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Identification, assessment and management of food-related microbiological hazards: historical, fundamental and psycho-social essentials[1]

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Abstract

Microbiological risk assessment aimed at devising measures of hazard management, should take into account all perceived hazards, including those not empirically identified. It should also recognise that safety cannot be ''inspected into'' a food. Rather hazard management should be the product of intervention strategies in accordance with the approach made mandatory in the EU Directive 93/43 and the USDA FSIS Pathogen Reduction HACCP system; Final Rule. It is essential too that the inherent variability of the biological attributes affecting food safety is recognised in any risk assessment. The above strategic principles may be conceptualised as a four-step sequence, involving (i) identification and quantification of hazards; (ii) design and codification of longitudinally integrated (''holistic'') technological processes and procedures to eliminate, or control growth and metabolism of, pathogenic and toxinogenic organisms; (iii) elaboration of microbiological analytical standard operating procedures, permitting validation of ''due diligence'' or responsible care, i.e. adherence to adopted intervention strategies. This should be supported by empirically assessed reference ranges, particularly for marker organisms, while the term ''zero tolerance'' is refined throughout to tolerable safety limit; (iv) when called for, the need to address concerns arising from lay perceptions of risk which may lack scientific foundation. In relation to infectious and toxic hazards in the practical context the following general models for quantitative holistic risk assessment are presented: (i) the first order, basic lethality model; (ii) a second approximation taking into account the amount of food ingested in a given period of time; (iii) a further adjustment accounting for changes in colonization levels during storage and distribution of food commodities and the effects of these on proliferation of pathogens and toxin production by bacteria and moulds. Guidelines are provided to address: (i) unsubstantiated consumer concern over the wholesomeness of foods processed by an innovative procedure; and (ii) reluctance of small food businesses to adopt novel strategies in food safety. Progress here calls for close cooperation with behavioural scientists to ensure that investment in developing measures to contain risk deliver real benefit. © 1998 Elsevier Science B.V.

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1. The logistics of microbiological risk containment

1.1. Actors and parties involved in consumer protection through hazard control

Public Health and Agriculture Regulatory Agencies seeking support for their decisions, and also consumers and their Associations, are keen to receive information about the safety of foods as marketed and of commodities processed by improved or novel technologies (Mazur, 1992). In both instances pursuit of this goal should take into account not only safety considerations, but also the *acceptability* of such foods. This latter consideration can be of critical importance. If the public refuses to eat, i.e. buy, a food, the industry is not going to produce it and all efforts and money invested in its development are wasted. Nowhere is this better demonstrated than in the almost world-wide experience with functional and genetically modified foods (Burke, 1995). Consumer concern even extends in some measure to Modified Atmosphere packaging, deemed to be dangerous, e.g. by column writers in popular magazines, and not entirely without justification (Farber, 1991; Drosinos and Board, 1994; Hudson et al., 1994). A further striking example is to be found in the all too frequent rejection of transradiated (''irradiated'') foods, largely because the public have embraced scientifically unsubstantiated concerns about their safety (Mossel and Drake, 1990; Richardson, 1995; Crawford and Ruff, 1996). Consequently, a clear case is made for cooperation between food safety professionals and experts in the psycho-sociological sector who can contribute a professional insight into the parameters which influence the transmission and assimilation of information.

In an attempt to inform and where necessary reassure the public, it is necessary initially to convey the message that containment of microbiological food risks is attainable; but that this goal can *not possibly* be achieved by *end product testing*. This can be a difficult message to put over owing to the proven efficacy of this backward control strategy, when directed towards *chemical* food safety. The microbial association of many foods, contrary to chemical contamination, is strongly stratified and moreover in a constant state of flux as a result of dynamic competition, invalidating the approach followed in ensuring chemical food safety. Consequently, what is required to manage *microbiological* hazards is a longitudinally integrated *forward intervention* strategy (Shapton and Shapton, 1993; Ehiri and Morris, 1994; Hall, 1995), validated by product testing during its elaboration and implementation (Struijk, 1996). This scenario is termed Hazard Analysis [carried out to achieve] Control of Critical Practices (HACCP); cf. Appendix A. It may be illustrated by the model, derived from studies on the important safety assurance of ''minimally processed'', ''sous-vide'', REPFED etc. food products (Mossel and Struijk, 1991).

The European Union in 1993 enforced a Rule, EU Directive 93/43, making an Autonomous Total Quality Assurance (ATQA) strategy mandatory; cf. Table 1. The Directive places the onus of assurance, as well as monitoring, of safety on the businesses themselves, irrespective of their size (Baird-Parker, 1995; Mossel et al., 1995b,c). This regulation has taken the line of full reliance on the HACCP strategy. In instances wherein a potentially hazardous link in the ''protective chain'' can not yet be brought under control, this should not be ignored but rather be considered an issue requiring full attention and prompting urgent remediation: of critical attention points as in Appendix A. Only this strategy can be construed as complying with the ''due diligence'' obligation of the food sector.

The American Food Safety and Inspection Service has more recently, recognising the importance of microbial risk analysis (Kindred, 1996), issued a similar rule. It was initially and colloquially termed MegaReg (Hall, 1995), because of the unusually

Table 1
The autonomous total quality assurance (ATQA) maxim, aiming at ensuring safety, quality and acceptability of foods and catered meals, as promulgated by European Union Directive 93/43

Stage 1
Design of modes of elimination of all identified critical sites and practices, relying on holistic quantitative risk analysis: **HACCP**.

Stage 2
Implementation of the required intervention steps all along the production, distribution and culinary preparation line: **LISA**.
Given the actual severe microbial contamination of the farm, abattoir and estuary environments, LISA includes almost invariably a processing-for-safety step (''pathogen reduction''), *sensu* Wilson's Triad (cf. Table 2).

Stage 3
Meticulous *codification* of procedures to be followed throughout by elaboration of Good Manufacturing and Distribution Practices: **GMDPs**; including *record keeping*.

Stage 4
Upon adoption of the Codes of Good Practices, *verification* of perpetual compliance by simple, reproducible monitoring, relying on **SOPs** i.e. rigorously standardized analytical operation procedures.

Source: Mossel et al., 1995a.

large size of the Regulation ([US] Department of Agriculture, 1996). The innovative, crucial hazard-reducing element of the legislation is constituted by virtually mandatory decontamination of raw foods of mammal and avian origin, which are frequently dangerously contaminated. Consequently, the new Regulation is more appropriately designated as: Pathogen Reduction/HACCP, abbreviated to PR/HACCP (Reed and Kaplan, 1997b; Watanabe and Guerrant, 1997).

An additional, most noteworthy component of PR/HACCP is that this regulation also explicitly applies to very small establishments, defined as those, with fewer than ten employees ([US] Department of Agriculture, 1996). The latter sector, though often constituting a major contributing factor to food infections incurred in eating out (Hedberg et al., 1991; Malfa and Mossel, 1991; Synnott et al., 1993; Vugia et al., 1993; Morgan et al., 1994; Bryan et al., 1997) nonetheless marred by limited capability for the acceptance and implementation of the new approaches. Consequently, small businesses constitute a challenge for incentivation (Ehiri and Morris, 1994; Aramouni et al., 1996). It is most rewarding that the President of the US has recently acknowledged his support for a markedly enhanced level of protection of the public against all food-transmitted hazards (Marwick, 1997), hence including efforts by the smaller businesses.

1.2. Essentials

Management of microbiological hazards intrinsic to foods consists of four sequential steps, which may be summarized as follows:

1.2.1. Step 1: Targets

This phase has to rely on robust epidemiological data (Stolley and Lasky, 1995; Altekruse and Swerdlow, 1996; Fletcher et al., 1996; Bryan et al., 1997; Tweedy, 1997). It includes identification of the microbiological hazards (Altekruse and Swerdlow, 1996), estimation of their severity (Elliott, 1996; Todd and Harwig, 1996) and assessment of the risk (probability) of consumers being exposed to any of these (Mossel and Struijk, 1993a; Rose et al., 1995; Teunis et al., 1997). Mathematical models which will be discussed in the next section have been elaborated allowing such analyses to be made.

The most debated aspect of this strategy is the dose–response relationship (Black et al., 1992; Crockett et al., 1996; Fletcher et al., 1996; Medema et al., 1996). This essential attribute is expressed in the so-called Minimal Infectious Range (MIR) of pathogenic organisms to be taken into account. Full protection, which must take cognisance of that segment of the Public with a substantially diminished antimicrobial host defence, requires to be pursued. Those exhibiting deficient immunocompetence in-

clude the increasing number of elderly citizens, AIDS patients and patients recovering from surgery, as well as pregnant women and young children (Foegeding and Robert, 1996; Gerba et al., 1996; Weenk et al., 1996; Jackson et al., 1997; Ryan et al., 1997). Persons included in this category are often termed the YOPI-group of vulnerable consumers (Mossel and Struijk, 1993a).

An alternative to taking these consumers into account in the formulation of safety targets, may be a recommendation to these vulnerable individuals to avoid particular types of foods, which, whilst not entailing an unacceptable risk for the general public, might nonetheless, harm them. However, this so-called diet counselling (Reed and Kaplan, 1997a) is likely to have only limited effect. Although of proven efficacy when delivered by a physician in instances where individuals suffer from diseases like diabetes, hypercholesteraemia and irritable colon, when applied to labelling of foods, diet counselling of YOPIs is not addressed to a particular person. Such advice can not be expected to be generally followed. This is demonstrated by decades of experience with attempts to control health-compromising behaviour in the general population (Lowry et al., 1996; Neumark-Stzainer et al., 1996), e.g. aimed at dissuading people from cigarette smoking, ingestion of unpasteurized milk (Keene et al., 1997) raw and undercooked meat, fish, seafood and poultry dishes (Mossel et al., 1995a; Mouzin et al., 1997) and avoiding venereal diseases, traffic accidents, alcohol and drug addiction, and obesity. The behavioural components of the predictable lack of full success of any anticipated ''diet counselling'' of YOPIs have been identified (Mouzin et al., 1997) They include: (i) misunderstanding and hence going unheeded of the health message; (ii) the advice even when understood not staying in vulnerable consumers' minds; (iii) unwillingness to change lifestyle habits; (iv) flat rejection, because resenting being discriminated against.

A more cautious approach has already been suggested by some experts, as illustrated by Appendix B. This calls for us to seek the protection of the *entire* citizenry, by the adoption of extremely low MIRs, i.e. of the order 1–10 (Laidley et al., 1974; D'Aoust and Pivnik, 1976; Lipson, 1976; Gustavsen and Breen, 1984; Willshaw et al., 1994; DuPont et al., 1995; Lehmacher et al., 1995; Parry et al., 1995; Bolton et al., 1996; Crockett et al., 1996; Hennessy et al., 1996; Hitchins, 1996).

1.2.2. Step 2: Intervention

1.2.2.1. Principles

Containment of identified and quantified hazards has to rely on design, codification and implementation of technological interventions in critical industrial *processes*, in distribution and retail *procedures*, and in catering and domestic culinary *practices* to eliminate pathogens through risk management in accordance with step 1–HACCP as introduced by Bauman (1974). To be effective, safety assurance must to be holistic (cf. Appendix A), i.e. extended ''from production of raw materials to the consumers' plate'' (Bauman, 1995; Roberts et al., 1995). The mnemonic LISA = Longitudinally Integrated Safety Assurance, has been suggested for this strategy (Mossel, 1991; Jakobsen and Lillie, 1992; Altekruse et al., 1993). The classic example of LISA *avant la lettre*, is the Wilson Triad (Wilson, 1933, 1935), summarized in Table 2. Assuming correct and meticulous application it rendered pasteurized milk and dairy products (Mossel, 1983) as well as egg products (Whiting and Buchanan, 1997), previously notorious sources of food-transmitted enteritis, entirely safe. However, any hiatuses in the Triad are likely to result in catastrophic events. This applies particularly to recontamination and recolonization after per se adequate, e.g. heat processing for safety. From such occasional breakdowns of the protective net resulted the massive Chicago milk outbreak (Ryan et al., 1987) and similar incidents caused by liquid dairy products (Upton and Coia, 1994; Dalton et al., 1997), the listeriosis explosion associated with soft cheese in California (Linnan et al., 1988) and the Minnesota ice-cream disaster (Hennessy et al., 1996).

