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# Past, current and potential utilisation of active and intelligent packaging systems for meat and muscle-based products: A review

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**Abstract**

Interest in the use of active and intelligent packaging systems for meat and meat products has increased in recent years. Active packaging refers to the incorporation of additives into packaging systems with the aim of maintaining or extending meat product quality and shelf-life. Active packaging systems discussed include oxygen scavengers, carbon dioxide scavengers and emitters, moisture control agents and antimicrobial packaging technologies. Intelligent packaging systems are those that monitor the condition of packaged foods to give information regarding the quality of the packaged food during transport and storage. The potential of sensor technologies, indicators (including integrity, freshness and time-temperature (TTI) indicators) and radio frequency identification (RFID) are evaluated for potential use in meat and meat products. Recognition of the benefits of active and intelligent packaging technologies by the food industry, development of economically viable packaging systems and increased consumer acceptance is necessary for commercial realisation of these packaging technologies.


*Keywords:* Meat; Packaging; Active; Intelligent

## 1. Introduction

Due to increased demands for greater stringency in relation to hygiene and safety issues associated with fresh and processed meat products, coupled with ever-increasing demands by retailers for cost-effective extensions to product shelf-lives and the requirement to meet consumer expectations in relation to convenience and quality (increased product range, easy use and minimum product preparation, provision of more product information and packaging impact on the environment), the food packaging industry has rapidly developed to meet and satisfy expectations. In fact, so rapid has this development been that food companies, and more specifically meat processors, struggle to keep pace with developments. Yet despite major developments in packaging materials and systems, the fundamental principles of packaging meat products remain the same.

Packaging fresh meat is carried out to avoid contamination, delay spoilage, permit some enzymatic activity to improve tenderness, reduce weight loss, and where applicable, to ensure an oxymyoglobin or cherry-red colour in red meats at retail or customer level (Brody, 1997). When considering processed meat products, factors such as dehydration, lipid oxidation, discoloration and loss of aroma must be taken into account (Mondry, 1996). Many meat packaging systems currently exist, each with different attributes and applications. These systems range from overwrap packaging for short-term chilled storage and/or retail display, to a diversity of specified modified atmosphere packaging (MAP) systems for longer-term chilled storage and/or display, to vacuum packaging, bulk-gas flushing or MAP systems using 100% carbon dioxide for long-term chilled storage. Due to the diversity of product characteristics and basic meat packaging demands and applications, any packaging technologies offering to deliver more product and quality control in an economic and diverse manner would be favourably welcomed. Two such packaging approaches currently exist and can be divided into two dis-

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tinct categories; active packaging technologies and intelligent packaging technologies.

Active packaging refers to the incorporation of certain additives into packaging systems (whether loose within the pack, attached to the inside of packaging materials or incorporated within the packaging materials themselves) with the aim of maintaining or extending product quality and shelf-life. Packaging may be termed active when it performs some desired role in food preservation other than providing an inert barrier to external conditions (Hutton, 2003). Active packaging has been defined as packaging, which 'changes the condition of the packed food to extend shelf-life or to improve safety or sensory properties, while maintaining the quality of packaged food' (Ahvenainen, 2003). The development of a whole range of active packaging systems, some of which may have applications in both new and existing food products, is fairly new. Active packaging includes additives or 'freshness enhancers' that can participate in a host of packaging applications and by so doing, enhance the preservation function of the primary packaging system (Table 1).

Intelligent packaging (also more loosely described as smart packaging) is packaging that in some way senses some properties of the food it encloses or the environment in which it is kept and which is able to inform the manufacturer, retailer and consumer of the state of these properties. Although distinctly different from the concept of active packaging, features of intelligent packaging can be used to check the effectiveness and integrity of active packaging systems (Hutton, 2003). Intelligent packaging has been defined as packaging 'systems which monitor the condition of packaged foods to give information about the quality of the packaged food during transport and storage' (Ahvenainen, 2003). Smart packaging devices, which may be an integral component or inherent property of a foodstuff's packaging, can be used to monitor a plethora of food pack attributes (Table 2).

From the outline descriptions of the numerous active and intelligent packaging technologies currently in existence, only a limited number are currently relevant to meat and meat product packaging applications. However, research developments in the areas of active packaging and intelligent packaging technologies are progressing rapidly and potential applications are likely. Therefore, the purpose of this review is to examine the active packaging and intelligent packaging systems that have been, or are currently being used for meat and meat product application, and assess new and developing systems that may have potential for commercial use with meat packaging systems into the future.

## 2. Active packaging of muscle foods

Preservative packaging, as applied to muscle foods, should maintain acceptable appearance, odour and flavour and delay the onset of microbial spoilage. A variety of packaging systems and technologies are currently available for muscle foods, specifically fresh and cooked meats and meat products. For example, fresh red meats may simply be placed on trays and over-wrapped with an oxygen permeable film or placed within a gaseous environment containing high levels of oxygen and carbon dioxide. Packaging of this type is termed MAP, which is distinguished from controlled atmosphere packaging (CAP), within which, invariant atmospheres are maintained throughout the time of storage (Brody, 1996). The atmosphere within an MAP pack may alter during storage due to reactions between components of the atmosphere and the product and/or due to transmission of gases in or out of the pack through the packaging film (Stiles, 1991).

Typically fresh red meats are stored in modified atmosphere packages containing 80% $O_2$:20% $CO_2$ (Georgala & Davidson, 1970) and cooked meats are stored in 70% $N_2$:30% $CO_2$ (Smiddy, Papkovsky, & Kerry, 2002). The function of carbon dioxide in MAP is to inhibit growth of spoilage bacteria (Seideman & Durland, 1984). Nitrogen is used in MAP as an inert filler gas either to reduce the proportions of the other gases or to maintain pack shape (Bell & Bourke, 1996). The major function of oxygen is to maintain the muscle pigment myoglobin in its oxygenated form, oxymyoglobin.

Important properties by which consumers judge meat are appearance, texture and flavour (Faustman & Cassens, 1990). Appearance, specifically colour, is an important quality attribute influencing the consumer's decision to purchase. In fresh red meats, myoglobin can exist in one of three chemical forms. Deoxymyoglobin, which is purple, is rapidly oxygenated to cherry red oxymyoglobin on exposure to air. Over time, oxymyoglobin is oxidised to metmyoglobin which results in a brown discoloration associated with a lack of freshness (Faustman & Cassens, 1990). Low oxygen concentrations favour oxidation of oxymyoglobin to metmyoglobin (Ledward, 1970). Therefore, in order to minimise metmyoglobin formation in fresh red meats, oxygen must be excluded from the packaging environment to below 0.05% or present at saturating levels (Faustman & Cassens, 1990). High oxygen levels within MAP also promote oxidation of muscle lipids over time with deleterious effect on fresh meat colour (O'Grady et al., 1998). Lipid oxidation

Table 1
Examples of active packaging applications for use within the food industry

| | |
|---|---|
| Absorbing/scavenging properties | Oxygen, carbon dioxide, moisture, ethylene, flavours, taints, UV light |
| Releasing/emitting properties | Ethanol, carbon dioxide, antioxidants, preservatives, sulphur dioxide, flavours, pesticides |
| Removing properties | Catalysing food component removal: lactose, cholesterol |
| Temperature control | Insulating materials, self-heating and self-cooling packaging, microwave susceptors and modifiers, temperature-sensitive packaging |
| Microbial and quality control | UV and surface-treated packaging materials |

Table 2
Examples of intelligent packaging applications for use within the food industry

| | |
|---|---|
| Tamper evidence and pack integrity | Breach of pack containment |
| Indicators of product safety/quality | Time-temperature indicators (TTI's), gas sensing devices, microbial growth, pathogen detection |
| Traceability/anti-theft devices | Radio frequency identification (RFID) Labels, tags, chips |
| Product authenticity | Holographic images, logos, hidden design print elements, RFID |

is a major quality deteriorative process in muscle foods resulting in a variety of breakdown products which produce undesirable off-odours and flavours.

