point PCR assay schemes that are now widely used for speciation of isolates. The sequencing of another 15 Cronobacter strains by Grim et al. (2013) fully corroborates both the taxonomic scheme described by Iversen et al. (2008a) and the MLST scheme described by Baldwin et al. (2009). Grim et al. (2013) concluded that, in particular, C. sakazakii and C. malonaticus must have evolved or acquired accessory genes that have enhanced their virulence capacity and host species adaptation, and thus augmented their overall pathogenicity. Furthermore, the MLST scheme has defined over 136 STs and C. sakazakii ST4 was the predominant ST found associated with CSF isolates from cases of neonatal meningitis (Joseph et al., 2012a). In fact, the MLST typing method has alone defined 55 STs for C. sakazakii (Sonbol et al., 2013). As suggested by Holy & Forsythe (2013), the clonality and prevalence of the ST4 strains are clearly associated with meningitis, but not NEC. Fortunately, this information gives direction for further meningitis research with the bacterium.

Nevertheless, C. sakazakii has been implicated in most of the infant and neonatal meningitis cases. Similarly, in another study by Hariri et al. (2013), the authors found that most serious meningitis cases were caused by C. sakazakii ST4. Furthermore, they also found that all the five CSF isolates were ST4. In another study, Joseph & Forsythe (2011) showed that half of the studied Cronobacter strains from all clinical sources over 50 years from seven countries were C. sakazakii ST4. These findings indicated the
predominance of this particular clonal or clonal complex in causing neonatal meningitis and provided evidence that ST4 may be a stable virulent clone. Furthermore, it was suggested that C. sakazakii ST4 may be composed of multiple STs and comprises a clonal complex, and ST4 was predominantly involved in infant meningitis and was frequently isolated from milk powder processing facilities. C. malonaticus contained other STs such as ST8 that were associated with clinical cases, but not necessarily associated with neonates, whilst ST7 was associated with adult infections (Sonbol et al., 2013). Sonbol et al. (2013) described the occurrence of different Cronobacter MLST STs in global surveys and their findings suggest that 24% of strains from PIF manufacturing sites are the ST4 clone. In their study, Müller et al. (2013) reported that 132 of 141 Cronobacter isolates obtained from an infant formula production factory were C. sakazakii, whilst only seven were C. malonaticus. Furthermore, when the isolates were analysed by MLST, C. sakazakii ST4 was the predominant type among them.

Molecular O-antigen typing

The O-antigen is a component of the LPS structure located on the outer surface of Gram-negative bacteria and is responsible for serological diversity. As a Gram-negative pathogen, the cell surface of Cronobacter is covered with a dense area of LPS (endotoxin) with a lipid A core, the toxic moiety forming ~8% of the total LPS weight (MacLean et al., 2009). It was found that different strains of Cronobacter have different LPS structures, and show differences in pathogenicity based on differences in structure (linear versus branched) and composition of LPS (MacLean et al., 2009). It was found that the LPS of C. sakazakii and C. malonaticus was branched, whilst LPS from other Cronobacter strains such as C. muytjensii was unbranched (Joseph et al., 2012c). Indeed, C. muytjensii LPS failed to provoke the production of mAbs due to its unbranched structure (Jaradat et al., 2011).

As a useful method of characterizing Gram-negative bacteria, O-antigen typing and studies describing the nature of the O-antigen associated with Cronobacter spp. have been reported (Mullane et al., 2008; Jarvis et al., 2011, 2013). Mullane et al. (2008) initially developed a molecular serotyping method, based on amplification of the rfb encoding locus (in Gram-negative enteric bacteria this is located between galF and gnd) followed by MboII digestion. Using this approach, a PCR-RFLP profile was generated that could be compared across several isolates. Based on this approach, the first two O-antigen serotypes were characterized, and denoted as O1 and O2. More recently, Sun et al. (2011) added five additional C. sakazakii O-antigen serotypes that correlated with the PCR-RFLP profiles. Jarvis et al. (2011) extended the original Mullane molecular characterization scheme to include other Cronobacter spp. and defined eight new molecular O-serotype gene clusters. Two of these O-serotype gene clusters were shared among C. sakazakii, C. muytjensii, C. malonaticus and C. turicensis strains (Jarvis et al., 2011, 2013). The structural composition of several O-serotypes has now been described (MacLean et al., 2009; Arbatsky et al., 2010, 2011; Shashkov et al., 2011). Presently, there are 17 recognized serotypes among the seven species. Over a 1 year period (2011–2012), Müller et al. (2013) found that C. sakazakii serotype O2 was the predominant serotype observed among 141 confirmed Cronobacter isolates obtained during a surveillance study of a Swiss PIF manufacturing facility. Correlations between ST4 and C. sakazakii serotypes O2/O3 and between ST83 and C. sakazakii serotype O7 were observed, suggesting that a ST may contain multiple serotypes.