Three ecologically distinct events are to be countered through the application of the HACCP-strategy, viz. contamination, colonization and microbial metabolism (Mossel and Struijk, 1992).

1.2.2.2. Contamination

Introduction of contaminated materials and recontamination of processed product has to be avoided by three different intervention measures. These include the use of raw materials of the best achiev-

Table 2
The 'Wilson Triad' approach to processing foods for safety

1.
Elimination of organisms, negatively affecting food safety at a sub-sterilization lethality level, as dictated by risk analysis, by two types of measures of intervention:
* keeping the initial colonization of raw materials to a minimum, with respect to both pathogens and to bacteria producing enterotoxins, pressor amines and endotoxins, whose adverse health effects can not, as a rule be contained by the subsequent decontamination treatment.
* adjusting microbial lethality of processing to a level ensuring a wholesome final product, though compatible with sparing nutritive value and sensory attributes, by relying on preventive measures ensuring paucimicrobial raw materials; vide supra.

2.
Avoiding recontamination of treated commodities which would not only nullify the effect of the microbial reduction process, referred to under 1, but in addition constitute an increased hazard in products, which, as a result of the decontamination step, would be devoid of most of the competing organisms which in raw products may keep pathogens under control.
This should rely on validated measures of prevention, including either processing after hermetic packaging, or else aseptic packaging of the treated commodity.

3.
When commodities are colonization-prone, i.e. lack intrinsic antimicrobial protection,ensuring *distribution and storage* of the final product under *conditions arresting* or at least markedly *delaying* the *proliferation* of the *infinitesimally low* numbers of pertinent viable organisms:
* *surviving* processing step 1;
* *sporadically contaminating* the final product, despite all attainable, maintainable and affordable precautions taken, during aseptic packaging, or, similarly, aspired into packaged treated product.

Source: Mossel and Struijk, 1993b.

able microbiological quality, introduction of expert environmental hygiene programmes and effective disinfection regimes.

With respect to raw materials there is a need, originating from high levels of environmental pollution, to decontaminate virtually all raw products of animal origin and a number of vegetable origin (cf. Table 3), before shipping these to the food and catering industries (Kayser and Mossel, 1984; van Netten et al., 1995; Hall, 1995). This intervention relating to critical attention points (Appendix A) has prompted a crucial element of the new legislation in the US referred to above, i.e. legally required surface decontamination of fresh meat of mammal and avian origin (Reed and Kaplan, 1997b).

In the area of food plant disinfection a particular hazard is presented by biofilms which readily develop on and in inadequately disinfected processing and transportation equipment (Costerton et al., 1995; Lappin-Scott and Costerton, 1995; Wimpenny and Colasanti, 1997; Zottola, 1997). The glycocalix structure of biofilms impedes the penetration of

Table 3
Examples of products of vegetable origin involved in outbreaks of intestinal infectious disease in humans

	Major pathogens transmitted
Apple juice	*E.coli* O157:H7; *Cryptosporidium parvum*
Cantaloupe	*E.coli* O157:H7; *Salm. poona*
Chocolate	*Salm. eastbourne, napoli, nima, typhimurium*
Coconut	*Salm. paratyphi* B, *typhi* and a broad range of enteritis strains
Fruits (soft)	*Cryptosporidium parvum,* hepatitis A virus
Peanuts	Exotic serotypes of *Salmonella*
Salad vegetables	*Listeria monocytogenes, Shigella sonnei*
Soya flour	*Salm. tennessee*
Spices	*Salm. oranienburg, weltevreden*
Tomatoes	*Salm. javana, montevideo*
Vegetable sprouts	*B. cereus, Salm. saint- paul*
Watermelon	*Salm. javana, Shig. sonnei*

Source: Mossel and Struijk, 1997.

bactericidal agents and, moreover, neutralizes a major part of many of such agents. Consequently, customarily used preparations lose the greater part of their potency as determined by in vitro testing (LeChevallier et al., 1988; Holah et al., 1990; Dhaliwal et al., 1992; Mosteller and Bishop, 1993). Negligence with respect to this molecular microbiological phenomenon has often resulted in underestimation of major hazards for product safety.

1.2.2.3. Microbial proliferation and metabolism

These occurrences are to be controlled by one or a combination of the following two interventions (Farber and Hughes, 1995): (i) where this is attainable without adverse health or organoleptic effects, intrinsic measures, i.e. compositional modification resulting in colonization containment, or (ii) in the case of unavoidably growth-supporting (''colonization-prone'') foods; mandatory strict management of the storage temperature/time integral throughout, i.e. during manufacture and up to the moment the food is ingested.

Adequate monitoring of temperature control, is well within reach (Taoukis et al., 1991). However, practice demonstrates that safety management in this area does not, in all instances, rely on measurement of *food* temperatures. As growth and metabolism of micro-organisms occur in or at the surface of foods, determining the temperature profile at those sites is imperative, unless food engineering strategies are tailored to measuring air temperatures (Mossel et al., 1995a).

1.2.3. Step 3: Validation

Verification of punctual and perpetual adherence to HACCP-based intervention strategies calls for the elaboration of standard operating procedures (SOPs; Struijk, 1996), which, in agreement with the longitudinal integration concept, should be applied throughout, i.e. to food plant operations, food/machinery interfaces, line samples and foods as marketed and ingested.

A minimal number of microbiological criteria should be used, mostly relying on marker organisms; vide infra (Mossel, 1982; Rodríguez-Alvarez et al., 1995). Methods to be used in assessing compliance with such criteria are to be as simple and rapid as possible, though as reliable as can be achieved to avoid conflicting results in different laboratories.

A crucial element of SOPs for use in the verification of adequate hazard control must be including, in the detection or enumeration of populations which survive elimination or growth inhibition, cells which have incurred sublethal injury; whether of cellular or metabolic nature. This is ipso facto the rule rather than the exception in the paucimicrobial association of foods processed for safety (Stewart, 1997). If effective attempts to recuperate such stressed cells by deliberate resuscitation treatments are ignored, the cfu numbers of surviving target organisms can be underestimated by up to the order of 6 log cycles (Mackey and Derrick, 1984). Consequently, Λ (lethality, cf. Appendix A)-values will be overestimated by the same order of magnitude (Struijk, 1996). This omission would therefore completely invalidate any estimate of hazard elimination or reduction.

When selecting SOPs, the designation ''rapid'' is often used lightly in attempts to suggest that validation of hazard containment can be achieved within a matter of minutes. This policy has, not infrequently, resulted in the ''excitement followed by disappointment'' syndrome (Mossel et al., 1994) where novel methodologies are initially enthusiastically embraced. In attempting to substitute reason for ritual in this essential area of verification of HACCP, the quantification in Appendix C may constitute a starting point for both users and industrial suppliers of innovative monitoring equipment.

Reference Ranges in recognition of their intrinsic breadth, and hence of the Three-Class-Acceptance-Type (Bray et al., 1973) should always be included. These have to be rational, i.e. required, attainable, maintainable and affordable (Mossel, 1995), which demands their assessment by surveys on lines previously verified as being in strict compliance with Good Manufacturing and Distribution Practices (GMDPs); cf. Table 1.

In the elaboration of microbiological target or reference values for foods, much debate has centred on the use of the terms ''zero'' or ''nil'' in relation to tolerance (Farber et al., 1996; Hitchins, 1996). The practical meaning of this designation is nonetheless clear. It conveys that if n samples of x grams of a food are examined for the target organism by prescribed methodology, that organism will not be isolated. Depending on the vulnerability of the consumers assumed to ingest the product (vide supra)

n and *x* vary from 1–60 and 1–25, respectively. To accommodate this quantification, Dr. G. Kleter, The Netherlands Ministry of Health, Welfare and Sports (Kleter, 1982), has suggested the introduction of the term ''tolerable safety limit'' or TSL, consonant with current terminology in food toxicology, where it denotes reasonable certainty that the level will cause no harm. The term TSL also avoids the use of the adjective ''acceptable'', a term hardly applicable to food-borne pathogens. It is relevant to note that, independently, the most recent revision of US Regulations also embodies this principle (Anon., 1996).

The EU-legislation referred to above requires food businesses by implication to monitor their operations. On the other hand, in addition to the industry's own accountability for the operations, PR/HACCP in the US explicitly entrusts the responsibility for verification of the efficacy of Hazard Control to the businesses (Reed and Kaplan, 1997c). This includes education of staff, expert monitoring and record-keeping (Mossel et al., 1995b). Well-trained laboratory staff, periodically appraised, are supposed to spend most of their time in quality and safety assurance. Thus more and more ''pass''-results will be obtained, which will provide reassurance to the Company's executive levels. In addition this releases valuable time for steady improvement of operations and risk-management-supporting research. The latter contributions to safety assurance comply fully with general requirements, such as ''due diligence'' or ''responsible care''.

1.2.4. Step 4: Consumer reassurance

Consumer concerns over the safety of novel risk-eliminating technologies and about newly identified (''emerging'') pathogens (vide infra) should be addressed promptly, honestly, and expertly.

Scientifically unjustified anxiety is often fuelled by irresponsible media sound bytes (Khan, 1996; Frost et al., 1997). Such situations should be redressed through timely interventions by informed professionals. This might involve issuing reports produced by *groups* of acknowledged, independent Public Health specialists who would, ideally, have developed in advance a consensus view. Failure to adopt such a strategy may lead to statements by individuals concerning risk, producing pessimism and despair, or else optimistic dismissal of the perceived danger, resulting in consumer scepticism. Mathematical modelling, to be dealt with in the next section, allows objective detachment. As documented in step 1 (Section 1.2.1), this will rely on the use of confidence *ranges* rather than point values; and this should be emphasized in all reassurance efforts.

In all fairness, beneficial effects of sound media reports should also be acknowledged. These will often result in the public becoming aware of hazards with which they were previously not too familiar. More general expression of concerns of this type may prompt pressure to be exerted on Governments to take effective steps to ensure adequate measures of control.

2. Mathematical principles of assessment and limitation of microbiological risks and validation of the latter

2.1. Validity of various elimination models

2.1.1. Basic lethality model

The first attempts to assess and control the microbiological hazard entailed by the ingestion of foods processed for safety were made by Esty and Meyer (1922). These workers were pursuing the production of safe canned foods of $pH > 4.5$, relying on the ''elimination'' of *Clostridium botulinum*; cf. Appendix A. In their basic model Esty and Meyer assumed a log linear order of death of spores of *Clostridium botulinum*. Gillespy (1951) later reassessed the risk of botulism transmitted by heat-processed (''appertized''), fully colonization-prone foods. These investigations were based on the lethality concept (Yawger, 1978; van Netten et al., 1995; Liu et al., 1996), where lethality (Λ) is defined as $\log N_0/N_f$, N_0 being the initial cfu and N_f the cfu of the target organism after the bactericidal treatment. Ingram and Roberts (1971) adapted the lethality concept to the heat treatment of foods with intrinsic colonization-resistance, viz. canned cured meats.