In cooked cured packaged meat products, for example, cooked hams, factors such as percentage residual oxygen, product to headspace volume ratio, oxygen transmission rate of the packaging material, storage temperature, light intensity and product composition are critical factors affecting colour stability and ultimately consumer acceptance (Møller et al., 2003). Nitrosylmyoglobin, formed from a reaction between myoglobin and nitrite is denatured upon cooking to nitrosylmyochrome which gives the characteristic pink colour to cooked cured ham (Juncher et al., 2003). Exposure to light in combination with oxygen is of critical importance to the colour stability of cooked cured ham as light exposure, even at low oxygen levels, can cause oxidation of nitrosylmyochrome to denatured metmyoglobin, which imposes a dull undesirable greyness to the meat surface (Møller, Jensen, Olsen, Skibsted, & Bertelsen, 2000). Lipid oxidation is generally low in cooked cured meat products (Morrissey & Tichivangana, 1985). Commercially, discoloration in pre-packed, cooked, cured ham is associated with low residual oxygen levels and is overcome with the use of oxygen scavengers or an oxygen scavenging film. Also, with respect to fresh red meats, oxygen scavengers used in conjunction with a carbon dioxide/nitrogen gas mixture extends the colour shelf-life of fresh beef (Allen et al., 1996). Oxygen scavengers are examples of entities described as 'active packaging components'.

### 2.1. Oxygen scavengers

High levels of oxygen present in food packages may facilitate microbial growth, off flavours and off odours development, colour changes and nutritional losses thereby causing significant reduction in the shelf life of foods. Therefore, control of oxygen levels in food packages is important to limit the rate of such deteriorative and spoilage reactions in foods. Oxygen absorbing systems provide an alternative to vacuum and gas flushing technologies as a means of improving product quality and shelf life (Ozdemir & Floros, 2004). Although oxygen sensitive foods can be packaged accordingly using MAP or vacuum packaging, such techniques do not always facilitate complete removal of oxygen. Oxygen which permeates through the packaging film or is trapped within the meat or between meat slices cannot be removed by these techniques. Using an oxygen scavenger, which absorbs the residual oxygen after packaging, quality changes in oxygen sensitive foods can often be minimised (Vermeiren, Devlieghere, Van Beest, de Kruijf, & Debevere, 1999). Existing oxygen scavenging technologies utilise one or more of the following concepts: iron powder oxidation, ascorbic acid oxidation, photosensitive dye oxidation, enzymatic oxidation (e.g. glucose oxidase and alcohol oxidase), unsaturated fatty acids (e.g. oleic or linolenic acid) rice extract or immobilised yeast on a solid substrate (Floros, Dock, & Han, 1997). More comprehensive information and details relating to oxygen scavengers can be obtained from other reviews (Floros et al., 1997; Vermeiren et al., 1999). Structurally, the oxygen scavenging component of a package can take the form of a sachet, label, film (incorporation of scavenging agent into the packaging film), card, closure liner or concentrate (Suppakul, Miltz, Sonneveld, & Bigger, 2003).

The majority of currently commercially available oxygen scavengers are based on the principle of iron oxidation (Smith, Ramaswamy, & Simpson, 1990):

$$Fe \rightarrow Fe^{2+} + 2e^-$$

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$$

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$$

$$Fe(OH)_2 + \frac{1}{4}O_2 + \frac{1}{2}H_2O \rightarrow Fe(OH)_3$$

Comprehensive details on a variety of commercially available oxygen scavengers are presented by Suppakul et al. (2003). Ageless® (Mitsubishi Gas Chemical Co., Japan) is the most common oxygen scavenging system based on iron oxidation. The sachets are designed to reduce oxygen levels to less than 1%. Additional examples of oxygen absorbing sachets include ATCO® (Emco Packaging Systems, UK; Standa Industrie, France), FreshPax® (Multisorb Technologies Inc., USA) and Oxysorb® (Pillsbury Co., USA).

The scientific literature contains a number of references to studies, which examine the influence of oxygen scavenger sachets on fresh beef discoloration. Gill and McGinnis (1995) performed an oxygen absorption kinetics study with a commercial oxygen scavenger (FreshPax™ 200R) and reported that discoloration could be prevented in ground beef if large numbers of scavengers were used in each pack to bring residual oxygen to <10 ppm within 2 h at a storage temperature of −1.5 °C. The inclusion of oxygen scavengers (Ageless® SS200) in master packs flushed with 50% $CO_2$:50% $N_2$ significantly improved the colour stability of *M. longissimus dorsi* and *M. psoas major*, relative to controls (Allen et al., 1996). Tewari, Jayas, Jeremiah, and Holley (2001) examined the effect of two commercial oxygen scavengers (Ageless® FX-100 and FreshPax® R-2000), in conjunction with CAP, on the discoloration of *M. psoas major* in master packs filled with nitrogen and stored at $1 \pm 0.5$ °C. Steaks packaged without oxygen scavengers had more discoloration and significantly higher proportions of metmyoglobin when compared to steaks packaged with oxygen scavengers. Prevention of metmyoglobin formation was influenced by the number but not the type of oxygen scavenger employed.

Payne, Durham, Scott, and Devine (1998) examined the effect of vacuum CAP with carbon dioxide, packs flushed with carbon dioxide, packs flushed with carbon dioxide and containing Ageless™ (Z50) oxygen scavengers and packages containing oxygen scavengers alone on the drip loss, microbial and sensorial properties of *M. longissimus lumborum* stored for up to 20 weeks at $-1.5$ °C. Beef in packs flushed with carbon dioxide and flushed containing the oxygen scavenger had lower drip loss than the standard CAP system. The packages flushed with carbon dioxide and those containing the oxygen scavenger alone gave the best results depending on the storage shelf-life required.

In addition to fresh beef oxygen scavenging technology has also been applied to pork (Doherty & Allen, 1998) and pork products, where, Martínez, Djenane, Cilla, Beltrán, and Roncalés (2006) reported that fresh pork sausages stored in 20% $CO_2$:80% $N_2$ plus an oxygen scavenger (Ageless® FX-40) for up to 20 days at $2 \pm 1$ °C had reduced psychrotrophic aerobe counts and an extended shelf-life in terms of colour and lipid stability. Oxygen scavenging labels are widely used commercially as oxygen scavengers in pre-packed cooked meat products. Emco Packaging Systems, specialists in active and intelligent packaging, are a UK manufacturer and distributor for ATCO® DE 10S self-adhesive oxygen absorbing labels. Emco supply ATCO® labels for use in pre-packed sliced cooked meats, especially hams, to meat processors in Ireland, throughout the UK and in Europe. While labels used in sliced cooked meat packages scavenge between 10 and 20 cc's of oxygen, Emco have recently launched larger oxygen scavenging labels onto the market (ATCO® 100 OS and 200 OS), which scavenge between 100 and 200 cc's oxygen, for use in larger capacity packaging applications.

An alternative to sachets involves the incorporation of the oxygen scavenger into the packaging structure itself. This minimises negative consumer responses and offers a potential economic advantage through increased outputs. It also eliminates the risk of accidental rupture of the sachets and inadvertent consumption of their contents (Suppakul et al., 2003).