Pathogenicity and virulence of Cronobacter

Despite the exponential increase in research on Cronobacter over the last decade, the exact mechanism of Cronobacter pathogenesis is still unknown. One of the first attempts to understand the pathogenicity of Cronobacter was the work of Pagotto et al. (2003), who investigated enterotoxin production among different Cronobacter strains using the suckling mice assay. To date, a number reports have been published on the putative virulence factors, such as toxin production, adhesion and invasion, adaptation to stress factors, presence of virulence genes, and antibiotic resistance. These factors are discussed separately throughout this review.

Toxins and proteolytic enzymes

Historically, enterotoxin production has been a major virulence factor that marks the pathogenicity of microbes. Pagotto et al. (2003) were the first to describe putative enterotoxin activity in Cronobacter. Using the suckling mice assay, they were able to show an enterotoxin effect by four of the 18 tested Cronobacter isolates. When tested on cultured mammalian cells, filtrates from one strain were toxic to Vero and Y-1 cells, causing rounding and cell lysis. Boiling the filtrates for 20 min did not affect the toxin activity in suckling mice, but it reduced the cytotoxic effect of the toxin on Vero cells. Yang et al. (2009) showed that filtrates from two out of eight strains studied were toxic to Vero cells. Raghav & Aggarwal (2007) were the first to purify and characterize a putative enterotoxin from Cronobacter isolates. The molecular mass of the toxin was determined to be 66 kDa, which is similar to the 62 kDa toxin of Shigella dysenteriae 1 and to the 65 kDa toxin of Pseudomonas aeruginosa with optimum activity observed at pH 6. Additionally, the activity of the toxin was unaffected by holding it at 50 or 70 °C and it was stable at 90 °C for 30 min, implying that it is a moderately heat-stable toxin. This indicates that the enterotoxin could be resistant to commercial milk pasteurization treatments and thus stays active in PIF.

However, it seems that the discovery of these toxins is still in its infancy, as the specific genes need to be identified to
shed light on the importance of these enterotoxins (Chenu & Cox, 2009). Molecular studies using genome sequencing will help with the further characterization of these toxins.

In addition to enterotoxins, Cronobacter also secrete proteolytic enzymes that lyse cells and create tissue damage at the site of infection in mice (Pagotto et al., 2003). Kotthary et al. (2007) reported the presence of a zinc metalloprotease that deforms CHO cells, eventually causing their rounding and leading to cell damage. The genes for a haemolysin (hly) have been identified, but no activity has been found (Kucerova et al., 2010; Cruz et al., 2011; Grim et al., 2013).

Townsend et al. (2007a) provided evidence that the presence of endotoxin along with C. sakazakii in infant formula enhanced the translocation of C. sakazakii from rat guts through the BBB. One possible mechanism is thought to be the disruption of the tight junctions by LPS, thus increasing the permeability of host barriers to the pathogen (Kim & Loessner, 2008). In addition, endotoxin was found to impair enterocyte migration and epithelial restitution, and therefore inhibited tissue repair following bacterial infection, which leads to the translocation of the pathogen from the gut into the blood and internal tissue (Cetin et al., 2004). As the endotoxin is heat stable at 100 °C, its presence in formulas might also play an important role in enhancing the pathogenesis of Cronobacter in human infants (Townsend et al., 2007a).

Attachment and invasion

Attachment. Many meningitis-causing bacteria, such as Neisseria meningitidis, Haemophilus influenzae and P. aeruginosa utilize type IV pili to colonize intestinal tissues and to later overcome the shear forces of the capillary blood flow before crossing the BBB (Kucerova et al., 2010; Joseph & Forsythe, 2011; Grim et al., 2013). Cronobacter have been mostly implicated in meningitis in infants following the consumption of reconstituted and temperature-abused PIF (Hunter & Bean, 2013). Hence, it is thought that the main colonization site of Cronobacter is the GIT, where it first colonizes the mucous membranes, gastric and intestinal epithelial or endothelial tissues prior to their internalization within enterocytes, or translocation through the lamina propria into the systemic blood flow and then invasion of the brain.

Several in vitro studies using human-derived cell lines investigated the behavioural characteristics of Cronobacter. Mange et al. (2006) examined non-fimbrial adhesive characteristics of Cronobacter with human brain microvascular endothelial cells (HBMECs), which make up the BBB, and with human epithelial cell lines (HEp-2 and Caco-2). They reported that neither mannose-sensitive type 1 fimbriae nor type 3 fimbriae were involved in the adhesion of Cronobacter to the cells. Comparatively, one striking difference among Cronobacter as reported by Kucerova et al. (2010), Jospeh & Forsythe (2011) and Stephan et al. (2011) is the finding that C. sakazakii does not possess the genes encoding curli, whereas C. turicensis does. However, the implications of these findings in virulence have not been fully studied.