A similar probabilistic approach was applied to the elimination of enteric, non-sporing pathogens from milk and dairy products by pasteurization (Daoust et al., 1961; Read et al., 1961, 1968). Depending on the severity of the hazard presented by the pathogen and the possibilities for recolonization of the treated

foods under the customary conditions of storage, lethality (Λ)-values between 12 and 5 decimal reductions were considered to afford adequate consumer protection (Peck and Fernandez, 1995; Faith et al., 1997). Non-linear survival curves identified later (Ng et al., 1969; Cerf, 1977; Ramaswamy et al., 1989; Kirby and Davies, 1990; Bhaduri et al., 1991; Fujikawa and Itoh, 1996; Humpheson et al., 1996) have since been taken into account in risk assessment; cf. Fig. 1 (Mossel, 1975).

Nonetheless, any point value for lethality as a ''pass criterion'', as introduced by Esty and Meyer in their basic model, is not at all decisive in hazard analysis (Peeler and Bunning, 1994, 1996; Riemann and Cliver, 1996). The determinant in these instances is the level of exposure of the most vulnerable consumer segment to a given pathogen. This depends on the final level of the pathogen in the food as ingested. Even if Λ is relatively small, the N_f-level attained can afford sufficient consumer protection, provided N_0 is conveniently low (Palumbo et al., 1996). This can be pursued by careful selection and hygienic handling of raw materials; it always pays to strive after low initial counts in order to achieve the lowest possible lethal treatment, thus sparing nutritive value, sensory quality, and cost.

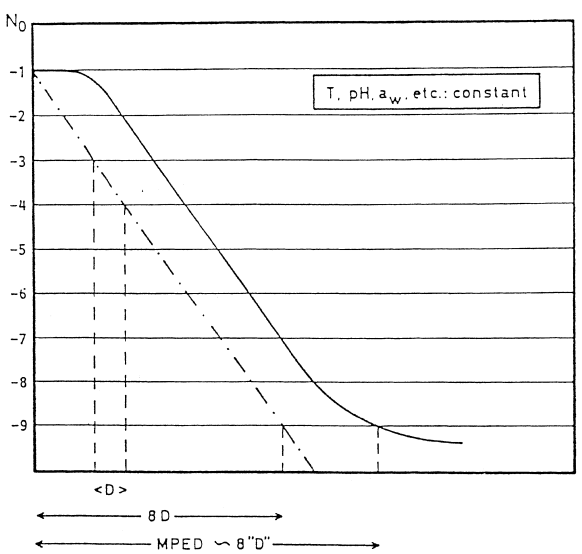

Fig. 1. Linear versus sigmoid survival curves, illustrating how lethality (Λ)-values are computed. D = decimal reduction time; MPED = most-probable effective dose; N_0 = initial count (cfu g^{-1} or ml^{-1}).

2.1.2. Second-order worst case approach

A crucial refinement of the basic lethality model takes into account the amount of potentially hazardous foods ingested by the consumer per unit of time (Mossel and Drion, 1979a,b; Hitchins, 1995; Crockett et al., 1996). The parameter Q was introduced for this purpose. This is defined as the probability that, at no time in a given period, a member of a given population will be exposed to numbers of infective units of pathogens transmitted by foods equal to, or exceeding, the minimal infectious range (MIR) of a given organism. Q depends on (i) the average number of infective units of a particular pathogen in each portion of food consumed; and (ii) the number of portions eaten by the whole population in a given period of time. Assuming that the pathogens concerned are randomly distributed throughout the food, if N_f infective units occur per portion of food at the time of consumption, the probability that one portion of food is not contaminated is $\exp(-N_f)$. If V equals the size of the population at risk and I equals the number of portions eaten by one person in one year, $Q = \exp(-N_f VI)$, and hence $N_f = -(VI)^{-1}\ln Q$ (Mossel and Drion, 1979b).

The above assumption of their random distribution is invalidated by the marked stratification of target organisms in virtually all types of food (Rishbeth, 1947; Turner and Campbell, 1962; Jarding, 1966; Juffs, 1970; Ray et al., 1971; Reyrolle and Letellier, 1979; Habraken et al., 1986; Gale, 1996). This is illustrated by Fig. 2, which represents the phantom distribution of Enterobacteriaceae, which is relatively homogeneous, versus that of *E. coli* and a *Salmonella* spp. in a lot of dried foods, and by Fig. 3 summarizing the results of a survey of the distribution of Enterobacteriaceae in a dried feed (van Schothorst et al., 1966). It is difficult, if not impossible, to develop mathematical models allowing these situations of extreme stratification to be dealt with (Foster, 1971). The best that can be done is to apply the increment approach, although this was elaborated for variable sampling and not for attribute sampling which applies to most situations in hazard containment (Lamé and Defize, 1993).

2.1.3. Ecological considerations: third order approximation

Levels of pathogens in food seldom remain constant, but increase or decrease during storage and

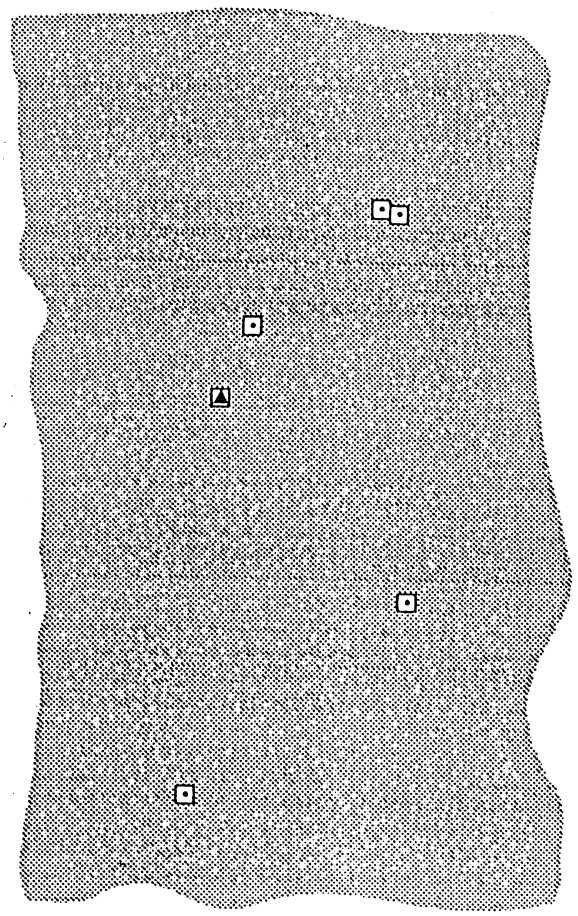

Fig. 2. Phantom print of the results of scanning an adequate area of an, in essence paucimicrobial, specific pathogen free (SPF), dried-food universe for Enterobacteriaceae as indicator (white spots), *E. coli*, both as indicator and as index organism for enterovirulent pathotypes of that species (⊡), and *Salmonella* spp. (▲). Scale: a surface of 0.2×0.2 cm corresponds to the base of mass of 10 gram of food.

Hence, titers very approximate: *Salmonella* 1 cfu/5kg, *E. coli* 1/1kg, Enterobacteriaceae $\leq 1/10$g.

distribution, dependent on intrinsic, extrinsic and implicit determinants of microbial proliferation (Mossel and Struijk, 1992; Peeler and Bunning, 1994; Holzapfel et al., 1995; Cassin et al., 1996; Muriana, 1996; Townes et al., 1996; Notermans et al., 1997; Wang et al., 1997). This calls for effective control measures to be implemented, wherein at least three ecologically determined classes of foods, summarized in Table 4, have to be distinguished. The marked stratification of colonization of foods is further compounded, in the ecological groups 1 and 2, by topographical factors. Micro-organisms close to the coldest area in refrigerated storage will grow much more slowly than those more remote from the cooling surface or air flow.

When pursuing an estimation and containment of the risk of food-transmitted infections and intoxinations, a further ecological determinant of major importance is whether or not the food or meal under review is thoroughly heated before its ingestion (Walls and Scott, 1997). Effective culinary heat treatment is, as a rule, defined as equivalent to a time/temperature exposure customary in milk pasteurization, and other products with $pH \geq 6.5$ and $a_w \geq 0.97$. This amounts to heating to such an extent, that the food's coldest spot reaches a temperature of at least 72°C for a short while (Mossel and Struijk, 1991). Consequently, a second ecology-based classification of foods is required in risk assessment. It is presented in Table 5. Clearly, such a thermal treatment will only ''eliminate'', i.e. reduce to values below TSLs (cf. Appendix A), non-sporing pathogenic bacteria, but not consistently all enteric viruses nor at all, prions (Taylor et al., 1994, 1996), staphylococcal, enterotoxins or pressor amines.

2.1.4. Dose–response functions

The infective potential expressed as MIR depends upon a variety of factors in addition to the attributes of the pathogenic organism itself (Mossel and Struijk, 1993a). As documented above, different *subjects* react in a quite diverging manner to a given challenge dose, depending on their age, general state of health, gastric function, nutritional status and whether or not exposed to stress. On the other hand, a social support network might reinforce the immune system and thereby decrease vulnerability.

In addition, in a *given* individual the MIR for an organism may vary considerably, with: (i) the vehicle in which the organism is ingested; (ii) whether the food is eaten on an empty stomach; and (iii) any other pathogenic organism, e.g. a virus or parasite being absorbed simultaneously with the pathogen under study – the phenomenon termed coinfection (Sutmoller et al., 1982; Schwartz et al., 1989; Pazzaglia et al., 1991; Albrecht and Sobottka, 1997; Layton et al., 1997; Smith et al., 1997).

From the above it follows that, particularly with respect to human dose response functions at low exposure levels, i.e. the order of the MIR, it is mandatory to abandon the assumption of a *constant*

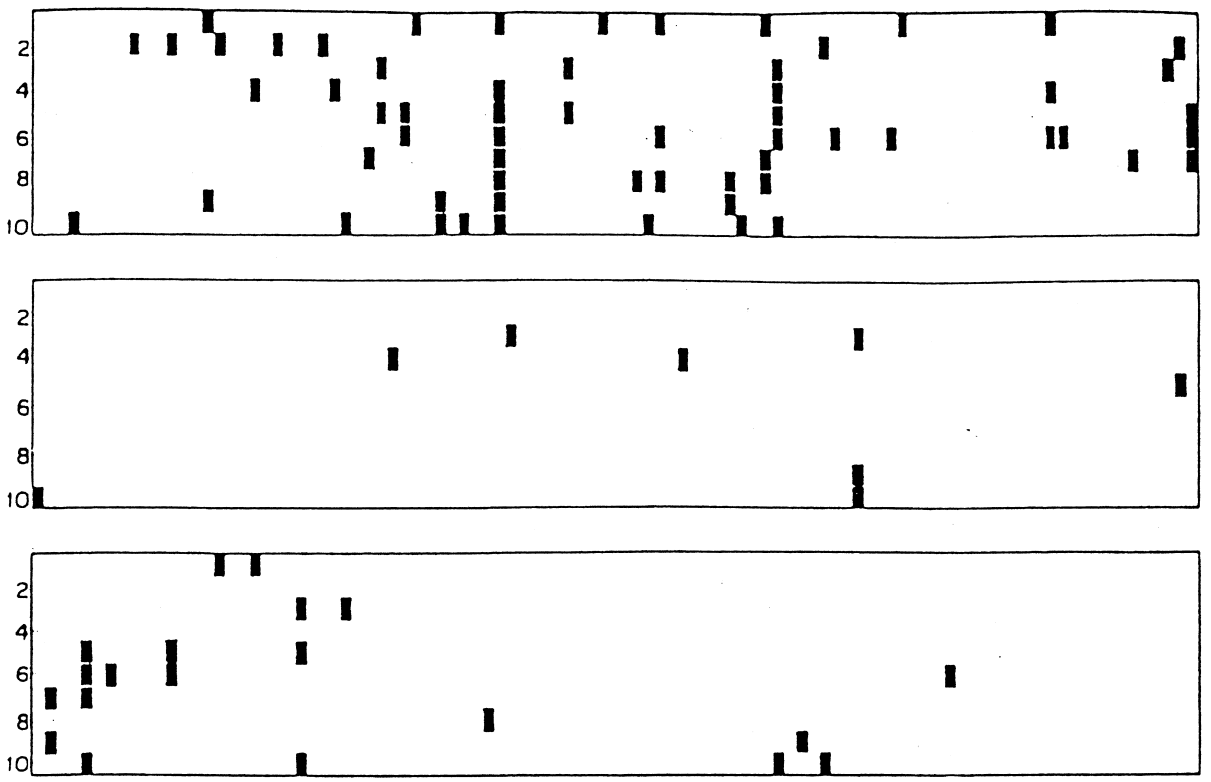

Fig. 3. Analytical impact of the stratification of the distribution of micro-organisms in three consignments of dried feeds. Black squares represent aliquots found positive for a target organism if the total consignment had been examined for that purpose; white areas were found negative for the target organism. (Source: van Schothorst et al., 1966).