Cryovac® OS2000™ polymer-based oxygen scavenging film has been developed by Cryovac Division, Sealed Air Corporation, USA. This UV light-activated oxygen scavenging film, which structurally is composed of an oxygen scavenger layer extruded into a multilayer film, can reduce headspace oxygen levels from 1% to ppm levels in 4–10 days, comparable with oxygen scavenging sachets. The OS2000™ scavenging films have applications in a wide variety of food products including dried or smoked meat products and processed meats (Butler, 2002). A similar UV light-activated oxygen scavenging polymer $ZERO_2$™, developed by CSIRO, Division of Food Science Australia in collaboration with VisyPak Food Packaging, Visy Industries, Australia, forms a layer in a multi-layer package structure and has many applications including reduced discoloration of sliced meats.

### 2.2. Carbon dioxide scavengers and emitters

The function of carbon dioxide with a packaging environment is to suppress microbial growth. Therefore, a carbon dioxide generating system can be viewed as a technique complimentary to oxygen scavenging (Suppakul et al., 2003). Since the permeability of carbon dioxide is 3–5 times higher than that of oxygen in most plastic films, it must be continuously produced to maintain the desired concentration within the package (Ozdemir & Floros, 2004). High carbon dioxide levels (10–80%) are desirable for foods such as meat and poultry in order to inhibit surface microbial growth and extend shelf life. Removal of oxygen from the package creates a partial vacuum, which may result in the collapse of flexible packaging. Also, when a package is flushed with a mixture of gases including carbon dioxide, the carbon dioxide dissolves in the product creating a partial vacuum. In such cases, the simultaneous release of carbon dioxide from inserted sachets, which consume oxygen, is desirable. Such systems are based on either ferrous carbonate or a mixture of ascorbic acid and sodium bicarbonate (Rooney, 1995). Examples of commercially available dual action combined carbon dioxide generators/oxygen scavengers are Ageless® G (Mitsubishi Gas Chemical Co., Japan) and FreshPax® M (Multisorb Technologies Inc., USA). Carbon dioxide emitting sachets or labels can also be used alone. The Verifrais™ package, manufactured by SARL Codimer (Paris, France) has been used to extend the shelf life of fresh meats. This innovative package consists of a standard MAP tray but has a perforated false bottom under which, a porous sachet containing sodium bicarbonate/ascorbate is positioned. When juice exudates from the packaged meat drips onto the sachet, carbon dioxide is emitted, thus replacing any carbon dioxide absorbed by the meat and preventing package collapse.

The inhibition of spoilage bacteria utilising active packaging technology may reduce bacterial competition and thus permit growth and toxin production by non-proteolytic *C. botulinum* or the growth of other pathogenic bacteria (Sivertsvik, 2003). Lövenklev et al. (2004) reported that while a high concentration of carbon dioxide decreased the growth rate of non-proteolytic *C. botulinum* type B, the expression and production of toxin was greatly increased which means the risk of botulism may also be increased, instead of reduced if used in MAP systems. Research into the safety risks associated with the use of carbon dioxide in packaging systems is necessary.

Carbon dioxide absorbers (sachets), consisting of either calcium hydroxide and sodium hydroxide, or potassium hydroxide, calcium oxide and silica gel, may be used to remove carbon dioxide during storage in order to prevent bursting of the package. Possible applications include their use in packs of dehydrated poultry products and beef jerkey (Ahvenainen, 2003).

### 2.3. Moisture control

The main purpose of liquid water control is to lower the water activity of the product, thereby suppressing microbial growth (Vermeiren et al., 1999). Temperature cycling of high water activity foods has led to the use of plastics with an anti-fog additive that lowers the interfacial tension between the condensate and the film. This contributes to the transparency of the film and enables the customer to clearly see the packaged food (Rooney, 1995) although it does not affect the amount of liquid water present inside the package. Several companies manufacture drip absorbent sheets or pads such as Cryovac® Dri-Loc® (Sealed Air Corporation, USA), Thermarite® or Peaksorb® (Australia), Toppan™ (Japan) and Fresh-R-Pax™ (Maxwell Chase Technologies, LLC, USA) for liquid control in high water activity foods such as meat and poultry. These systems consist of a super absorbent polymer located between two layers of a micro-porous or non-woven polymer. Such sheets are used as drip-absorbing pads placed under whole chickens or chicken cuts (Suppakul et al., 2003).

### 2.4. Antimicrobial packaging

Microbial contamination and subsequent growth reduces the shelf life of foods and increases the risk of food borne illness. Traditional methods of preserving foods from the effect of microbial growth include thermal processing, drying, freezing, refrigeration, irradiation, MAP and addition of antimicrobial agents or salts. However, some of these techniques cannot be applied to food products such as fresh meats (Quintavalla & Vicini, 2002). Antimicrobial packaging is a promising form of active packaging especially for meat products. Since microbial contamination of meat products occurs primarily at the surface, due to post-processing handling, attempts have been made to improve safety and to delay spoilage by the use of antibacterial sprays or dips. Limitations of such antibacterials include neutralisation of compounds on contact with the meat surface or diffusion of compounds from the surface into the meat mass. Incorporation of bactericidal agents into meat formulations may result in partial inactivation of the active compounds by meat constituents and therefore exert a limited effect on surface microflora (Quintavalla & Vicini, 2002). Antimicrobial food packaging materials have to extend the lag phase and reduce the growth phase of microorganisms in order to extend shelf life and to maintain product quality and safety (Han, 2000). Comprehensive reviews on antimicrobial food packaging have been published by Appendini and Hotchkiss (2002) and Suppakul et al. (2003). To confer antimicrobial activity, antimicrobial agents may be coated, incorporated, immobilised, or surface modified onto package materials (Suppakul et al., 2003). A comprehensive list of antimicrobial agents for use in antimicrobial films, containers and utensils is presented in a review by Suppakul et al. (2003). The classes of antimicrobials listed range from acid anhydride, alcohol, bacteriocins, chelators, enzymes, organic acids and polysaccharides. Examples of commercial antimicrobial materials in the form of concentrates (e.g. AgION™, AgION Technologies LLC, USA) extracts (Nisaplin® (Nisin), Integrated Ingredients, USA) and films (Microgard™ Rhone-Poulenc, USA) were also presented. Antimicrobial packages have had relatively few commercial successes except in Japan where Ag-substituted zeolite is the most common antimicrobial agent incorporated into plastics. Ag-ions inhibit a range of metabolic enzymes and have strong antimicrobial activity (Vermeiren et al., 1999). Antimicrobial films can be classified into two types: those that contain an antimicrobial agent which migrates to the surface of the food and, those which are effective against surface growth of microorganisms without migration.

#### 2.4.1. Coating of films with antimicrobial agents

Coating of films with antimicrobial agents can result in effective antimicrobial activity. Natrajan and Sheldon (2000) carried out a study to evaluate the potential use of packaging materials as delivery vehicles for carrying and transferring nisin-containing formulations onto the surfaces of fresh poultry products. The efficacy of nisin coated (100 μg/ml) polymeric films of varying hydrophobicities (polyvinyl chloride (PVC), linear low-density polyethylene (LLDPE) and nylon) in inhibiting *Salmonella typhimurium* on fresh broiler drumstick skin was evaluated. It was concluded that packaging films coated with nisin were effective in reducing *S. typhimurium* on the surface of fresh broiler skin and drumsticks.