Later, Townsend et al. (2008) showed that there was no direct correlation between rates of attachment to and invasion of Cronobacter by Caco-2 cells. In fact, this was the case with other pathogens, such as Listeria monocytogenes, where there was no relation between the attachment and invasion, and the most highly attaching isolates showed low or moderate invasion capabilities (Jaradat & Bhunia, 2003).

However, with the advent of whole-genome sequencing, Grim et al. (2013) reported that the Cronobacter genome contains genes for the type IV pili in addition to a P pilus homologous to that found in uropathogenic Escherichia coli that causes meningitis in infants. Interestingly, not all Cronobacter spp. contain the genes for these pili. For instance, C. sakazakii BAA-894 and C. malonaticus LMG 23826 harbour a unique type 1 fimbriae (GR82), which was absent in other genomes. This may explain the variation in the pathogenicity observed among the different Cronobacter spp. Furthermore, some Cronobacter genomes contain genes for other types of fimbriae that are found in other well-known pathogens. A gene for the curli fimbriae homologous to that of E. coli and another gene related to the tafi fimbriae of Salmonella were also identified (Grim et al., 2013).

Other adherence mechanisms might be involved in the colonization of GIT cells by Cronobacter spp. Cronobacter use host surface proteins such as fibronectin – a major glycoprotein component of the extracellular matrix – to adhere to the intestinal epithelial or endothelial cells as an initial step before their internalization (Mange et al., 2006; Nair & Venkitanarayanan, 2007; Mittal et al., 2009a). Blocking fibronectin binding reduced the number of Cronobacter cells attaching to INT-407 epithelial cells (Nair & Venkitanarayanan, 2007), whilst it had no significant impact on the adherence of C. sakazakii to HBMECs (Nair et al., 2009). These differing results indicate that Cronobacter attachment mechanisms mediated by fibronectin are likely host cell-type specific, where some Cronobacter spp. use their OmpA, not fimbriae, to adhere to the fibronectin receptors as an initial step in colonization. These results also emphasize the critical role of this outer-membrane protein in bacterial invasion (Mange et al., 2006; Kim et al., 2010; Liu et al., 2012b; Yan et al., 2012).

Invasion. After the successful attachment of Cronobacter to intestinal cells, the pathogen invades these cells in a process that ends up with the pathogen translocating across the intestinal tissue layers to enter the systemic blood flow, resulting in extra-intestinal infection, such as sepsis and meningitis (Nair & Venkitanarayanan, 2007). The invasive capability of Cronobacter was studied by several researchers using mammalian cell lines. Singamsetty et al. (2008) suggested that HBMECs are more susceptible to Cronobacter invasion, demonstrating a higher invasion frequency in HBMECs than endothelial and epithelial cells from different
tissue origins. Townsend et al. (2008) showed a variation in Cronobacter invasion capacity with intestinal and BBB cells, indicating that Cronobacter invade HBMECs in a strain-dependent fashion, whereas no direct connection between attachment and invasion rates for Caco-2 cells was detected. Kim & Loesner (2008) found that Cronobacter entry into and invasion of Caco-2 cells is an active process that needs de novo protein synthesis, and depends on exposure time and m.o.i. Recently, Giri et al. (2012) demonstrated that Cronobacter isolates were able to transcytose across tight monolayers of Caco-2 cells and HBMECs, thus mimicking the in vivo ability to cross the intestine and subsequently the CNS BBB to cause meningitis. Not only that, the rate of transcytosis of some strains was equivalent to that of the control meningitis-causing E. coli K1 strain. Interestingly, the rate of transcytosis among the isolates varied significantly.

**Role of OmpA in Cronobacter invasion of mammalian cells**

OmpA appears to play a major role in Cronobacter invasion. In vitro, it was found that OmpA plays a critical role in the invasion of human intestinal epithelial cells (INT-407), Caco-2 cells and HBMECs (Nair & Venkitanarayanan, 2007; Kim & Loesner, 2008; Singamsetty et al., 2008; Kim et al., 2010). An 87% reduction of Cronobacter invasion of INT-407 cells was observed in the absence of OmpA expression. Similarly, Nair et al. (2009) reported that OmpA is a determinant that influences the invasion of C. sakazakii into HBMECs, by providing evidence that the absence of OmpA expression resulted in 83% reduction in C. sakazakii invasion. However, adherence of an OmpA mutant did not differ significantly from the WT strain, possibly because there are other surface determinants that contribute to C. sakazakii attachment to host cells that may not play a role in the invasion.