Table 4
Ecological classification of foods based on intrinsic colonization resistance

Risk group 1:	commodities offering ample opportunities for microbial proliferation after processing, e.g. pasteurized milk.
Risk group 2:	foods with certain, although limited, intrinsic antimicrobial properties, e.g. cured meat products.
Risk group 3:	products in which the possibilities for microbial proliferation are remote, including foods with a reduced a_w, low pH and implicit antimicrobial protection, such as fermented sausage. In such products, prepared according to Good Manufacturing and Distribution Practices (GMDPs), growth of any surviving pathogenic bacteria is only possible as a result of dramatic changes in the intrinsic antimicrobial attributes.

probability of initiation of infection by a given organism. That supposition should be superseded by a model allowing for this probability to be described by a distribution pattern like the β-Poisson model (Haas, 1983; Haas et al., 1997). This does not, however, greatly complicate the assessment of N_f-values.

2.2. Use of index marker organisms to estimate the elimination of pathogens by processing for safety, sensu Appendix A

2.2.1. Rationale

The estimation of the lethality of processing required to attain tolerable N_f values, as in Table 6,

Table 5
Classification of the major potentially hazardous foods in risk categories determined by being exposed or not to culinary heat treatment, resulting in the elimination of non- sporing bacteria (CHE)

Class I products: invariably ingested without CHE
Pasteurized milk, fermented milks, cream-filled pastry, soft cheeses, bavaroises, ice-cream, fish mousses
Cooked and fermented meat products: sausages, hams, patés, etc.
Carpacios, pickled fish products, ''tartar'' meats
Salad vegetables, breakfast cereals
Class II products: as a rule ingested without CHE, though Health Authorities discourage this practice
Oysters, raw fish dishes, filet Américain, raw egg dishes
Class III products: always exposed to CHE
(Mechanically deboned) meat and poultry, fish, crustaceans, eggs
Refrigerated pasteurized meals of extended durability (''sous vide'' products)
Pizzas, quiches, etc.

Table 6
Acceptable final levels of contamination (N_f – per *portion eaten*) of foods processed-for-safety

Lowest value of MIR	Population at risk ($\times 10^6$)	
	15	250
1	3.4×10^{-12}	2.1×10^{-13}
10	3.3×10^{-1}	2.5×10^{-1}
100	4.6×10	4.4×10
1000	7.9×10^{2}	7.8×10^{2}

Source: Mossel and Drion, 1979b.
Note: Level of consumer protection $Q_{72} = 0.99$, corresponding to exposure of 72% of the population not exceeding once in about 100 years, when eating one portion daily.

following the procedure described in the previous section, calls for the *availability* of N_0 values and their spread, or alternatively their *determination* by surveys. Even for the extensively studied genus *Salmonella*, relatively few initial contamination ranges have been published, while their assessment is rather cumbersome due to the low figures, calling for MPN methodology, with the attendant problem of broad confidence intervals irrespective of analytical effort. For other enteric pathogens, virtually no data are available and, e.g., in the case of *Shigella* spp., sound quantitative methodology is lacking (Armstrong, 1954; Fishbein et al., 1972; Iveson, 1973; Price, 1976; Mehlman et al., 1985; Smith and Dell, 1990; June et al., 1993). Hence, use is made of so-called index organisms. Bacteria or phages chosen for this purpose must be physiologically and ecologically similar to the target pathogens, though much more abundant in raw foods and hence more conveniently and reliably detectable than the pathogenic agents whose occurrence they are supposed to indicate (Gillespie, 1963; Mossel, 1982; Craun et al., 1997). For these reasons marker organisms are also termed model bacteria or phages (Havelaar et al., 1986; Maillard, 1996).

Index organisms should not be confused with a different class of markers, viz. indicator organisms; cf. Table 7. Indicators are used to assess the performance of processing for safety i.e. meticulous adherence to the Wilson Triad, introduced in Table 2. Detection of suitably chosen indicator organisms at levels exceeding the low values attainable and maintainable by GMDPs (cf. Table 1) points to a process being out of control and calls for measures of rectification to be taken without delay. Acceptable levels of indicator organisms therefore represent ''normality'', whereas excess numbers of cfu reveal divergence from normality – as in the case of the

Table 7
Rationale for the application of two *distinct* classes of marker organisms in the microbiological monitoring of foods with the purpose of validating adequate processing-for-safety (Ingram, 1977)

Definition of marker organisms
Marker organisms are defined as types of bacteria whose response in foods processed-for-safety reflects the microbicidal or microbistatic goals of the treatment process. Boundary tests for appropriately selected markers may consequently supplement, or eventually substitute, direct searches for food-transmitted pathogens in commodities processed-for-safety. Premature acceptance of markers could, however, result in misleading interpretation of food safety data. Hence laboratory experiments should always be validated using industrial conditions.

Classification of marker organisms
When considering the use of marker organisms, it is necessary to distinguish between *index* organisms and *indicator* organisms.
Index organisms may be defined as those whose detection at certain levels implies the potential presence of physiologically, but particularly *ecologically* related *pathogens*; the latter occurring at very much lower concentrations than the index organisms in the raw material used for processing.
Indicator organisms are those whose detection in pre-determined numbers suggests a *failure of a process*, aiming at decontamination or improving shelf life.

Inappropriate use of marker organisms
In the following instances specific *pathogens*, not marker organisms must represent the ultimate target organisms for testing:
(1) epidemiological investigations;
(2) the study of health risks in predictive microbiology; and
(3) when it is not yet certain that a negative result of a particular boundary test for an index organism is sufficiently sensitive to point to the limitation of a pathogen at or below the tolerable safety limit (TSL).

Quantification
The requirement for quantitatively defining *indicator* organisms is implicit in the expression of criteria for these markers: Acceptable Quality Levels (AQLs). Such numerical limits are determined by surveys on products manufactured, stored and distributed under conditions complying with validated, expertly elaborated GMDPs.
Quantification is of no less importance in the use of *index* marker organisms, where it is expressed as Minimal Marker Ranges of concern (MMRs), which are related to the pathogens' TSLs. MMRs can be derived from empirically assessed data banks of food specific determinants called *epsilon* (ϵ) factors. Epsilon factors are the reciprocals of the abundance, defined as the proportion of the target pathogen within the index group. For example, if, in a particular product, 10 cfu per gram of the pathogen within a population of 10^4 Enterobactericeae are found, the ϵ-factor will be $10^4/10 = 10^3$. Then, if the TSL for the target pathogenis amounts to $< 10^{-4}$ per gram, the MMR for the index in the commodity under review will be 10^{-1} per gram.

A pitfall to be avoided in the use of marker index organisms
Failure to detect a particular *index* organism, such as *Enterococcus* spp., at a certain level may provide some assurance that pathogens, originating from the same niche and having similar resistance to adverse extrinsic and intrinsic conditions, particularly certain enteric viruses, are likely to be absent in predetermined quantities of the food product being tested. However, a positive result for the index organism should not be interpreted as a demonstration that the *target* virus is present in levels exceeding its TSL.

Hierarchy of indicator markers
The significance of negative results in semi-quantitative tests for indicator organisms increases in the following order of ranking, according to the relative resistance to inhibitory and lethal influences:
1. Gram-negative non-fermenters[a]
2. Gram-negative fermenters[b]
3. Gram-positive bacteria[c]
4. Listeriform bacteria
5. Staphylococci
6. *Staphylococcus aureus*
7. *Listeria monocytogenes*
8. The most robust *Enterococcus* spp.

Exceptions to the rule may occur in specific ecological situations.

[a] The genera *Acinetobacter*, *Brevundimonas*, *Burkholderia*, *Comamonas*, *Flavobacter*, *Moraxella*, *Pseudomonas*, *Psychrobacter*, *Shewanella* and *Sphingomonas*.
[b] The groups *Aeromonas* and Enterobacteriaceae and non strictly halophilic *Vibrio* spp.
[c] Most of the species of the genera *Carnobacterium*, *Lactobacillus*, *Lactococcus*, *Micrococcus*, *Staphylococcus* and *Streptococcus*.

chemical or biochemical markers of clinical management of disease, which are determined by surveys on healthy subjects (Amador, 1975; Gräsbeck and Alström, 1981; Silver, 1984; Oesterling, 1993; de Winter et al., 1996).

2.2.2. Reliance on ecological determinants or ϵ-factors

Ecological determinants are defined as the proportion between cfus of an individual marker or a group of markers, and cfus of a target organism (Drion and Mossel, 1977). Hence an ϵ-factor equals the reciprocal of the relative abundance – or rather scarcity! – of the target organism within the marker group; cf. Table 7 and Fig. 2. Numerical ϵ-values vary widely with ecological attributes of the niches and the organisms to which they apply; ranges span between 1 and 10^7.

Biotic parameters affecting the magnitude of every individual ϵ-factor include the types of organisms constituting both the markers and the target. As an example, $\epsilon_{\text{Enterobacteriaceae}/\textit{Salmonella}}$ will greatly exceed those of $\epsilon_{\text{Enterobacteriaceae}/\textit{E. coli}}$. The abiotic determinants of ϵ-factors invariably include the intrinsic growth-limiting factors characteristic for a food product and its mode of processing. Commodities exposed to abundant faecal contamination and low colonization resistance (Table 4), like fresh chicken, exhibit a different microflora composition in comparison to e.g. roller-dried cereal flakes, sparsely contaminated with non-sporing bacteria to begin with, subsequently heat-decontaminated and, in addition, colonization resistant. Accordingly the $\epsilon_{\text{Enterobacteriaceae}/\textit{E. coli}}$ is of the order of 10 in fresh chicken skin (Brewer et al., 1995), but exceeds 10^4 in specific pathogen-free, dried infant formulae (Weenk et al., 1996).

The ϵ-concept was, historically, first applied to members of the taxon Enterobacteriaceae. It has since successfully also been used in the assessment of the sanitary condition with respect to mesophilic, predominantly proteolytic (non-saccharolytic) members of the genus *Clostridium* (Weenk et al., 1995), where it could render services in tracking, besides *Clostridium botulinum* and *Cl. perfringens*, non-toxinogenic *Clostridium* spp., emerging as pathogens as a consequence of the transfer of botulinum toxin genes (Meng et al., 1997). Similarly the $\epsilon_{\textit{Enterococcus}\ \text{spp.}/\textit{Listeria monocytogenes}}$ could be of value in studies on the validation of processing for safety of naturally contaminated food raw materials (Ingham and Tautorius, 1991). This includes an estimation of the size and significance of post-process recontamination, a phenomenon frequently causative in foodborne outbreaks as emphasized before (Mossel et al., 1995a; Hennessy et al., 1996; Dalton et al., 1997).