#### 2.4.2. Incorporation of antimicrobial agents

The direct incorporation of antimicrobial additives in packaging films is a convenient means by which antimicrobial activity can be achieved. Ouattara, Simard, Piette, Bégin, and Holley (2000) carried out a study to assess the inhibition of surface spoilage bacteria in processed meats following the application of antimicrobial films prepared with chitosan. Antimicrobial films were prepared by incorporating acetic or propionic acid into a chitosan matrix, with or without addition of lauric acid or cinnamaldehyde, and were applied onto bologna, regular cooked ham or pastrami. During the storage period, packages were opened and the amounts of antimicrobial agents remaining in the chitosan matrix were measured. Propionic acid was released from the matrix must faster than acetic acid. Addition of lauric acid, but not cinnamaldehyde, to the chitosan matrix reduced the release of acetic acid and the release was more limited onto bologna than onto ham or pastrami. Lactic acid bacteria were unaffected by the antimicrobial films studied whereas growth of *Enterobacteriaceae* and *Serratia* *liquefaciens* (surface-inoculated onto the meat products) was delayed or completely inhibited as a result of film application. The strongest inhibition was observed on drier surfaces (bologna), onto which, acid release was slower, and with films containing cinnamaldehyde, as a result of its greater antimicrobial activity under these conditions. Vermeiren, Devlieghere, and Debevere (2002) reported that a 1.0% triclosan film had a strong antimicrobial effect in vitro simulated vacuum packaged conditions against the psychrotropic food pathogen *Listeria monocytogenes*. However, the triclosan film did not effectively reduce spoilage bacteria and growth of *L. monocytogenes* on refrigerated vacuum packaged chicken breasts stored at 7 °C.

Ha, Kim, and Lee (2001) examined the effect of grapefruit seed extract (GFSE), a natural antimicrobial agent, incorporated (0.5% or 1% concentration) by co-extrusion or a solution-coating process in multilayered polyethylene (PE) films, on the microbial status and quality (colour (L, a, b), TBARS and pH) of fresh minced beef. The antimicrobial activity of the fabricated multilayer films was also evaluated using an agar plate diffusion method. It was reported that coating the PE film with GFSE with the aid of a polyamide binder resulted in greater antimicrobial activity compared to GFSE incorporation by co-extrusion. Using the agar diffusion test, the co-extruded film with 1% w/w GFSE showed antimicrobial activity against *Metaphycus flavus* only, whereas a film coated with 1% GFSE showed activity against several microorganisms such as *Escherichia coli*, *Staphylococcus aureus* and *Bacillus subtilis*. Both types of GFSE-incorporated multilayer PE films reduced the growth of aerobic and coliform bacteria in minced beef wrapped with film and stored for up to 18 days at 3 °C, relative to controls. The film coated with a higher concentration (1%) of GFSE had a more pronounced effect in inhibiting bacterial growth compared to the other films tested. GFSE-coated films were better than co-extruded films in preserving the chemical quality (TBARS) of packaged beef. Beef colour was unaffected by packaging treatment. The level of GFSE employed (0.5% and 1%) did not differ significantly in terms of film efficacy for preservation of beef quality.

There is a growing interest in edible coatings due to factors such as environmental concerns, the need for new storage techniques and opportunities for creating new markets for under utilised agricultural commodities with film forming properties (Quintavalla & Vicini, 2002). Edible coatings and films prepared from polysaccharides, proteins and lipids have a variety of advantages such as biodegradability, edibility, biocompatibility, aesthetic appearance and barrier properties against oxygen and physical stress. Advantages of using edible coatings and films on meat and meat products have been discussed by Gennadios, Hanna, and Kurth (1997). Edible coatings could:

- Help alleviate the problem of moisture loss during storage of fresh or frozen meats.
- Hold juices of fresh meat and poultry cuts when packed in retail plastic trays.
- Reduce the rate of rancidity caused by lipid oxidation and myoglobin oxidation.
- Reduce the load of spoilage and pathogenic microorganisms on the surface of coated meats.
- Restrict volatile flavour loss and foreign odour pick up.

As an application of active packaging, edible coatings carrying antioxidants or antimicrobials can be used for the direct treatment of meat surfaces. In the case of edible films and coatings, selection of the incorporated active ingredient is limited to edible compounds therefore edibility and safety is important. Siragusa and Dickson (1993) demonstrated that alginate coatings containing organic acids were marginally effective on beef carcasses, reducing levels of *L. monocytogenes*, *S. typhimurium* and *E. coli* 0157:H7 by 1.80, 2.11 and 0.74 log cycles, respectively. Complete inhibition of *L. monocytogenes* on ham, turkey breast and beef was achieved using pediocin or nisin fixed on a cellulose casing (Ming, Weber, Ayres, & Sandine, 1997). Commercial application of this technology is described in a US Patent (5,573,797) assigned to a manufacturer of cellulose food casings (Viskase Co. Inc., USA). The package is a film, such as a polymer film or a regenerated cellulose film, containing heat resistant *Pediococcus*-derived bacteriocins in synergistic combination with a chelating agent to inhibit or kill *L. monocytogenes* on contact with food (Katz, 1999).

### 2.4.3. Immobilisation

Some antimicrobial packaging systems utilise covalently immobilised antimicrobial substances which suppress microbial growth. Scannell et al. (2000) investigated the immobilisation of bacteriocins nisin and lacticin 3147 to packaging materials. The plastic film (PE/polyamide (70:30) formed a stable bond with nisin, in contrast to lacticin 3147, and maintained activity for a 3 month period both at room temperature and under refrigerated storage conditions. The antimicrobial packaging reduced the population of lactic acid bacteria in ham stored in MAP (60% $N_2$:40% $CO_2$) thereby extending product shelf life. Nisin-adsorbed bioactive inserts reduced the level of *L. innocua* and *S. aureus* in hams.

### 2.4.4. Naturally derived antimicrobial agents

The use of naturally derived antimicrobial agents is important as they represent a lower perceived risk to the consumer (Nicholson, 1998). Skandamis & Nychas (2002) studied the combined effect of volatiles of oregano essential oil and modified atmosphere conditions (40% $CO_2$:30% $O_2$:30% $N_2$, 100% $CO_2$, 80% $CO_2$, vacuum packaged and aerobic storage) on the sensory, microbiological and physiochemical attributes of fresh beef stored at 5 and 15 °C. Filter paper containing absorbed essential oil was placed in the packages but not in direct contact with the beef samples. The shelf life of beef samples followed the order: aerobic storage < vacuum packaged < 40% $CO_2$:30% $O_2$:30% $N_2$ < 80% $CO_2$:20% air < 100% $CO_2$. Longer shelf life was observed in samples supplemented with the volatile compounds of oregano essential oil.

### 2.5. Miscellaneous and potential future applications

In addition to active packaging techniques mentioned earlier, additional active technologies, application to other foodstuffs (Ahvenainen, 2003) may have potential applications in meat and meat products. For example, self-heating aluminium or steel cans and containers, currently used by coffee manufacturers (Nescafe, 'hot when you want it'), may have applications in the production of ready meals containing various meats. Since consumer demands for ready to eat convenience meals are constantly increasing, packaging of ready meals in self-heating active packaging is an important future application. Microwave susceptors consist of aluminium or stainless steel deposited on substrates such as polyester films or paperboard and serve to dry, crisp and ultimately brown microwave food. Modifiers for microwave heating consist of a series of antenna structures, which alter the way microwaves, arrive at food thereby resulting in even heating, surface browning and crisping (Ahvenainen, 2003). Incorporation of such susceptors or modifiers into meat or meat product packages is an additional future application for active packaging of meat and meat products. Flavour/odour adsorbers may have potential in active packaging technology for muscle foods. Adsorber systems employ mechanisms such as cellulose triacetate, acetylated paper, citric acid, ferrous salt/ascorbate and activated carbon/clays/zeolites. The Swedish company EKA Noble, in cooperation with the Dutch company Akzo, developed a range of synthetic aluminosilicate zeolites, which they claim absorb odorous gases within their highly porous structure. Their BHM™ powder can be incorporated into packaging materials, especially those that are paper based and apparently odorous aldehydes are adsorbed in the pore interstices of the powder (www.pira.co.uk/admin/_private/TechnicalArticles/00123.pdf). Such technology may prove useful in removing off odours and flavours generated, for example, as a result of the oxidation of lipids in packaged muscle foods. Similar applications may exist for various flavour emitting polymers (Ahvenainen, 2003).