Mittal et al. (2009a) showed that OmpA expression is important for the onset of meningitis caused by Cronobacter in a newborn rat model as OmpA+ Cronobacter were present in high numbers in the brains of infected animals. They also showed that OmpA expression is essential for Cronobacter resistance to blood and serum killing (Mittal et al., 2009a). Although both OmpA+ and OmpA- Cronobacter were efficiently taken up by dendritic cells, only OmpA+ Cronobacter resisted killing and multiplied in these cells, thus highlighting the critical role of OmpA in protecting the intracellular survival of this pathogen (Mittal et al., 2009b).

Similarly, Kim et al. (2010) reported that OmpA and OmpX of C. sakazakii are important for both apical and basolateral adhesion to and invasion of host cells, as well as for movement into deeper organs, such as the spleen and liver. Invasion studies proved that OmpA and OmpX are crucial for C. sakazakii invasion of INT-407 and Caco-2 cells. However, adherence studies demonstrated that OmpA was essential for binding to Caco-2 cells, but not INT-407 cells. OmpX did not show any significant role in binding to both types of cells examined. The authors concluded that C. sakazakii adherence to Caco-2 cells is mediated by OmpA, but adhesion to INT-407 cells is not, and that the initial interaction of C. sakazakii with Caco-2 and INT-407 cells is independent of OmpX. Nonetheless, not all Cronobacter spp. were positive for OmpA using the primers described by Nair & Venkitanarayanan (2007), as reported by Jaradat et al. (2009) and Giri et al. (2012).

**Role of cytoskeleton rearrangement in Cronobacter invasion**

To enable smooth entrance into the cytoplasm of a host cell, most pathogenic bacteria are able to manipulate the cytoskeleton of the host cell either by the secretion of effector molecules or by interfering with the phosphorylation cascades in the intracellular signal transduction pathways (Singamsetty et al., 2008; Kim & Loesner, 2008; Mittal et al., 2009b).

Results of several studies clearly demonstrated that Cronobacter exploit both microfilaments and microtubules to invade host cells. Actin microfilaments are the most well-known structures in this process. This was supported by the fact that treating INT-407 cells, Caco-2 cells and HBMECs with the actin-depolymerizing agent cytochalasin D completely blocked the invasion by C. sakazakii of these cell lines (Nair & Venkitanarayanan, 2007; Kim & Loesner, 2008; Li et al., 2010). C. sakazakii invasion of HBMECs involves participation of distinct signal transduction processes in which the PI3K/Akt signalling pathway also plays an essential role to initiate the rearrangement of actin filaments and subsequent bacterial internalization (Singamsetty et al., 2008; Li et al., 2010). Liu et al. (2012a) found that host cytosolic phospholipase A2 is a downstream effector of PI3K/Akt signalling, which is needed for the actin reorganization in HBMECs elicited by C. sakazakii infection. In contrast, it was shown that Cronobacter severely impair the phosphorylation of p38, extracellular signal-regulated kinase 1/2 and c-Jun N-terminal kinase, which are major components of the MAPK pathway, and prevent the activation and maturation of dendritic cells by disarming the MAPK pathway – a process that may aid the pathogen in evading the immune system (Mittal et al., 2009b).

**Tight junction disruption**

The tight junction constitutes the principal barrier in intestinal epithelial cells. Kim & Loesner (2008) showed that when the tight junctions of Caco-2 cells were disrupted, the efficiency of C. sakazakii adhesion and invasion increased substantially. Apparently, after binding of Cronobacter to the intestinal enterocyte cell surfaces, Cronobacter caused the generation of increased amounts of nitric oxide, which is thought to have led to the disruption of the tight junctions between individual enterocytes. Disruption of the tight junctions subsequently led to apoptosis (Liu et al., 2012b). This, in turn, led to the leakage of the pathogen...
through these localized disruptions, eventually reaching the systemic circulation (Liu et al., 2012b).

Interestingly, the inhibition of the PKC-α intracellular signalling pathway abolished the disruption of the tight junctions. These results indicate that PKC-α influences the permeability of the intestinal epithelium to *C. sakazakii* (Liu et al., 2012b). Singamsetty et al. (2008) showed that PKC-α activation is also critical for *Cronobacter* invasion of HBMECs. The disruption of tight junctions might be a result of *C. sakazakii* interaction with dendritic cells, which could modulate the expression of the ‘tightness’ of the tight junctions (Emami et al., 2011).

**Evading the immune response**

It is expected that *Cronobacter* possess virulence factors that help in the colonization and invasion of the various human mucosal cells as a first step in the systemic spread of the organism. Furthermore, such pathogens have evolved mechanisms to avoid the immune system lines of defence, such as surviving within macrophages, and possessing resistance to the bactericidal action of complement and serum. *Cronobacter* appear to evade the host’s immune system by adapting to a lifestyle of replication in the intracellular environment confined within macrophages. Townsend et al. (2007b) showed that *Cronobacter* can persist within human U937 macrophages and survival varied between strains, *Cronobacter* persisting intracellularly for up to 96 h. In another study, most *Cronobacter* strains persisted in macrophages for 48 h (Townsend et al., 2008). These results suggest that *Cronobacter* possess virulence properties that enable them to tolerate the intracellular environment of macrophages.