As implied by its definition, the use of ϵ-factors for index organisms still calls for the determination of approximate levels of the target pathogens. It is sufficient, however, to ascertain presence or absence, an exercise which consumes much less effort than MPN assessments. Estimation of a total of i isolations made from r repeat tests applied to a grammes samples, whereas none or virtually none are isolated from r aliquots of 0.1 a grammes, constitutes sufficient baseline information. An additional essential advantage of the use of ϵ-factors is that in daily monitoring practice the simple enumeration of the index organisms provides adequate information to estimate the N_0 range for the pathogens; cf. Table 8, steps 1–3.

2.2.3. Other applications of index organisms

Reflecting the situation which obtains with respect to enteric pathogens, an extreme scarcity of reliable N_0-data for *Cl. botulinum* in food products to be appertized complicates risk assessment in this area. This applies particularly to minor components of canned foods of vegetable origin (Smelt and Mossel, 1982). Hence, a *Cl. sporogenes* strain, whose spores display a markedly higher intrinsic thermal resistance at pH = 6 in the temperature range 100–120°C than those of any toxotype of *Cl. botulinum*, has been selected as target organism in appertized foods (Smelt and Mossel, 1982). The extra margin of safety introduced by this approach conforms to the worst case philosophy introduced previously in Appendix A. It is most appropriate here, where erring on the side of caution is essential.

In all examples dealt with above, once both N_0 as well as N_f data are known, the required lethalities can be calculated from the previously presented formula $\Lambda = \log N_0/N_f$, as in Table 8, steps 4 and 5. These lethality levels require, subsequently, to be ''translated'', in close cooperation with food-processing specialists, into processing parameters. When the processed food belongs to Risk group 1 or 2, defined in Table 4, the increase of the cfus of the in-

Table 8
Matrix for providing guidance with respect to required processing-for-safety assuming homogeneous distribution of the target pathogen

(1) A survey on the distribution of index organisms (Ix) in a particular commodity provides spread between the minimal value ${}_{m}N_0^{Ix}$ and the maximum ${}_{M}N_0^{Ix}$ with, for example, 95th percentile* $= \phi_{Ix}$ (cfu g^{-1}).
(2) A survey of ϵ-factors (cfu index/cfu pathogen) in that particular commodity provides spread between the minimal value ${}_{m}\epsilon$ and the maximum ${}_{M}\epsilon$ with 5th percentile* ϕ_{ϵ}.
(3) This allows calculation of probable initial level (cfu g^{-1}) of the target pathogen, N_0^P, i.e. from $N_0^P = \phi_{\epsilon}^{-1} \cdot \phi_{Ix}$.
(4) Assessment of process lethality, Λ, leads to spread between minimum and maximum values Λ_m and Λ_M, with 95th percentile* at ϕ_{Λ}, equalling n overall decimal reductions.
(5) Consequently the subfinal level of pathogen, i.e. in processed product immediately after processing, N_{sf}^P, is calculated as $N_{sf}^P = \phi_{\Lambda} \cdot N_0^P = \phi_{\Lambda} \cdot \phi_{\epsilon}^{-1} \cdot \phi^{Ix}$.
(6) Ecological line studies on the fate of the pathogen during distribution results in 95% probability of change equalling Δ_{ϕ}, i.e. either increase or decline, in cfu g^{-1}.
(7) The pathogen level ultimately reaching the consumer then amounts to $N_f^P = \Delta_{\phi}$. $N_{sf}^P = \Delta_{\phi} \cdot \phi_{\Lambda} \cdot \phi_{\epsilon}^{-1} \cdot \phi^{Ix}$.
(8) Values of N_f^P have to be evaluated against the data in Table 6.

* In these calculations the worst case in every step has been assumed. This leaves the possibility open to adjust the computations by applying the Monte Carlo modelling of the frequency distribution of every event (Whiting and Buchanan, 1997).

finitesimally low residual levels of pathogens (cf. Table 2, element number 3) during distribution must be studied experimentally and the ultimate risk presented by exposure to the food upon ingestion must be gauged (Table 8, steps 6–8). Foods in Risk group 3 of Table 4 may be slowly lethal, over a protracted period, to the rare surviving non-sporing pathogenic bacteria, particularly the Gram-negative rod shaped types. As this process is difficult to properly and reliably anticipate (Mossel, 1963; Di-Girolamo et al., 1970; Foster and Mead, 1976; Harrison et al., 1991), such extra safety margins are not always taken into account, and reliance is placed on the worst case scenario, i.e. assuming no post-process reduction in cfu.

3. Elaboration and application of risk analysis and hazard containment models in food-processing practice

3.1. Elimination of pathogens from foods

Emphasis on hygiene along the slaughter line should ensure that fresh meats are obtained that are of relatively good microbiological quality, though not necessarily, and in practice far from, free of enteric pathogens (Gerats et al., 1981; Berends et al., 1997; Gill et al., 1997). This hazardous situation is entirely similar to that of raw milk which, in spite of all possible precautions, can not offer an assurance of microbiological safety at the point of delivery to the consumer. Consequently, in attempts to ensure that the food industry, catering and the domestic kitchen are provided with safe raw meats, a de-contamination treatment has to be applied to freshly slaughtered raw meat and poultry (Mossel, 1984; van der Marel et al., 1988; Zeitoun and Debevere, 1991, 1992; Zeitoun et al., 1994; Corry et al., 1995; van Netten et al., 1995). Whether a physical (e.g. hot water treatment or transradiation), or chemical (e.g. lactic acid) pathogen-reduction technology is used, it has to be designed so as to attain adequate reduction of initially and unavoidably occurring enteric pathogens. At any rate pathogen reduction intervention has to be mandatorily linked, as indicated in Table 2, to meticulous hygienic care of the raw material (Gill et al., 1997), avoidance of recontamination (Mossel, 1984) and control of recolonization (LeChevallier et al., 1996). In Table 9 a risk analysis and containment model is presented, allowing a choice and design of an effective decontamination technology, which will henceforth be mandatory in the US ([US] Department of Agriculture, 1996). A significant shift in the ranking of hazard reduction efficacy will, however, result from acid habituation occurring in enteric pathogens; vide infra. This will markedly reduce the lethality arising from lactic acid decontamination, but not negatively affect heat and transradiation

Table 9
Effect of decontamination procedures on the risk of contracting meat-borne enteric infections[a]

Mode of culinary heating of meat when minced	Decontamination procedure	Probability of infection with	
		Salmonella	*E. coli*
Rare	None	6.1×10^{-1}	6.7×10^{-4}
	LAD[b], 2% Hlac[c], pH 2.6, applied 2 min at 55°C	4.0×10^{-4}	1.3×10^{-4}
	Gamma transradiation, 3kGy	1.2×10^{-5}	Negligible
Well done	None	2.3×10^{-2}	1.3×10^{-5}
	LAD, 2% Hlac, pH 2.6, applied 2 min at 55°C	6.0×10^{-6}	3.3×10^{-6}
	Gamma transradiation, 3kGy	2.4×10^{-7}	Negligible

[a] For the assumptions made in this risk assessment, see legends to Table 8 of van Netten (1996), from which publication the data have been derived.
[b] LAD = surface decontamination of freshly slaughtered carcasses with lactic acid solutions.
[c] Hlac = lactic acid.

decontamination; and hence favour the latter intervention technology.

A similar model has been elaborated for the elimination of *Listeria monocytogens* from raw milk to be processed into dried skimmed milk powder. This product differs in two ecological respects from the one previously discussed. It benefits from three pathogen reduction interventions; and, in addition, the final product belongs to risk group 3 in Table 4 which might ensure a slow decay of the pathogen during storage (Harrison et al., 1991). The matrix used in this instance is summarized in Table 10.

3.2. Risk analysis and hazard containment of toxinogenic food pathogens by inhibition rather than elimination

3.2.1. Principles: relying on predictive microbiology

It is often not possible, for organoleptic or other reasons, to eliminate toxinogenic and a few infective pathogens from foods. An example is meat products, where the customary addition of a mixture of sodium chloride and sodium nitrite at a given pH may not achieve hazard control (Gibson et al., 1987). Such products remain colonization-prone, toxic metabolites can not be inactivated by culinary preparation, and indeed many of these foods may even be ingested without any prior heat treatment; cf. Table 5. Hence the safety of such commodities has to be ensured by increasing their colonization resistance, primarily based on external limiting factors. A strategy of reliance on intrinsic factors – in addition to extrinsic ones – in food safety assurance is pursued by the approach termed ''predictive modelling'' (McMeekin et al., 1993; Baker, 1995; Farber and Dodds, 1995; Buchanan and Whiting, 1996; Elliott, 1996; Ross, 1996; Zwietering et al., 1996; Armitage, 1997). This culminated, e.g., in the UK Food Micromodel approach (McClure et al., 1994; Baranyi and Roberts, 1995; Curtis et al., 1995).

In creating models, it is necessary to consider both growth profiles and metabolic activities of relevant toxinogenic organisms when subjected to normal conditions of preshipping storage and distribution. For hazard control it is essential to recognise that proliferation of, and toxin formation by, the same organisms are as a rule affected to a different extent by the same numerical values of the applied extrinsic limiting factors, namely temperature and partial pressure of carbon dioxide. Growth and the production of metabolites are consequently usually out of phase, resulting in the occurrence of proliferation

Table 10
Risk analysis matrix for the transmission of *L. monocytogenes* by dried, skimmed milk powder[a]

(1) Raw milk phase	
Fraction of total number of cows, supplying raw milk, which are suffering from subclinical *Listeria* mastitis	d
Mean number of cfu of *Listeria* per 1 ml intra vitam milk of shedding cows	c
Contamination with *Listeria* from environment	e
Proliferation of initial total contamination	Δ_r
(2) Pasteurization stage	
Reduction resulting from clarification	R_c
Contamination from pre-pasteurization area, including inadequately cleaned apparatus	ρ_P
Lethality of pasteurization process	Λ_P
Recontamination from raw milk circuit through microleaks	ρ_r
Environmental contamination after pasteurization	ρ_e
Proliferation before condensation	Δ_p
(3) Drying process	
Lethality of condensation	Λ_c
Lethality of spray drying	Λ_d
Lethality during storage in dried condition	Λ_s

Source: Mossel et al., 1987.
[a] Assumption: contamination with and colonization by *L. monocytogenes* during centrifugation, clarification and domestic reconstitution, preparation and pre-ingestion storage under control; cf. Table 8, stage (6). Also, see footnote to Table 8.

of organisms without, necessarily, production of toxins at clinically relevant levels.

The effect of primarily extrinsic retardation of growth can be enhanced by promoting antagonistic inhibition of the target toxinogenic organism by the saprophytic Gram-positive bacteria which commonly occur in these foods, or are added to them (Kafel and Ayres, 1969; Hurst, 1973; Gilliland and Speck, 1972, 1977; Mossel and Struijk, 1992; Holzapfel et al., 1995). This illustrates the need, in predictive microbiology, to take account of the phenomena which are termed implicit, in keeping with the terminology used in mathematics. Implicit phenomena denote interactions taking place between components of the initially arising microbial population of foods during storage, distribution etc., as a result of intrinsic and extrinsic pressures (Mossel and Struijk, 1992). Implicit effects include, besides antagonism, as above, synergism: the promotion of other organisms.