## 3. Intelligent packaging

Perhaps the most commonly encountered definition of intelligent packaging (and one to which these authors shall adhere for the purposes of this review) is provided by the European study 'Evaluating Safety, Effectiveness, Economic-environmental Impact and Consumer Acceptance of Active and Intelligent Packaging (ACTIPAK-FAIR CT 98-4170, 1999–2001) as 'systems that monitor the condition of packaged foods to give information about the quality of the packaged food during transport and storage'.

Although much information is available on the internet, in technical journals, the media and elsewhere, relatively little information on intelligent packaging generally, and intelligent packaging of meat products in particular, is available in the scientific literature. Many ideas have been proposed, numerous patent applications filed (particularly US and Japanese) and much research in a wide range of disciplines undertaken but very little commercial application has resulted. The number of currently available commercial intelligent packaging systems used in meat products is negligible. To this end, any discussion on intelligent packaging of meat products must, to some degree, be speculative in nature. In so doing, we shall attempt to describe intelligent packaging types, concepts and applications in the light of their use, actual or potential, in the packaging of muscle based food products.

### 3.1. Sensors

Many intelligent packaging concepts involve the use of sensors and indicators. For the purposes of clarity these two areas will be discussed separately although such a distinction is somewhat arbitrary and some overlap is unavoidable. The use of these systems is generally envisaged in terms if incorporation into established packaging techniques such as MAP and vacuum packaging.

MAP is an extremely important packaging technique used extensively for the distribution, storage and display of meat products in markets with a controlled cold distribution chain (Sivertsvik, Rosnes, & Bergslien, 2002). It is expected that the number of packs in Europe using MAP technology will exceed 20 billion a year by 2007. MA packaging works by replacement of the air surrounding a meat product with formulated gas mixtures, thereby extending shelf life and quality. The most important (non-inert) gases in MAP products are oxygen and carbon dioxide and their headspace partial pressures serve as useful indicators of the quality status of a meat product. The profiles of oxygen and carbon dioxide can change over time and are influenced by product type, respiration, packaging material, pack size, volume ratios, storage conditions, package integrity, etc. A number of analytical techniques are available to monitor gas phases in MAP products. Instrumental techniques such as GC and GC/MS require breakage of package integrity and are time-consuming and expensive. Portable headspace oxygen and/or carbon dioxide gas analysers use 'minimally destructive' techniques (packages can be resealed) but tend not to be applicable to real-time, on-line control of packaging processes or large scale usage. An optical sensor approach offers a realistic alternative to such conventional methods (Peterson, Fitzgerald, & Buckhold, 1984).

A sensor is defined as a device used to detect, locate or quantify energy or matter, giving a signal for the detection or measurement of a physical or chemical property to which the device responds (Kress-Rogers, 1998a). To qualify as a sensor, a device must be able to provide continuous output of a signal. Most sensors contain two basic functional units: a receptor and a transducer. In the receptor, physical or chemical information is transformed into a form of energy, which may be measured by the transducer. The transducer is a device capable of transforming the energy carrying the physical or chemical information about the sample into a useful analytical signal.

Research and development of sensor technology has, until recently, been largely concentrated in biomedical and environmental applications (Demas, DeGraff, & Coleman, 1999). The specifications of such sensors are, however, quite different from those required for food packaging applications. The development of improved methods to determine food quality such as freshness, microbial spoilage, oxidative rancidity or oxygen and/or heat induced deterioration is extremely important to food manufacturers. In order to maximise the quality and safety of foodstuffs, a prediction of shelf-life based on standard quality control procedures is normally undertaken. Replacement of such time-consuming and expensive quality measurements with rapid, reliable and inexpensive alternatives has lead to greater efforts being made to identify and measure chemical or physical indicators of food quality. The possibility of developing a sensor for rapid quantification of such an indicator is known as the marker approach (Kress-Rogers, 2001). Determination of indicator headspace gases provides a means by which the quality of a meat product and the integrity of the packaging in which it is held can be established rapidly and inexpensively. One means of doing so is through the production of intelligent packaging incorporating gas sensor technology.

Chemical sensor and biosensor technology has developed rapidly in recent years. The main types of transducers with potential use in meat packaging systems include electrical, optical, thermal or chemical signal domains. Sensors can be applied as the determinant of a primary measurable variable or, using the marker concept, as the determinant of another physical, chemical or biological variable (Kress-Rogers, 1998a). Recent developments in sensor technology have narrowed the gap between the theoretical and the commercially viable, and although practical uses of sensors in the meat industry remain very limited, significant practical steps towards more widespread use have been made (Kerry & Papkovsky, 2002). High development and production costs, strict industry specifications, safety considerations and relatively limited demand (in comparison with the biomedical sector) from industry and consumer alike, have proved the main obstacles to commercial use. Very few systems to date have been able to match exacting industry standards required for successful application. However, developments in materials science, continuous automation processes, signal processing and process control, along with transfer of technology from the biomedical, environmental and chemical sectors all lead towards the likelihood of more universal adoption of sensor technology in food packaging. Greater pressure on food manufacturers to guarantee safety, quality and traceability is also likely to promote the establishment of commercial sensor technology in food packaging.

#### 3.1.1. Gas sensors

Gas sensors are devices that respond reversibly and quantitatively to the presence of a gaseous analyte by changing the physical parameters of the sensor and are monitored by an external device. Systems presently available for gas detection include amperometric oxygen sensors, potentiometric carbon dioxide sensors, metal oxide semiconductor field effect transistors, organic conducting polymers and piezoelectric crystal sensors (Kress-Rogers, 1998b). Conventional systems for oxygen sensors based on electrochemical methods have a number of limitations (Trettnak, Gruber, Reiniger, & Klimant, 1995). These include factors such as consumption of analyte (oxygen), cross-sensitivity to carbon dioxide and hydrogen sulphide and fouling of sensor membranes (Gnaiger & Fortsner, 1983). Such systems also involve destructive analysis of packages.

In recent years, a number of instruments and materials for optical oxygen sensing have been described (Papkovsky, Ponomarev, Trettnak, & O'Leary, 1995; Thompson & Lakowicz, 1993; Trettnak et al., 1995). Such sensors are usually comprised of a solid-state material, which operate on the principle of luminescence quenching or absorbance changes caused by direct contact with the analyte. These systems provide a non-invasive technique for gas analysis through translucent materials and as such are potentially suitable for intelligent packaging applications. The solid-state sensor is inert and does not consume analyte or undergo other chemical reactions (Wolfbeis, 1991). Optochemical sensors have the potential to enhance quality control systems through detection of product deterioration or microbial contamination by sensing gas analytes such as hydrogen sulphide, carbon dioxide and amines (Wolfbeis & List, 1995).

Approaches to optochemical sensing have included: (a) a fluorescence-based system using a pH sensitive indicator (Wolfbeis, Weis, Leiner, & Ziegler, 1988), (b) absorption-based colourimetric sensing realised through a visual indicator (Mills, Qing Chang, & McMurray, 1992) and (c) an energy transfer approach using phase fluorimetric detection (Neurater, Klimant, & Wolfbeis, 1999). The latter allows for the possibility of combining oxygen and carbon dioxide measurements in a single sensor through compatibility with previously developed oxygen sensing technology. Most carbon dioxide sensors, however, have been developed for biomedical applications and the potential use of existing carbon dioxide sensors for food packaging applications is still somewhat distant (Kerry & Papkovsky, 2002).

#### 3.1.2. Fluoresence-based oxygen sensors

Flourescence-based oxygen sensors represent the most advanced and promising systems to date for remote measurement of headspace gases in packaged meat products. Reiniger, Kolle, Trettnak, & Gruber (1996) first introduced the concept of using luminescent dyes quenched by oxygen as non-destructive indicators in food packaging applications. A number of oxygen sensing prototypes have been developed and are expected to appear in large-scale commercial applications in the near future. These sensors can be produced cheaply, are disposable and when used in conjunction with accurate instrumentation provide rapid determination of oxygen concentration (Kerry & Papkovsky, 2002).