Studies using both scanning and transmission electron microscopy revealed that *Cronobacter* were taken up by dendritic cells by a conventional phagocytic mechanism and internalized cells were enclosed inside membrane-bound compartments of dendritic cells. However, it was shown that *Cronobacter* could interfere with the maturation of dendritic cells and exploit them as a replication permissive ecosystem. *Cronobacter* targeted DC-SIGN to survive in myeloid dendritic cells (Mittal et al., 2009b). Emami et al. (2011) showed that dendritic cell recruitment to the intestine upon infection with *C. sakazakii* is responsible for the intestinal barrier dysfunction. Dendritic cells infected with OmpA *Cronobacter* displayed higher production of IL-10 and transforming growth factor (TGF)-β, and very low levels of proinflammatory cytokines – a phenotype associated with tolerogenic dendritic cells. Thus, *Cronobacter* could exploit IL-10- and TGF-β-producing tolerogenic dendritic cells to escape potent host immune defence mechanisms temporarily (Mittal et al., 2009b; Emami et al., 2011).

Hunter et al. (2009) demonstrated that enterocyte injury caused by *Cronobacter* appears to be dependent on the production of high levels of nitric oxide, as inhibition of inducible nitric oxide synthase (iNOS) by small interfering RNA prevented apoptosis of intestinal epithelial cells. Blocking TGF-β by a specific antibody also reduced iNOS production, and prevented monolayer leakage and apoptosis. The presence of TGF-β seems to be required for upregulation of iNOS and subsequent epithelial cell injury (Emami et al., 2011). The increased mucosal cytokine response and nitric oxide production in the absence of polymorphonuclear leukocytes and macrophages may also be responsible for an increase in mucosal injury (Emami et al., 2012).

Once inside phagocytic cells, *Cronobacter* showed an increased level of superoxide dismutase activity. Superoxide dismutases are metalloenzymes that help bacteria resist intracellular oxidative stressed environments within the polymorphonuclear leukocytes (Townsend et al., 2007b). Additionally, overexpression of outer-membrane protease Cpa (plasminogen activator) was reported following the entry of *Cronobacter* systemically. Cpa provides resistance against the bactericidal activity of serum by cleaving complement components C3 and C4b, and also activates plasminogen and inactivates α2-AP (plasmin inhibitor) (Franco et al., 2011a; Schwizer et al., 2013). Interestingly, it was reported that, of the different *Cronobacter* spp., *C. sakazakii* was the most tolerable to the killing effects of serum – a fact that might explain its strong pathogenic potential and the possession of pESA3-borne *cpa* by *C. sakazakii* strains. The role of other surface structures, such as LPS, OmpA and exopolysaccharide (capsule), which enable the pathogen to resist the bactericidal activity of serum and avoid the immune system is unknown currently (Schwizer et al., 2013).

**Virulence genes and plasmids**

Several virulence genes and plasmids were identified, and found to be specific to *Cronobacter* spp. Kothary et al. (2007) identified the gene locus of zinc-containing metalloprotease (*zpx*) – a protein that caused rounding of CHO cells in tissue culture. In addition, the presence of putative *sodA* genes might provide resistance for *Cronobacter* against intracellular macrophage oxidase and acidic conditions, and may contribute to its intracellular persistence (Townsend et al., 2007b). However, these genes and OmpA and OmpX were found in all *Cronobacter* spp., and thus cannot be responsible for the variation in pathogenicity among the different *Cronobacter* strains (Joseph et al., 2012c).

The complete genome sequence of *C. sakazakii* ATCC BAA-894 enabled Cruz et al. (2011) to compare other *Cronobacter* genome sequences with the sequence of *C. sakazakii* in their attempt to identify virulence genes. Three putative virulence genes – type III haemolysin (*hly*), siderophore-interacting protein (*sip*) and plasminogen activator (*cpa*) – were identified. Among the annotated genes inspected, Kucerova et al. (2010) also showed that the complete cation efflux system (*cusA, cusB, cusC* and *cusF*) and its regulatory gene *cusR* were present in strains associated with neonatal infections, but missing in the other strains, which may explain the fact that not all *Cronobacter* spp. are equally pathogenic and cause meningitis.
Virulence characteristics of Cronobacter