The effect of such combinations of inimical interventions is to approach the boundaries of growth conditions for target micro-organisms. This induces the organisms to turn into the stationary phase, which increases their resistance to adverse effects. Such responses should definitively be taken into account in predictive microbiology (Stewart, 1997).

3.2.2. Acid stabilized products

Relying on intrinsic or implicit inhibition of pathogenic micro-organisms by lowered pH calls for addressing the emergence, briefly discussed before in the context of risk analysis applied to lactic acid decontamination, of acid habituation after exposure of bacteria to acid environments, first observed in Gram-negative enteric pathogens (Smith et al., 1975; Leyer and Johnson, 1992, 1993; Leyer et al., 1995; van Netten, 1996). In risk assessment and containment, the acid habituation phenomenon should prompt meticulous experimental studies of certain issues.

Firstly, the actual effect of typically used reduced pH-values as, e.g. in vinegar-based meat, poultry and vegetable salads, in controlling enteric pathogens in such commodities should be studied (Holtzapffel and Mossel, 1968). Secondly, it is equally important to assess whether acid-habituated cells of these taxa are less drastically reduced in numbers by exposure to gastric acidity than has been previously assumed (Giannella et al., 1971, 1972; Blaser and Newman, 1982; Peterson et al., 1989; Gorden and Small, 1993). Such effects may necessitate compensation to be made for reduced in vivo incurred lethality in enteric pathogens, such as *Salmonella enteritidis*

PT4 in eggs (Humphrey et al., 1995), using technological intervention.

An, at that time, novel strategy, relying on predictive microbiology, in pursuit of the lowest attainable N_f-values in acidified products as ingested, was elaborated in principle almost three decades ago by Tuynenburg-Muys (1971), (1975) termed ''microbiological composition assurance''.

3.2.3. Minimally intrinsically preserved foods

When *Staph. aureus*, a thermotropic bacterium, is the only pathogen of concern, moderate temperature control, i.e. ensuring food temperatures below 10°C during distribution (events 2 and 3 in Table 11) will suffice. However, the situation is different when the organism under consideration is a psychrotroph and intrinsic colonization resistance of the food is minimal. An example is to be found in attempts to ensure the safety of mildly smoked fish. In this instance psychrotrophic *Cl. botulinum* species constitute a major health risk (Eklund, 1982; Garren et al., 1994). Consequently limitation of the food temperature during storage and distribution to well below 5°C is mandatory, while predictive modelling studies have to produce numerical values for the maximal period of time of safe storage.

The situation is even more critical in the case of soft curd cheeses manufactured from raw milk. Although this is a hazard to be averted (Mossel, 1983) the industry alleges that many products of this class can not be successfully produced from pasteurized milk. This has prompted attempts to contain potential microbiological risks presented by soft curd raw milk cheeses through a combination of extreme hygiene, the use of rapid production of inhibitory factors by starter organisms and temperature control throughout (Struijk, 1997). Such efforts call for very meticulous monitoring and immediate intervention when potentially dangerous situations are identified.

3.2.4. Hard cheeses

An example of containment of a, mainly, toxinogenic bacterium, *Staph. aureus* in a food of risk category 3 in Table 4, is presented by control of the production and persistence of staphyloenterotoxins in hard cheese, e.g. cheddar. The calculations summa-

Table 11
Assessment of the risk of staphyloenterotoxins being transmitted, at a level leading to disease, by hard cheeses manufactured according to GMP including: (1) use of adequately pasteurized milk; (2) under conditions where starter culture activity was checked and found satisfactory

Event 1: post-pasteurization contamination with Staph. aureus	
Total recontamination in cfu g^{-1}	r
Fraction of population being *Staph. aureus*	s
Enterotoxinogenic part of *Staph. aureus* population	e
Event 2: proliferation of enterotoxinogenic strains during the various stages of manufacture and maturation (Δ)	
Abuse temperature/time integral	$\int T\mathrm{d}t$
Inhibition due to the development of *Lactobacteriaceae* resulting in acidification of the curd and the production of nitrogen-containing inhibitory metabolites	I
Growth retardation resulting from progressively anaerobic conditions	an
Event 3: enterotoxin formation (τ); cf Appendix A	
Time/temperature integral as under 2	$\int T\mathrm{d}t$
Competition,	I
Retardation,	an
Integration of effects of events 1–3.	
Assuming consumption of a portion of about 100 g cheese and the minimum toxic dose of enterotoxins being of the order of 1 μg, the risk of contracting staphyloenterotoxicosis as a result of the consumption of one portion of a *given* consignment of hard cheese, equals: $100 \cdot rse \cdot \Delta\ [f_1\ (\int T\mathrm{d}t \cdot I \cdot \mathrm{an})] \cdot \tau \cdot [f_2\ (\int T\mathrm{d}t \cdot I \cdot \mathrm{an})]$	

Source: Mossel and Dijkman, 1984.
Note: growth and toxin formation are, as a rule, affected to a different extent by the same numerical values of extrinsic and implicit parameters, such as temperature and antagonism. Consequently $f_1 \neq f_2$. Also, see footnote to Table 8.

rized in Table 11 enable the design of appropriate remedial technological interventions, where required. This may have to include the use of improved, i.e. bacteriocin producing starters, or the addition of authorized antimicrobial constituents of abiotic or biological origin (Terplan, 1962; Holzapfel et al., 1995; Muriana, 1996).

3.3. Elaboration of a rationale for the experimental assessment of microbiological reference values for dried nutriceuticals destined for premature infants and severely immunocompromised adults

Premature neonates and severely immunodebilitated adults, such as patients undergoing intensive surgery and persons suffering from an HIV-infection, constitute the most vulnerable element of the YOPI-group described above. The manufacture of dried foods to be consumed by these individuals carries the risk that there will be present very low, erratically distributed, numbers, particularly of *Salmonella* species, as illustrated by Fig. 2. That this problem occurs is demonstrated by the infrequent, though most unpleasant episodes of infections, particularly in newborn babies associated with dried milk products (Collins et al., 1968; Blackburn and Ellis, 1973; Habraken et al., 1986; Rowe et al., 1987). Manufacturing processes, meticulously adhering to longitudinally integrated measures of safety assurance, must be supported by carefully elaborated reference ranges, whose assessment calls for a risk analysis with reference to a ''worst case ''scenario.

In the case of infective pathogens, the critical parameter is the minimal infectious range, as illustrated by Table 12 and accounted for in Table 13. The tolerable safety limit (TSL), sensu Kleter, is subsequently derived from MIRs and the growth potential (expressed as Δ_{Σ}; cf. Appendix A) of the target micro-organism in the reconstituted product (Mossel et al., 1973) during storage and use by the consumer, illustrated by Table 14, steps 3–5. As indicated previously, reliance is, in addition, often placed on index organisms. In this case this is mandatory, as demonstrated by Figs. 2 and 3. For index organisms the guiding parameter is the Minimal Marker Range of Concern (MMR), defined as MIR $\times$ ϵ, as in Tables 12 and 13. Unusually low ϵ-levels, e.g. not markedly exceeding the order of 10^{-2}, may compromise this approach.

For the assessment of reference ranges for toxinogenic organisms, including *Staph. aureus*, *B. cereus*, bacteria producing pressor amines and mycotoxinogenic moulds, the crucial parameter is the Minimal Toxic Level Range (MTR; cf. Appendix A), as in Table 11. MTRs depend on numbers of producing cells and severity, degree of toxinogenicity and extent of expression of toxin production, quantified in Table 13.

The three-class reference range system introduced by Bray et al. (1973) acknowledges a second parameter termed *m*, besides the TSL, also designated *M*. Small *m* is the limit arising from meticulous adherence to Good Manufacturing and Distribution Practices (GMDPs). Numerical values for *m* are calculated from surveys on commodities originating from manufacturing operations, which have been previously validated for strict adherence to GMDPs. This is done by plotting the cfu-frequency distribution of the production data and determining the 95th percen-

Table 12
Parameters used in elaborating reference ranges

Target organisms	Determinat = lower value of	Examples of organisms
Infectious organisms	Minimal Infectious Range (MIR)	*Salmonella* spp.
Markers for pathogens	Minimal Marker Range of concern (MMR) = MIR $\times$ ϵ	Enterobacteriaceae
Toxin producers	Minimal Toxic Level Range (MTR)	Type 1[a]: *S. aureus*, *B. cereus* Type 2[b]: enterococci, aerobic colony counts 30°C and 55°C, moulds

[a] Organisms for which *specific* limits have been elaborated, based on the fraction of the population which may be toxin producers: symbol τ.
[b] Organisms included in *non-specific* indicator groups, where one overall level of concern is handled, because of hazard of potential production of pressor amines, mycotoxins and possible other toxic metabolites.

Table 13
Procedure adopted to rationalize numerical levels for the parameters relied on in the elaboration of reference ranges

Organism	Parameter[a]	cfus	Justification
Salmonella	MIR	1	Clinical evidence
B. cereus	MTR	$10^5.\tau$*	Clinical evidence
Staph. aureus	MTR	$2.10^4.\tau$*	Clinical evidence
Enterobacteriaceae	MMR	MIR $\times$ ϵ* = MIR $\times$ 2.10^5	Ecological data
Enterococci[a]	MTR	2.10^5	Data from clinically relevant pressor amine production
Mesophilic, predominantly non-saccharolytic ('sulphite reducing') clostridia[b,c]	MTR	5.10^4	Data from clinically relevant toxin production and index function for *Clostridium* spp. of health significance; cf. text.

* Definitions: cf. legend to and contents of Table 12.
[a] Organisms of this category include active agents of spoilage. Their main use in monitoring nutriceuticals relates to health protection, however. Consequently, the occurrence of vancomycin-resistant biotypes has to be avoided and carefully monitored.
[b] Cf. Weenk et al., 1995.
[c] Clostridia are also mainly spoilers; however, in monitoring nutriceuticals they also serve a most relevant public health purpose.

Table 14
Stages model for first-order microbiological risk assessment and hazard control of products destined for debilitated consumers (nutriceuticals). Similar calculation models can be used for toxinogenic organisms using the corresponding parameters of Table 12

Step	Action	Calculation
1	Estimate from the literature	MIR[a] or MIR $\times$ ϵ^b for markers. Adherence to the ''worst-case'' principle dictates to choose the lowest recorded values for both MIR and ϵ, however, cf footnote to Table 8.
2	Assess intake (I) from instructions for use accompanying the commodity	$I = U \times n$ (g), where U = weight content (g) of unit package of product; n = number of units, ingested within ca. 6 h
3	Derive from the literature	Δ_Σ = total increase factor in cfu, calculated from the generation times of pathogen or marker (γ_T), at abuse temperatures, chosen as model. – Ignore lag-time (worst-case scenario) – If so preferred, calculations may be simplified by choosing between $\Delta_\Sigma = 10$ (3–4 divisions) and 10^2 (6–7 divisions)
4	Calculate from data above	E = exposure (cfu) = $I \times N_0 \times \Delta_\Sigma$, where N_0 = initial cfu g^{-1} of target organism in the nutriceutical.
5	Determine the *tolerable safety limit* TSL	$E <$ MIR[c] or MIR $\times$ ϵ, thus $I \times N_0 \times \Delta_\Sigma <$ MIR $\times$ $\epsilon \rightarrow$ TSL = (MIR $\times$ ϵ)/$I \times \Delta_\Sigma$

[a] Minimal infectious range (cfu).
[b] Ecological determinant.
[c] The attempted safety margin MIR $\times$ ϵ/E is dependent on the target pathogen, and the attainability of N_0 under optimal conditions of GMDP.