The active component of a fluorescence-based oxygen sensor normally consists of a long-delay fluorescent or phosphorescent dye encapsulated in a solid polymer matrix. The dye-polymer coating is applied as a thin film coating on a suitable solid support (Wolfbeis, 1991). Molecular oxygen, present in the packaging headspace, penetrates the sensitive coating through simple diffusion and quenches luminescence by a dynamic, i.e. collisional mechanism. Oxygen is quantified by measuring changes in luminescence parameters from the oxygen-sensing element in contact with the gas or liquid sample, using a pre-determined calibration. The process is reversible and clean: neither the dye nor oxygen is consumed in the photochemical reactions involved, no by-products are generated and the whole cycle can be repeated.

Materials for oxygen sensors must meet strict sensitivity and working performance requirements if they are to prove suitable for commercial intelligent packaging applications. They must also have fluorescent characteristics suited to the construction of simple measuring devices. Fluorescence and phosphorescence dyes with lifetimes in the microsecond range are best suited to oxygen sensing in food packaging. Other necessary features include suitable intensity, well-resolved excitation and emission longwave bands and good photostability characteristics of the indicator dye. Such features allow sensor compatibility with simple and inexpensive optoelectronic measuring devices (LEDs, photodiodes, etc.), minimise interference by scattering and sample fluorescence and allow long-term operation without recalibration (Papkovsky, 1995). Materials using fluorescent complexes of ruthenium, phosphorescent palladium(II)– and platinum(II)–porphyrin complexes and related structures have shown promise as oxygen sensors (Papkovsky et al., 1991; Papkovsky et al., 1995; Wolfbeis, 1991). Subsequent work on phosphorescent complexes of porphyrin–ketones elucidated favourable sensing properties such as high stability, water insolubility, non-volatility and low toxicity (Papkovsky et al., 1995).

The combination of indicator dye and the encapsulating polymer medium in which oxygen quenching occurs determine the sensitivity and effective working range of such sensors. For the purposes of food packaging applications, dyes with relatively long emission lifetimes (~40–500 μs) such as Pt-porphyrins combined with polystyrene as polymer matrix appear to offer greatest potential (Papkovsky, Papovskaia, Smyth, Kerry, & Ogurtsov, 2000). Sensors on microporous support materials (Papkovsky, Ovchinnikov, Ogurtsov, Ponomarev, & Korpela, 1998) also provide a number of unique features for special sensing applications including those applicable to food packaging systems. Other polymers with good gas-barrier properties such as polyamide, polyethylene terephthalate and PVC are not suitable for oxygen sensing as oxygen quenching is slow in such media (Comyn, 1985). The use of plasticized polymers is also unsuitable due to toxicity concerns associated with potential plasticizer migration.

Sensor fabrication involves a simple process of dissolution of lipophilic indicator dye and appropriate polymer support in an organic solvent. This cocktail is applied to a solid substrate such as a polyester film or glass and allowed dry to produce a fluorescent film coating or spot. A number of coating techniques that lend themselves to large scale, continuous production (casting, dipping, spin coating, drop dispensing and spraying) offer possibilities for commercial production. Sensors, normally 1–2 cm in diameter, are coloured (due to the dye) and are readily visible on different support materials.

Oxygen sensor active elements can be manufactured on a large scale using relatively inexpensive materials and equipment. They are robust, suitable for long term/continuous monitoring and can be disposed of easily. Such materials have been successfully used in a variety of non-food applications. In order to ensure successful commercial uptake in food packaging a number of practical criteria must be considered.

*Working range*. Most oxygen sensors work effectively within two orders of oxygen concentration (or more in some cases). Most of the sensors described work within the range from 0 to 100 kPa of oxygen, or at least 0–21 kPa (0–21%) with detection limits of 0.01–0.1 kPa (where, in simple terms, kPa corresponds to percentage oxygen pressure (at room temperature and ambient air pressure)). Such working ranges are, in general suitable for many meat packaging applications and MA packaging in particular.

*Temperature dependence*. Sensors for food packaging applications are required to operate over a wide temperature range (~−20 to +30 °C). A lack of systematic and comparative data exists on the behaviour of oxygen sensors over such wide temperature ranges with few studies having addressed this issue (Papkovsky et al., 2000). Further research is required to ensure the effectiveness of such systems under all meat storage and distribution conditions.

*Response*. The use of thin film coatings for the sensing material results in low diffusion barrier properties and very fast sensor responses to changes in oxygen concentration – in some case as low as tenths of milliseconds (Kolle et al., 1997). This feature is important for real-time, on-line quality control of large volume throughput of packages. Such rapid screening allows for immediate identification of improperly sealed units and their removal.

*Stability*. Sensors incorporated into meat packages are required to remain operable and reliable from the point of packaging to the point of opening. In the case of chill storage of meat products this can be up to several weeks duration. Exposure to light, including UV/retail display lighting can cause gradual photobleaching of certain dyes or ageing of polymers. In the case of phase fluorimetric oxygen sensors this is not important but can be problematical for other sensor types.

*Intrinsic toxicity*. Sensor materials, i.e. dyes, polymers, residual solvents and additives are the main cause for concern in terms of potential toxicity issues. In general, the total quantity required to produce a single pack sensor is normally less than 1 mg, of which the encapsulating polymer represents >95%. The amount of dye per sensor usually varies to within a few micrograms. For most organic dyes, such quantities are far below established toxicity levels. It is advisable that solvents normally used in the food industry be used in sensor manufacture in order to avoid dangers associated with residual solvents. O'Riordan, Voraberger, Kerry, & Papkovsky (2005) examined the migration of active components of two metalloporphyrin and one ruthenium dye-based oxygen sensors and established their stability, safety and suitability for large scale use in food packaging applications.

Other recent publications on the suitability of fluorescence-based oxygen sensors have provided much useful data on their effectiveness in meat packaging applications. Fitzgerald et al. (2001) examined the potential of platinum based disposable oxygen sensors as a quality control instrument for vacuum-packed raw and cooked meat and MA packed sliced ham. Direct contact of sensors on the foods provided accurate oxygen profiles over time and correlated well with conventional (i.e. destructive) headspace analysis. Smiddy, Papkovskaia, Papkovsky, & Kerry (2002) used oxygen sensors to examine the effects of residual oxygen concentration on lipid oxidation in both anaerobically packaged MA and vacuum-packed cooked chicken and in raw and cooked beef (Smiddy et al., 2002). These studies further demonstrated the suitability of such sensors to measure, oxygen levels (non-destructively) in commercially used meat packaging and their potential as predictors of quality in processed muscle foods. Papkovsky, Smiddy, Papkovskaia, & Kerry (2002) used oxygen sensors to measure oxygen content in the headspace of four commercial sliced ham products. Accurate measurements were made under ambient light conditions, in direct contact with the product and under conditions of significant temperature variation. Although the sensor demonstrated minor changes in calibration as a result of direct physical contact with the meat surface over a prolonged period, these effects were minimised through optimisation of the sensor material. It is unlikely, in any case, that the presence of sensors in direct contact with a meat product would be acceptable to either producer or consumer. O'Mahony et al. (2004) used fluorescent oxygen sensors printed directly onto the packaging material of sous vide beef lasagne. Although a clear correlation between oxygen profiles, microbial growth and lipid oxidation was established, further studies appear necessary to investigate issues relating to sensor/packaging material compatibility.

Fluorescent oxygen sensors are also useful in detecting the substantial fraction of commercial anearobically MA or vacuum packed meat products containing elevated levels of oxygen (Papkovsky et al., 2002; Smiddy et al., 2002).