In addition, Franco et al. (2011a) showed that all Cronobacter RepFIB plasmids encode two iron acquisition systems – a siderophore-mediated iron acquisition system (iucABCD/iutA operon) and ATP-binding cassette transport-mediated iron uptake and siderophore system (eitCBAD operon) – suggesting that these plasmids are common important virulence plasmids and may also contribute to systematic survival of Cronobacter. The ability to acquire iron is crucial for most pathogens in establishing infection after entering a host cell. Franco et al. (2011b) showed that the iucABCD/iutA siderophore (cronobactin) is the only functional siderophore possessed by Cronobacter. However, Grim et al. (2013) demonstrated that cronobactin – a hydroxamate-type, aerobactin-like siderophore – was not the only iron acquisition system possessed among Cronobacter. The cronobactin locus consists of five genes homologous to biosynthetic genes iucABCD and the receptor gene iutA. Indeed, iron acquisition is considered as growth promotion as it is related to utilization of iron in milk, but as iron utilization genes were found in all Cronobacter spp. its role is still not understood (Joseph et al., 2012c). Grim et al. (2013) reported targeted in silico sequence analysis of nine Cronobacter genomes, and showed that Cronobacter shared iron acquisition systems among the seven species and also possessed iron acquisition genes encoding ferric and ferrous transporters and haem-iron extractors, as well as putative TonB-dependent iron receptors and ferric reductases. For acquisition of ferrous iron, all Cronobacter have both the Feo and Efe systems, and for transport of ferric iron, all plasmid-harbouring strains (97%) have the aerobactin-like siderophore cronobactin. All Cronobacter have the genes encoding the enterobactin-like siderophore, but this siderophore is thought not to be functional. Grim et al. (2013) also reported that in addition to receptors for cronobactin and enterobactin, all Cronobacter have five common receptors (FhuA, YncD, FoxA, FhuE and PfeA) for siderophores that are also produced by other organisms. The ferric dicitrate transport system was found specifically in a small subset of C. sakazakii and C. malonaticus strains, most of which were isolated from clinical samples, suggesting that this iron acquisition system plays a role in the virulence of Cronobacter. These studies also provided evidence that C. dublinensis and C. muytjensii have two other receptors, Fct and FcuA, for heterologous siderophores produced by plant pathogens, indicating that these receptors may give an advantage to these Cronobacter spp. to compete more successfully for iron in a plant niche. This also supports the hypothesis that Cronobacter emerged from a common ancestor that possessed a plant-associated lifestyle prior to its species-level bi-directional divergence.

Secretion systems, referred to as type IV secretion systems, that can transfer proteins and nucleoprotein complexes are considered to be important virulence factors as they were identified in C. sakazakii and C. turicensis as a plasmid-borne (pESA2/pCTU2) gene cluster (Franco et al., 2011b). In contrast, several newly identified type VI secretion systems (T6SSs) were found in the chromosomes of most Cronobacter spp. as well as on pESA3 carried by C. sakazakii, including pathogenic C. sakazakii ST4 strains (Joseph et al., 2012c). Interestingly, the T6SS was also found to be important for E. coli K1 invasion of the BBB (Joseph et al., 2012c).

Other virulence characters

Whole-genome studies of Cronobacter revealed that C. sakazakii is the only Cronobacter species that has the nanAKT gene cluster encoding utilization of exogenous sialic acid as a carbon source (Joseph et al., 2013b). Other genome-sequencing studies revealed the presence of two genomic regions (GR127 and GR129) that are involved in the utilization of sialic acid in the genome of C. sakazakii BAA-894 (Grim et al., 2013). Furthermore, Grim et al. (2013) found that 55 out of 57 strains of C. sakazakii were able to utilize sialic acid or its derivative N-acetylmuraminic acid, whilst no other Cronobacter strains were able to do this. Sialic acid is found in breast milk, infant formula, the mucin lining of the intestinal tract and is a component of the brain ganglioside complex (Siqueira Santos et al., 2013). Hence, it is possible that the ability of C. sakazakii to utilize sialic acid will enhance its pathogenicity for neonates and young infants. Cronobacter might use sialic acid to produce its exopolysaccharide (capsule) which helps it to avoid the immune system, and this behaviour is probably exacerbated in the presence of different milk sources and their products, which also contain sialic acid or its precursors. In addition, C. sakazakii sialic acid may also help in colonizing the intestinal tract via interactions with host mucins (Joseph et al., 2012c).

Inositol fermentation has been proposed recently as a marker of pathogenicity for Cronobacter based on the presence of the inositol monophosphatase gene (suhB) in some pathogenic strains. However, the inositol utilization operon GR29 was found in Cronobacter strains isolated from the environment, whilst also being absent in genomes of pathogenic strains (Grim et al., 2013). Therefore, its role in virulence is unclear at present.