Examples of calculation of safety limits according to stages model above
1. *Staph. aureus*: MTR $\leq 10^4$, $\tau = 10$*, $I = 10^2$, $\Delta_\Sigma = 10 \rightarrow$ safety limit function TSL = $(10^4 \times 10)/10^2 \times 10 = 10^2$ cfu g^{-1}.
2. *Salmonella* spp.: MIR = 1, $\epsilon = 1$, $I = 10^2 \rightarrow$ safety limit functions: **a** $\Delta_\Sigma = 10^2 \rightarrow$ TSL = $(1 \times 1)/10^2 \times 10^2) = 10^{-4}$ cfu g^{-1} **b** $\Delta_\Sigma = 1 \rightarrow$ TSL = 10^2 cfu g^{-1}

* Assumption made when calculating the parameter τ (cf. rider of Table 12): the order of 20% of *S. aureus* strains isolated from marketed foods produces the most aggressive enterotoxins (Ewald and Christensen, 1987).

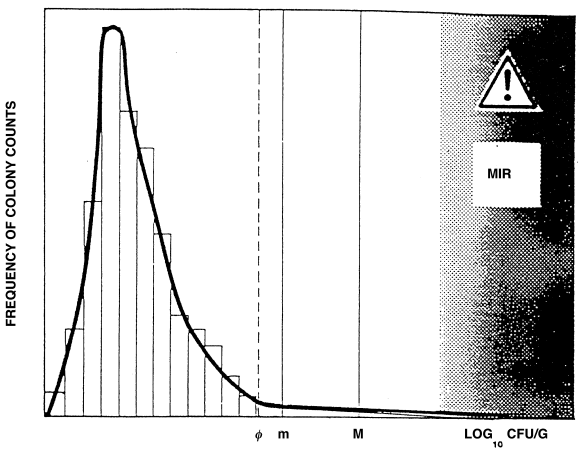

Fig. 4. Empirical assessment of reference values (''standards'') for foods, relying on surveys on the microbiological condition of samples,drawn from consignments that were manufactured, stored and distributed under prescribed good conditions, which had been validated previously, both as such and with respect to strict adherence by the corporations from whose production lines the specimen were drawn. Legend: ϕ = 95th percentile; m = reference value proper; M = maximal count expected under conditions of GMDP; cfu = colony forming units; MIR = minimal infective range.

tile of the curve as illustrated by Fig. 4. In instances wherein *m* approaches the TSL too closely, this will not have to be taken for granted. Rather, in these instances, manufacturing and distribution practices should be adjusted to produce safe values in future.

3.4. More recently identified food-transmitted pathogens

Consumers often express concern about emerging and resurgent pathogens. These have been defined respectively as infective agents, identified more recently (Wilson, 1995; Armstrong et al., 1996), and those known for at least a century, but now recurring due to complacency, i.e. a failure to continue implementing preventive strategies, previously successfully applied to avert epidemics (Tauxe et al., 1995). These consumer concerns have been excited by reports in the lay press about, often lethal, high fevers and haemorrhages transmitted by viruses. However, often serious food-borne incidents associated with infective pathogens which were not previously considered transmissible by foods, are nonetheless far less devastating than the fevers of viral origin which fuelled the original public concern (Khan et al., 1996; Plyusmin et al., 1996; Levis et al., 1997; Schmaljohn and Hjelle, 1997).

A review of the most prevalent ''emerging'' infective as well as toxinogenic agents transmitted by food and drinking water, is presented in Table 15.

Table 15
More recently identified (''emerging'') food-transmitted infections and intoxinations (organism, group of organisms or toxins)

Novel pathotypes of the genera *Campylobacter* and *Arcobacter*
Classical and novel pathotypes of enterohaemorrhagic *E. coli*
Enterovirulent *Hafnia* species
Enterovirulent *Aeromonas* spp.
Enterovirulent *Plesiomonas* spp.
Enterobacter sakazakii
Non conventional enterotoxin producing staphylococci
Non *B. cereus* species of the genus *Bacillus*
Non-cholera, non-*parahaemolyticus Vibrio* spp.
Mycobacterium paratuberculosis
Vancomycin resistant *Enterococcus* spp.
Gram-negative, rod-shaped, and a few other bacteria producing endotoxins
Prions: abnormal, distorted peptides, the causative agents of transmissible, progressive, fatal spongiform encephalopathies of man and animals
Cryptosporidium parvum
Cyclospora cayetanensis
Enterocytozoon bieneusi
Fumonisins
Cyanobacterial toxins, carried over from water bodies.
Enteric viruses – not literally emerging, though frequently disregarded or ignored.

Source: Mossel and Struijk, 1997.

Mostly containment of these novel agents does not present specific problems. For example, campylobacters are much more fragile and markedly less thermoresistant than *Salmonella* and enterovirulent *E. coli* species (Doyle and Jones, 1992). However, a few exceptions do call for extra attention in risk analysis and management, as survival of these organisms may constitute a severe hazard.

Enterococcus (Magnus et al., 1986, 1988) and *Mycobacterium* (Erasmus et al., 1995; McFadden and Fidler, 1996) species are more robust than the customary Gram-positive pathogens, such as *Staph. aureus* and *Listeria monocytogenes.* Another reason for vigilance is unusual, acquired acid tolerance in enterohaemorrhagic pathotypes of *E. coli* (Conner and Kotrola, 1995; Leyer et al., 1995; Liu et al., 1996), *Salmonella* spp. (Dickson and Kunduru, 1995; Baik et al., 1996) Humphrey et al., 1996) and in *L. monocytogenes* (Kroll and Patchett, 1992; Davis et al., 1996; O'Driscoll et al., 1996), previously discussed. The pathogens of most concern in this context are, however, undoubtedly those of the prion group, putative agents of human infection by a zoonotic pathway (Collinge et al., 1996). This is because these transmissible peptides show an extremely high thermal resistance (Brown et al., 1990; Taylor et al., 1994; Taylor, 1996).

It is necessary to consider such experimental results when elaborating containment measures relying on asepsis as well as decontamination. They are also indispensable when elaborating and adopting reference ranges for foods, particularly those intended for severely immunocompromised consumers, summarized in Table 16.

4. The psycho-sociology of safety communication and persuasion

4.1. Reassurance of the public

Irrespective of how expertly crafted they may be, control measures have little worth if outcomes following their application are inappropriately communicated to, and consequently not accepted by consumers. Public trust is unfortunately often eroded by the hesitation and indolence of Government Agencies to adopt or enforce consumer protection strategies (Day, 1997). Consumers may, however, benefit from the urgency injected by recent comments by both EU Authorities (Mossel and Struijk, 1996) and the President of the US (Marwick, 1997) which reinforce the need to pursue management of microbial hazards in foods. It is, on the other hand, prejudicial for Public Health that various contributors are playing down, or even denying the existence of hazards, and thus further impeding substantial progress in consumer protection. This compounds the task of the safety communicator.

In attempting to allay concerns, a further hurdle is

Table 16
Reference ranges for pathogens and marker organisms in nutriceuticals (dried foods to be ingested by debilitated consumers), derived by the risk analysis and hazard containment procedure (Weenk et al., 1996)

Target organisms	Segment of consumer population	Sampling scheme		Reference range*	
				m (cfu g^{-1})	M (cfu g^{-1})
Salmonella	Debilitated	$n = 60$	$c = 0$	Not detected in 25 g of a well	
	Fully vital	$n = 5$	$c = 0$	homogenized sample	
B. cereus	All	$n = 5$	$c = 1$	0.5×10^2	$10^2 - 10^3$
Staph. aureus	All	$n = 5$	$c = 1$	10	10^2
Enterobacteriaceae	Debilitated	$n = 5$	$c = 1$	1–10	$0.1–1 \times 10^2$
	Fully vital	$n = 5$	$c = 1$	0.5×10^3	10^3
Enterococcus spp.	All	$n = 5$	$c = 2$	0.5×10^2–0.5×10^3	10^2–10^3
Mesophilic *Clostridium* spp.	All	$n = 5$	$c = 1$	$0.1–0.3 \times 10^2$	$10–10^2$
Yeast and mould propagules	All	$n = 5$	$c = 2$	$0.5–1.0 \times 10^2$	$0.1–0.5 \times 10^3$
Aerobic colony count 30–32°C	All	$n = 5$	$c = 1$	10^3–10^4	$0.05–0.5 \times 10^5$

[a] m = alert level; M = safety limit or action level; cf. Fig. 4, dependent on vulnerability of consumer group; n = number of samples examined, c = number of samples between m and M.

presented by the greater weight people seemingly accord to risks imposed by others, when compared to those not so readily appreciated, often more serious risks, which they face as a result of personal life style choices. A few examples are presented in Table 17.

Gaining credibility and earning trust with the public is an essential precursor to the successful dissemination of health advice or reassurance. In seeking to ensure messages are assimilated, it is advisable to follow Socrates who developed the notion of dialogue–discourse on the basis of equivalence. To be arrogant, to patronise or to become irritated by opinionated stands is counterproductive and must be avoided. Rather, the communicator should be aware of the public's concern and should display a willingness to respond with understanding, even to anxiety which is not necessarily rooted in science. In such efforts it is imperative to take into account, as conveyed by Appendix D, that most segments of the consumer community have been exposed to enduring myths about microbiological food safety before information stemming from experts in this field ever reached them.

Safety communicators who embrace these principles are more likely to engender fruitful debate and substantive dialogue. Implicit in this approach is a desire to express opinions in the most succinct and simple way possible, and thus facilitate understanding. Once trust and credibility have been established, it will only be maintained in a climate of openness in which information is never purposefully, or even accidentally withheld. In particular, any deficiencies in the protective web of risk management should not be concealed, but always clearly exposed. By following this policy, scientists can expect a reasoned and sensible response from consumers, which will further the cause of food safety.

Many benefits will accrue through the acceptance of, e.g., decontamination by surface treatment with steam or hot water (Nutsch et al., 1997), lactic acid or sodium triphosphate (van Netten, 1996; Dorsa et al., 1997) or else transradiation (Mossel, 1987; Clavero et al., 1994) to ensure pathogen reduction. This will allow scientific knowledge to be harnessed effectively to assist the food industry in pursuit of public health. The alternative would be a public refusal to buy the foods manufactured by the new technology – in spite of their proven safety.

4.2. Providing incentives for management and staff of smaller food businesses

Larger and middle sized food manufacturers and caterers have by-and-large embraced the novel approach of microbiological safety assurance relying on hazard identification and containment. By contrast, many smaller operators have not yet followed this example, at least not in the absence of legal compulsion. Hence, such operations constitute a primary target group for education and persuasion.

As in the context of consumer reassurance, the first step must be to explore the perceptions, opinions and attitudes of employers and employees of smaller businesses (Ehiri and Morris, 1994). Following this, the shortcomings of the traditional retrospective approach and the benefits of the novel European and US strategies require to be explained.

Such endeavours may be facilitated by demonstration of *observable* facts in food microbiology. This may serve to reconcile opinions arising from myths, anecdotes and tradition with facts rooted in science.

Table 17
Hazards originating from ''life style'', often ignored or at least played down

≠ Alcohol ingestion leading to liver damage, foetal syndromes in pregnant women, and more generally to traffic accidents arising from abuse.
≠ Smoking and its association with primary bronchial carcinoma.
≠ Excessive intake of calories resulting in obesity.
≠ Diets adopted without due attention being paid to daily allowances, resulting in malnutrition, or the ingestion of exaggerated doses of nutrients, giving rise to adverse effects.
≠ Exposure to excess sunlight, leading to squamous cell carcinoma of the skin.
≠ During the general public's inhalation of vapours while pumping petrol, exposure to benzene in quantities substantially exceeding that of chemical workers, which is closely observed and controlled in an attempt to prevent benzene-induced leukemias.
≠ Imprudent habits in intercourse.