The development of oxygen sensors outlined above is indicative of the move towards commercialisation of indicator-type intelligent packaging. The result, given the viable outcome of future research initiatives, may ultimately see the incorporation of sensors in every meat pack produced. Such a scenario would mean the production of millions of sensors and thousands of measurement devices at different points in the production and distribution chain. It has been estimated that in today's terms, each sensor should cost less than one cent to produce (Kerry & Papkovsky, 2002) and impact minimally on packaged meat production costs.

OxySense® (http://www.oxysense.com) is the first commercially available fluorescence quenching sensor system for measurement of headspace or dissolved oxygen in transparent or semi-transparent, sealed packages. The system uses an oxygen sensor ($O_2$xyDot™) placed in the package before filling and is non-destructive, rapid (measurements take less than 5 s) and able to withstand pasteurisation temperatures without loss of sensitivity.

### 3.1.3. Biosensors

Other approaches to freshness indication, which may find commercial application in intelligent meat packaging systems are those based on recently developed biosensor technologies.

Biosensors are compact analytical devices that detect, record and transmit information pertaining to biological reactions (Yam, Takhistov, & Miltz, 2005). These devices consist of a bioreceptor specific to a target analyte and a transducer to convert biological signals to a quantifiable electrical response. Bioreceptors are organic materials such as enzymes, antigens, microbes, hormones and nucleic acids. Transducers may be electrochemical, optical, calorimetric, etc., and are system dependent. Intelligent packaging systems incorporating biosensors have the potential for extreme specificity and reliability. Market analysis of pathogen detection and safety systems for the food packaging industry suggests that biosensors offer considerable promise for future growth (Alocilja & Radke, 2003).

The majority of available biosensor technology is not yet capable of commercial realisation in the food sector. At present two biosensor systems are commercially available. ToxinGuard™ developed by Toxin Alert (Ontario, Canada) is a visual diagnostic system that incorporates antibodies in a polyethylene-based plastic packaging and is capable of detecting *Salmonella* sp., *Campylobacter* sp., *E. coli 0517* and *Listeria* sp. (Bodenhammer, 2002; Bodenhammer, Jakowski, & Davies, 2004). The Food Sentinel

System™ (SIRA Technologies, California, USA) is a biosensor system capable of continuous detection of contamination through immunological reactions occurring in part of a barcode. The barcode is rendered unreadable by the presence of contaminating bacteria. Such systems give some insight into products likely to become more mainstream in the years to come.

### 3.2. Indicators

An indicator may be defined as a substance that indicates, the presence or absence of another substance or the degree of reaction between two or more substances by means of a characteristic change, especially in colour. In contrast with sensors, indicators do not comprise receptor and transducer components and communicate information through direct visual change.

#### 3.2.1. Integrity indicators

An alternative approach to package-destructive, quality assurance techniques is the use of non-invasive indicator systems as part of an MA package. Such systems usually provide qualitative or semi-quantitative information through visual colorimetric changes or through comparison with standard references. The majority of indicators have been developed for package integrity testing, an essential requirement for the maintenance of quality and safety standards in packaging of meat products. The most common cause of integrity damage in flexible plastic packages is associated with leaking seals (Hurme, 2003). Permanent attachment of a leak indicator or sensor (i.e. visual or optochemical) to a package appears to hold most promise in ensuring package integrity throughout the production and distribution chain. A number of studies on package integrity in MAP meat products (Ahvenainen, Eilamo, & Hurme, 1997; Eilamo, Ahvenainen, Hurme, Heiniö, & Mattila-Sandholm, 1995; Randell et al., 1995) have established critical leak sizes and associated quality deterioration. Although a number of destructive manual methods are available for package integrity and leak testing such tests are laborious and can test only limited numbers of packs (Hurme, 2003). Available non-destructive detection systems (which include a number of stimulus response techniques) have other disadvantages such as the need for specialised equipment, slow sampling time and an inability to detect leakages that are penetrable by pathogens (Hurme & Ahvenainen, 1998; Stauffer, 1988).

Much work on the development of integrity detection for packaged foods has focused on visual oxygen indicators in MAP foods (as opposed to those oxygen sensors previously discussed, which are also applicable to integrity testing). With the exception of high oxygen content MA packaging of fresh meat (primarily to enhance colour) many foods are packaged in low (0–2%) oxygen atmospheres. In such cases, leaks normally result in a significant increase in oxygen concentration. Many visual oxygen indicators consisting mainly of a redox dyes have been patented (Davies & Gardner, 1996; Krumhar & Karel, 1992; Mattila-Sandholm, Ahvenainen, Hurme, & Järvi-Kääriänen, 1995; Yoshikawa, Nawata, Goto, & Fujii, 1987). Such devices have been tested as leak indicators in MA packaged minced steaks and minced meat pizzas, respectively, and reported as reliable (Ahvenainen et al., 1997; Eilamo et al., 1995). Disadvantages of such devices include high sensitivity (~0.1% oxygen concentration required for colour change means indicators are susceptible to residual oxygen in MA packs) and reversibility (undesirable where increased oxygen due to a leak is consumed during subsequent microbial growth). Few of these devices have been taken up commercially. One indicator system, specifically designed for MAP foods contains, in addition to an oxygen sensitive dye, an oxygen absorbing component and exemplifies active and intelligent packaging in a single system (Mattila-Sandholm, Ahvenainen, Hurme, & Järvi-Kääriänen, 1998).

A number of companies have produced oxygen indicators, the main application of which has been for the confirmation of proper functioning of oxygen absorbers (an active packaging function). Trade names of such devices have included Ageless Eye®, Vitalon®, and Samso-Checker® (Smolander, Hurme, & Ahvenainen, 1997).

A visual carbon dioxide indicator system consisting of calcium hydroxide (carbon dioxide absorber) and a redox indicator dye incorporated in polypropylene resin was described by Hong & Park (2000) and may be applicable to certain meat packaging applications.

#### 3.2.2. Freshness indicators

The information provided by intelligent packaging systems on the quality of meat products may be either indirect (i.e. changes in packaging oxygen concentration may imply quality deterioration through established correlation) or direct. Freshness indicators provide direct product quality information resulting from microbial growth or chemical changes within a food product. Microbiological quality may be determined through reactions between indicators included within the package and microbial growth metabolites (Smolander, 2003). As yet the number of practical concepts of intelligent package indicators for freshness detection is very limited. Despite this, considerable potential exists for the development of freshness indicators based on established knowledge of quality indicating metabolites. The chemical detection of spoilage of foods (Dainty, 1996) and the chemical changes in meat during storage (Nychas, Drosinos, & Board, 1998) provide the basis for which freshness indicators may be developed based on target metabolites associated with microbiologically induced deterioration. Using the marker concept in this manner may result in the more widespread commercial development of freshness indicators for meat products in the not too distant future.

The formation of different potential indicator metabolites in meat products is dependent on the product type, associated spoilage flora, storage conditions and packaging system. A number of marker metabolites associated with muscle food products exist upon which indicator development may be based.

Changes in the concentration of organic acids such as *n*-butyrate, L-lactic acid, D-lactate and acetic acid during storage offer potential as indicator metabolites for a number of meat products (Shu, Håkanson, & Mattiason, 1993). Colour based pH indicators offer potential for use as indicators of these microbial metabolites.

Ethanol, like lactic acid and acetic acid, is an important indicator of fermentative metabolism of lactic acid bacteria. Randell et al. (1995) reported an increase in the ethanol concentration of anaerobically MA packaged marinated chicken as a function of storage time.