Biofilm formation

Cronobacter have been reported to attach to and form biofilms on stainless steel, glass, latex, silicon, polyvinyl chloride and polycarbonate (Iversen et al., 2004; Lehner et al., 2005). Capsular polysaccharides on the bacterial cell surface play a pivotal role in biofilm formation. Colanic acid production is encoded by ESA_0115-01175, the wzABCKM gene in all Cronobacter spp. (Joseph et al., 2012c). Bacterial cells appear to attach more rapidly to hydrophobic non-polar materials such as Teflon and plastics than to hydrophilic surfaces such as glass or metals (Lehner et al., 2005). Furthermore, Cruz-Córdova et al. (2012) reported that flagella from C. sakazakii are involved in biofilm formation. In addition to flagella, two hypothetical proteins (ESA_00281 and ESA_00282) were identified as possible adhesin proteins that may contribute in biofilm formation (Cruz-Córdova et al., 2012). Flagella seem to aid Cronobacter...
cells to adhere to mammalian cells such as Caco-2 and other epithelial cells.

The ability of Cronobacter spp. to form biofilms provides protection from environmental stresses that impart resistance to cleaning and sanitizing agents (Ravishankar & Juneja, 2003; FAO/WHO, 2006). Kim et al. (2007) showed that resistance of Cronobacter spp. to disinfectants was increased when they formed biofilms compared with planktonic cells that were inoculated and dried onto the surface of stainless steel or even planktonic cells in culture. Additionally, a higher UV dose was required to kill Cronobacter growing in a biofilm than in the planktonic state (Jo et al., 2010).

Biofilm formation is of special importance in the food industry, because biofilms can act as a source of microbial contamination that might lead to spoilage of foods or contamination of food products undergoing processing (Lehner et al., 2005; Hartmann et al., 2010). Biofilms of Cronobacter formed on feeding areas and on equipment surfaces used in formula preparation are thought to have contributed to several neonatal outbreaks (Kim et al., 2006). Indeed, these observations support the increased risk of Cronobacter for formula-fed infants.

Antibiotic susceptibility and resistance

Prior to 1985, patients with Cronobacter infections were frequently treated with ampicillin, gentamicin and/or chloramphenicol. Willis & Robinson (1988) recommended the combination of gentamicin and ampicillin for the treatment of meningitis caused by Cronobacter. In contrast, Lai (2001) found that all Cronobacter isolates were uniformly resistant to ampicillin, cefazolin and extended-spectrum penicillins, whereas they were uniformly susceptible to trimethoprim/sulfamethoxazole and aminoglycosides. Recently, Al-Nabulsi et al. (2011) showed that streptomycin, gentamicin, kanamycin and ciprofloxacin are effective against both stressed and unstressed C. sakazakii cells, and thus these antibiotics might be appropriate choices for patient treatment regimes. Nevertheless, Nazarowec-White & Farber (1999) found that two Cronobacter strains out of eight were resistant to tetracycline and chloramphenicol. Kim et al. (2008) described Cronobacter strains recovered from foods that were resistant to cephalothin or ampicillin and susceptible to tetracycline. Hochel et al. (2012) found that all Cronobacter isolates varied in their susceptibility to tetracycline.

Muytjens & van der Ros-van de Repe (1986) examined Cronobacter susceptibility to 29 antimicrobial agents and found that Cronobacter were the most susceptible among other Enterobacteriaceae studied. This was supported by the finding of Stock & Wiedemann (2002) who showed that Cronobacter were repeatedly susceptible to β-lactams with no evidence for the expression of β-lactamase. In contrast, Pitout et al. (1997) demonstrated that some strains of Cronobacter produce β-lactamase at low levels. Caubilla-Barron et al. (2007) identified two Cronobacter isolates with extended-spectrum β-lactamase activity. Furthermore, Zhou et al. (2011) showed that one Cronobacter isolate from PIF produced extended-spectrum β-lactamase. According to the same study, susceptibility results showed that each isolate had different levels of resistance to β-lactam antibiotics (Zhou et al., 2011).

Although multiple antibiotic resistance (mar) operons were found in Cronobacter (Burgos & Varela, 2002), the overall level of antibiotic resistance was low compared with other food-borne pathogens and the increase of antibiotic-resistant Cronobacter could be a result of the overuse of antibiotics (Lee et al., 2012).

Environmental adaptation

Cronobacter spp. might be exposed to different environmental stresses during processing and preparation of PIF or post-infection after entering the host. The ability of Cronobacter spp. to withstand the harmful effects of these stresses is crucial for their survival, persistence and infectivity.

Heat adaptation

Some reports indicated that Cronobacter are more thermotolerant than most other bacteria belonging to the Enterobacteriaceae, whilst other studies reported that some Cronobacter isolates have no such tolerance (Nazarowec-White & Farber, 1997; Breeuwer et al., 2003; Osaili et al., 2009). The contradiction between these studies might be attributed to the growth conditions, isolate source (i.e. food or clinical) and growth phase or due to variation among the different Cronobacter strains (Arroyo et al., 2009; Walsh et al., 2011). In addition, different properties of food or formula, including low water activity and high fat content, affect thermotolerance of Cronobacter (Osaili et al., 2009). Nonetheless, adequate pasteurization conditions are sufficient to inactivate Cronobacter spp. during processing and reconstitution of PIF (Al-Nabulsi et al., 2011). Recently, an 18 kbp region containing 22 ORFs that are upregulated under heat adaptation conditions has been reported (Gajdosova et al., 2011). The major feature of the region is a cluster of conserved genes – most of them having significant homologies with known bacterial proteins involved in some type of stress response, including heat, oxidation and acid stress.