Sources: Klein, 1996; Marmot, 1996; Anon., 1997; Lewis et al., 1997.

Visual demonstration of bacterial contamination and proliferation by simple ''dip slide'' methods are within the capacity of staff with only marginal, i.e. elementary ad hoc training (Mossel et al., 1976). These convenient and cheap self- monitoring techniques allow verdicts to be reached without *the need to consult* third parties, a procedure often perceived as threatening to the autonomy and ego of the food business operator. Where the opinion of professional microbiologists is *requested*, an understanding response and attention to good practice in counselling enquirers (Mossel et al., 1997) prompted and supported by the use of self-monitoring devices, will lead to improved skills, competence and commitment within the industry. Thus a promising future for progress in risk-assessment-based management of microbial hazards, even in the smallest food businesses is created (Ehiri et al., 1995).

5. Retrospect

A recurring criticism of risk assessment and management procedures *in general* centres on their perceived complexity, juxtaposed with a failure to discriminate properly, because underlying data are insufficiently robust.

The estimation of *chemical* health risks relying on data obtained in the customary rodent feeding assays, using arbitrary safety margins, calls for at least three extrapolations of response data (Maga and Tu, 1994; Rodericks, 1996). These include (i) converting results derived from animal studies to humans per se; (ii) taking into account that, whereas rodent populations are as a rule genetically homogeneous, human beings at risk constitute a wildly heterogeneous target group; and (iii) the exalted animal challenge exposures required to arrive at no observable adverse effect levels (NOAELs), are quite distant from the low levels to be encountered in real life situations. Accordingly, confidence intervals on many estimates of risk from low level chemical hazards may be very wide (Mazur, 1992). To remedy this situation, more recently innovated toxicological approaches have been introduced that substantially improve extrapolation of animal assay data to the human consumer (Andersen et al., 1987; Hissink, 1996; Liem and Theelen, 1997).

Estimation, and hence control of *microbiological* hazards presented by foods, though compounded by biological diversity and variability (Bernard and Scott, 1995) are, nonetheless, less beset by the problems of inaccuracy which exist in relation to adverse effects from chemicals in foods. The impacts of the hazards posed by microbiological contamination of foods are generally better defined. Incidents are, unfortunately, rather common, in sharp contrast to those resulting from exposure to chemical food additives, allowing better risk assessments. Finally, the effects of exposure to microbiological hazards contained in foods are relatively well quantified. Low TSLs and MIRs may overestimate the overall hazard, but this is not necessarily undesirable because it results in an in-built safety margin and can always be adjusted by substituting the Monte Carlo approach for the worst case scenario (Whiting and Buchanan, 1997). Erring on the safe side is in the interests of the food industry too. It vindicates the industry's *voluntary* pursuit of responsible care, and promotes greater understanding of the scientific basis underpinning *mandatory* controls with which the sector must comply.

It has also been highlighted that a risk management approach entails considerable cost. However, demonstrable benefits include (i) reductions in the amount of acute illness, serious chronic sequelae and deaths; and (ii) the avoidance of the stress, financial penalty and loss of public confidence associated with food recalls where there is a demonstrated association of a particular brand with outbreaks of infectious disease; cf. Appendix E. Such expenses (Todd, 1985; Roberts and Foegeding, 1991; Ament et al., 1993; Sockett, 1993) markedly exceed those entailed by scrupulous adherence to GMDPs to ensure consistent hazard containment (Mossel et al., 1995b).

Successful microbiological risk management calls for close cooperation between food microbiologists, mathematicians, food-processing specialists and the regulatory authorities (McKone, 1996). Additionally, success in protecting the consumer demands the closest cooperation between the food microbiology profession and behavioural scientists. The latter constitute an invaluable resource if success is to be achieved in (i) inducing consumers to accept safe measures of intervention, which are required for health protection, whilst not engendering alarm; and (ii) winning over smaller food operators, who resist risk-analysis-based prevention strategies, because

they fail to understand the principles, and to recognise that they too will benefit, and not just the larger companies, who embraced the concept often in advance of legal compulsion.

Academic education and training should take these essential elements of hazard control into account (Mossel et al., 1997).

Appendix A
Abbreviations and symbols used in this review

Abundance	The proportion of a particular organism within a specific group of organisms, or amongst the total microbial population of a group.
AQL	Acceptable Quality Level: defect level for organisms, exempt of Health Significance, in a food, at probability of acceptance, upon a defined sampling examination plan = 0.95.
Association	Specific equilibrium microbial community structure of a food at the moment of marketing.
ATQA	Autonomous Total Quality Assurance strategy, wherein the responsibility for (microbiological) safety and quality of the ultimate food product is entrusted to the successive enterprises all along the production and distribution line.
Coinfection	Food-transmitted infectious, primarily enteric disease probably caused by the simultaneous presence in the ingested commodity of more than one pathogenic agent, each not necessarily at a level exceeding its applying MIR; *vide infra*.
Colonization prone	Condition of a food which allows proliferation and metabolic activities of a broad range of micro-organisms.
Colonization resistant	Condition of a food that inhibits the development of virtually all micro-organisms, unless a dramatic change in the intrinsic antimicrobial attributes of the commodity occurs.
Critical attention ''point''	Location or practice constituting a hazard, which cannot yet be reduced to an extent required by health protection.
Critical control ''point''	Location where a hazard exists, or a practice has been identified as potentially hazardous, over which control is required and within reach.
Δ_{Σ}	Total cfu increase level: multiplier for the growth of a particular micro-organism in a colonization prone food as a result of exposure to a time/temperature span, estimated to occur under worst case conditions, though far below the frank temperature abuse range.
D_T-value	Time wherein 90% lethality in a given population of a particular micro-organism is achieved at a given temperature T°C and under accurately defined intrinsic and extrinsic conditions.
Due diligence	Elliptical expression of the obligation of food manufacturing industries and caterers to comply with competently elaborated Codes of Good Manufacturing and Distribution Practices.
Elimination	Reduction of initially occurring numbers of cfu of a pathogenic organism to the extent that the tolerable safety limit (*vide infra*) is no longer exceeded.
ϵ-factor	Epsilon ecological determinant: proportion between cfu numbers of index organisms and the cfu numbers of a particular pathogenic target organism.
Extrinsic factor	Conditions of storage and distribution affecting the fate of micro-organisms in a given food product.
GMDP	Good Manufacturing and Distribution Practices, as laid down in codes, elaborated by expert panels at a national or international level.
HACCP	For linguistic reasons slightly modified original mnemonic to: Hazard Analysis [carried out to achieve] Control of Critical Practices.
Hazard	Event or condition that has been *empirically demonstrated* to endanger human health.
Holistic	Taking into account *every* event with an adverse effect on safety that may occur *all along* the raw material, production, storage, distribution and consumption stages.
Implicit factors	Effects resulting from *interactions*, antagonism or synergism, between components of the *primary selection* amongst naturally occurring contaminants, which arise from intrinsic and extrinsic selective pressures.
Intrinsic factors	Physico-chemical and chemical attributes of a food affecting the fate of micro-organisms under given extrinsic conditions of storage and distribution.
Λ = Lethality	Reduction of cfu numbers of a given micro-organism achieved by a precisely defined exposure to adverse intrinsic or extrinsic conditions, and determined by accurately standardized analytical procedures.
Limits, specific	The highest cfu values which are acceptable in the case of criteria for spoilers or marker organisms, or tolerable for organisms of health significance.
LISA	Longitudinally Integrated Safety Assurance, taking into account *every* hazardous event that can occur *throughout* the *entire* production, storage and distribution line.
MIR	Minimal Infectious Range of infective units, capable of triggering disease upon

	ingestion with a particular food by a given group of consumers.
MMR	Minimal Marker Range of Concern, i.e. pointing to an imminent risk of *infection*, when applied to index marker organisms; or to a potential risk of a *process* being out-of-control, when pertaining to indicator markers.
MTR	Minimal numbers of cfus of microbial cells capable of expressing their oral toxinogenicity by producing clinically significant amounts of toxin(s).
Nutriceuticals	Commodities prepared with special care, destined for the nutrition of severely debilitated consumers.
Paucimicrobial	Technical term derived from latin paucus = few, denoting the condition of a food which is colonized at a level far below 10^4 g^{-1} or ml^{-1}.
Processing for safety	Any food technological intervention affecting the presence and/or fate of hazardous micro-organisms to the extent that ingestion of the food thus processed will not expose consumers to any pathogens at levels exceeding their TSL (*vide infra*), or to toxinogenic organisms in cfu numbers exceeding their MTR (*vide supra*).
Reference ranges	Range of numerical limits for microbiological criteria, *empirically* determined by surveys on specimens originating from manufacturing industries or caterers consistently complying with GMDPs and gauged against MIRs or MTRs.
Responsible care	Synonymous with due diligence; *vide supra*.
Risk	Probability of occurrence of a hazard.
Safety target	Syn. TSL.
SOP	Standard Operating Procedure: accurately phrased, rigorously standardized method of examination.
τ-factor	Reciprocal of the fraction of a toxinogenic population that will express toxin production under accurately defined intrinsic and extrinsic conditions.
Transradiation	Designation introduced, particularly by food processing specialists in The Netherlands, to emphasize the *transient* effect of the decontamination treatment of foods with ionizing radiation; thereby laying stress upon the similarity with the use of X-rays in diagnostic and curative medicine and allaying concerns about the safety of this intervention, not infrequently expressed by consumers, though arising from perception of hazards, lacking scientific foundation.
TSL	Tolerable Safety Limit (syn. safety target and Food Safety Objective), very low defect level for a pathogenic organism that is deemed not to present a health risk when ingested with a given food by an accurately specified group of consumers.
Worst case scenario	Course of events of hazardous occurrences, including exceptional, though nevertheless possible situations.
YOPI	Segment of consumers with substantially diminished defense against infections: the young, old, pregnant and immunodeficient.

Appendix B
Definition of target groups

Of further benefit to the consumer is the fact that in determining hazards and their control, the HACCP system takes into account the effect of any hazard on target groups within the population, such as infants, the elderly, those with compromised immune systems, those undergoing antibiotic treatment and unique situations existing in nursing homes and hospitals (Bauman, 1995).

For FDA, a standard of reasonable certainty of no harm for all population groups should be applied in making all food safety decisions (Hanson, 1997).

Appendix C
An attempt by the authors to quantify the amounts of time required to complete microbiological procedures to be applied in hazard containment verification

* Real time = reliable results available within the order of magnitude of one hour.
* Same day = obvious without clarification, though we suggest: when the test is started before 10 a.m. the results are known no later than 5 p.m.
* Accelerated = resulting in *at least* one day earlier results, in comparison to customarily used standard procedures, without sacrificing accuracy or precision.

Appendix D
Academic efforts to substitute facts for fables

Students much exposed to mass media may internalize erroneous information from popular culture before they are exposed to scientific meanings in the

class room. Professors need to be aware of these alternative definitions and address them in class before proceeding.

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Appendix E

The costs entailed by a recall include the following:

1. The cost of the product and/or its reprocessing or destruction.
2. The diversion of management time during the period of crisis.
3. The loss of sales while locating and picking up product.
4. The loss of future sales, because of negative publicity about the product.
5. Possibility of legal action and/or financial responsibility.
6. The loss of Company reputation with the consumers and government agencies.
7. The adverse effects on sales of other Company products, not incriminated in the recall

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Bauman, 1995.

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