Desiccation adaptation

Cronobacter are considered more resistant to dry and osmotic stresses than other members of the Enterobacteriaceae (Feeney & Sleator, 2011). It is thought that this is probably due to the accumulation of trehalose inside the cells, which works as a protectant (Breeuwer et al., 2003). Furthermore, Álvarez-Ordóñez et al. (2014) concluded that de novo protein synthesis, DNA repair proteins and the maintenance of the structural integrity of cells are vital for the survival of Cronobacter in hyperosmotic media. Another
exploration was offered by Barron & Forsythe (2007), who showed that Cronobacter were recoverable from PIF even after 2.5 years, assuming that their extracellular polysaccharides could protect the cells against the desiccation effects. Furthermore, Feeney & Sleator (2011) bioinformatically that C. sakazakii contained multiple copies of the osmotolerance homologues ProP and OpuC, and they concluded that the osmotic stress response of C. sakazakii appears to be regulated at the transcriptional, translational and post-translational levels, with RpoS most likely functioning as the global transcriptional regulator of the osmolarity response.

Gurtler & Beuchat (2007) reported that the reduction in the viability of Cronobacter in PIF was less evident in formulas with water activity (aw) values 0.25–0.30 compared with formulas with aw = 0.43–0.50. Additionally, Cronobacter spp. can survive in infant cereals at low populations (2 c.f.u. g⁻¹) over a wide range of aw (0.30–0.83) for up to 12 months with enhanced viability at lower aw values (Lin & Beuchat, 2007). Furthermore, Dancer et al. (2009) showed that Cronobacter grown and dried in PIF survived better throughout drying than those cells grown and dried in tryptic soy broth, highlighting the role of some PIF components in the process of desiccation adaptation. Genes involved in desiccation resistance and osmotic stresses have been identified. For instance, genes encoding osmoprotectant glycine betaine and trehalose were found in all Cronobacter (Joseph et al., 2012c). Furthermore, all Cronobacter contain genes for β-carotene production, which is believed to protect bacteria against harmful oxygen radicals (Joseph et al., 2012c). Products of these genes are believed to help the bacteria to survive in dry food ingredients utilized for making infant formula preparations. Furthermore, several other genes were identified whose products could help Cronobacter to tolerate low water activity environments. The identified genes include cellulose biosynthesis operons, colonic acid exopolysaccharide, the capsular biosynthetic operon, the environmental persistence capsule and the curli GR55. The synergistic expression of these genes might provide resistance to desiccation stress (Grim et al., 2013). Using transposon mutagenesis, Álvarez-Ordóñez et al. (2014) identified genes responsible for the desiccation tolerance of Cronobacter. They found that the Cpx system, known as an envelope stress response regulator, and the sigma factors RpoN and RpoS seem to be the main signals regulating the bacterial response to hyperosmotic conditions. Furthermore, among the other identified genes, only dnaK and dnaJ, encoding two molecular chaperones, were important for C. sakazakii survival under desiccation.

Acid adaptation

Dancer et al. (2009) reported that 72 Cronobacter strains were able to grow at pH 4.5, whilst 98.6, 95.8 and 79.2% of these tested strains were able to grow at pH 4.3, 4.1 and 3.9, respectively, indicating that Cronobacter cells are more acid tolerant than most related enteric pathogens. In addition, Edelson-Mammel et al. (2006) reported that 10 out of 12 strains showed <1 log decline at pH 3.5 over a 5 h incubation at 37 °C, whilst the most acid-sensitive strain showed ~3.5 log decline. Johler et al. (2010) showed that Cronobacter strains not only survived low pH, but were also able to grow to ~10⁹ c.f.u. ml⁻¹ at pH 4.5 within 24 h. Overall, Cronobacter have a good potency to survive in acidic environments that may enable them to cope with stomach acidity. This in turn may explain the increased susceptibility of infants to infection with Cronobacter spp., where stomach acidity is not fully developed.

Conclusions

Although a great deal of research has been conducted over the past decade to understand the nature of Cronobacter spp., and to elucidate their mechanisms of pathogenicity, survival and genetics, there is still much to be revealed about their hidden traits. Future work both in vitro and in vivo will continue to uncover these properties, and will eventually lead to better control of this pathogen and minimize its infections in infants as well as the elderly and immunocompromised.

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Virkulence characteristics of *Cronobacter* species.