Biogenic amines such as histamine, putrescine, tyramine and cadaverine have been implicated as indicators of meat product decomposition (Kaniou, Samouris, Mouratidou, Eleftheriadou, & Zantopolous, 2001; Okuma, Okazaki, Usami, & Horikoshi, 2000; Rokka, Eerola, Smolander, Alakomi, & Ahvenainen, 2004). Given toxicological concerns associated with these compounds and their lack of impact on sensory quality, the development of effective amine indicators would be of benefit. Detection systems described by Miller, Wilkes, & Conte (1999), and Loughran & Diamond (2000) provide potential for commercial development. In 1999, COX Technologies, USA, launched FreshTag® colour change indicator labels that react to volatile amines produced during storage of fish and other seafoods.

Carbon dioxide produced during microbial growth can in many instances be indicative of quality deterioration. In MA packaged meat products containing high carbon dioxide concentration (typically 20–80%), indication of microbial growth by changes in carbon dioxide content is problematical, although application of pH dye indicators may hold promise in other meat packaging systems.

Hydrogen sulphide, a breakdown product of cysteine, with intense off-flavours and low threshold levels is produced during the spoilage of meat and poultry by a number of bacterial species. It forms a green pigment, sulphmyocin, when bound to myoglobin and this pigment formed the basis for the development of an agarose-immobilised, myoglobin-based freshness indicator for unmarinated broiler pieces (Smolander et al., 2002). The indicator was not affected by the presence of nitrogen or carbon dioxide and offers potential.

A variety of different types of freshness indicators have been described (Smolander, 2003), the majority of which are based on indicator colour change in response to microbial metabolites produced during spoilage. Freshness indicators based on broad-spectrum colour changes have a number of disadvantages which need to be resolved before widespread commercial uptake is likely. A lack of specificity means that colour changes indicating contamination can occur in products free from any significant sensory or microbiological quality deterioration. The presence of certain target metabolites is not necessarily an indication of poor quality. More exact correlations appear necessary between target metabolites, product type and organoleptic quality and safety. The possibilities of false-negatives are likely to dissuade producers from adopting indicators unless specific indication of actual spoilage can be guaranteed.

### 3.2.3. Time-temperature indicators

A time-temperature indicator or integrator (TTI) may be defined as a device used to show a measurable, time-temperature dependent change that reflects the full or partial temperature history of a food product to which it is attached (Taoukis & Labuza, 1989). Operation of TTIs is based on mechanical, chemical, electrochemical, enzymatic or microbiological change, usually expressed as a visible response in the form of a mechanical deformation, colour development or colour movement (Taoukis & Labuza, 2003). The visible response thus gives a cumulative indication of the storage temperature to which the TTI has been exposed. TTIs may be classified as either partial history or full history indicators, depending on their response mechanism. Partial history indicators do not respond unless a temperature threshold has been exceeded and indicate that a product has been exposed to a temperature sufficient to cause a change in product quality or safety. Full history TTIs give a continuous temperature-dependent response throughout a products history and constitute the main focus of interest for research and commercial exploitation.

Essentially TTIs are small tags or labels that keep track of time-temperature histories to which a perishable product is exposed from the point of manufacture to the retail outlet or end-consumer (Fu & Labuza, 1995). Their use in meat and poultry products, where monitoring of the cold distribution chain, microbial safety and quality are of paramount importance, offers enormous potential.

The basic requirement of an effective TTI is to indicate clear, continuous, irreversible reaction to changes in temperature. Ideally, TTIs should also be low cost, small, reliable, easily integrated into food packaging, have a long pre- and post-activation shelf life and be unaffected by ambient conditions other than temperature. TTIs should also be flexible to a range of temperatures, robust, pose no toxicological or safety hazard and convey information in a clear manner.

A large number of TTI types have been developed and patented, the principles and applications of which have been previously reviewed (Fu & Labuza, 1995; Selman, 1995; Taoukis & Labuza, 2003). TTIs currently commercially available include a number of diffusion, enzymatic and polymer-based systems. All of which offer potential in meat and poultry products.

*Diffusion-based TTIs*. The 3M Monitor Mark® (3M Company, St. Paul, MN, USA) is an indicator dependent on the diffusion of a coloured fatty acid ester along a porous wick made of high quality blotting paper. The measurable response is the distance of the advancing diffusion front from the origin. The useful range of temperatures and the response life of the TTI are determined by the type and concentration of ester.

Another diffusion-based TTI, Freshness Check®, produced by the same company incorporates a viscoelastic material that migrates into a diffusively light-reflective porous matrix at a temperature dependent rate. This causes a progressive change in the light transmissivity of the porous matrix and provides a visual response.

*Enzymatic TTIs*. The VITSAB® TTI (VITSAB A.B., Malmö, Sweden) is based on a colour change induced by a drop in pH resulting from the controlled enzymatic hydrolysis of a lipid substrate. The indicator consists of two separate compartments containing an aqueous solution of lipolytic enzymes and another containing the lipid substrate suspended in an aqueous medium and a pH indicator mix. Different enzyme–substrate combinations are available to give a variety of response lives and temperature dependencies. Activation of the TTI is brought about by mechanical breakage of a seal separating the two compartments and may be done manually or by on-line automation. Hydrolysis of the substrate causes a drop in pH and a subsequent colour change in the pH indicator from dark green to bright yellow. Visual evaluation of the colour change is made by reference to a five-point colour scale. CheckPoint® labels are the latest TTIs developed by VITSAB, which comprise a label type designed to create a better subjective reading response for users and offer direct application to poultry and ground beef products. VITSAB, in conjunction with British Airways, has also recently developed a TTI system (Flight 17 Smart Label) that allows airline personnel to check the status of perishable pre-prepared foods.

*Polymer-based TTIs*. Lifelines Freshness Monitor® and Fresh-Check TTIs (Lifelines Technology Inc., Morris Plains, NJ, USA) are based on temperature dependent polymerisation reactions in which diacetylene crystals polymerise via 1,4 addition polymerisation to a highly coloured polymer. Resulting changes in reflectance can be measured by scanning with a laser optic wand. The Fresh-Check® consumer version uses a circular label in which the colour of the inner circle is compared to that of an outer circle in order to establish use-by status.

Initial expectations on the potential of TTIs to contribute to improved standards in food distribution, quality and safety have not been realised to date. Factors such as cost, reliability and applicability have all been influential in this regard. The cost of TTIs has been estimated at $0.02 to $0.20 per unit (Taoukis & Labuza, 2003). VITSAB CheckPoint® labels are estimated at $0.10 per label (http://www.vitsab.com). Given normal economies of scale, cost-benefit analysis should favour more widespread use of TTIs. Faith in the reliability of TTIs has been undermined somewhat by insufficient supporting data. It appears now that TTI systems have achieved high standards of production and quality assurance and provide reliable and reproducible responses according to BSI specifications (BS 7908, 1999). The most substantial hurdle to extensive commercial TTI use has been the question of applicability. Generalisations on the relationship between temperature and food quality of general food classes have proved insufficient, as even foods of similar type differ markedly in terms of response. For successful application of TTIs to meat and poultry products, and food products in general, there is a requirement that the TTI response matches the behaviour of the food. Whilst the expectation for a TTI to strictly match the behaviour of a foodstuff over a wide temperature range is unfeasible, a thorough knowledge of the shelf-life loss behaviour of a food system based on accurate kinetic models is essential (Taoukis & Labuza, 2003). Advances in food modelling are now making this possible and these have been reviewed by Taoukis (2001).

A number of validation studies have been undertaken in order to establish the usefulness of TTIs in food products (Riva, Piergiovanni, & Schiraldi, 2001; Shimoni, Anderson, & Labuza, 2001; Welt, Sage, & Berger, 2003). Yoon, Lee, Kim, Kim, & Park (1994) showed a positive correlation between oxidative stability and TTI colour change using a phospholipid/phospholipase-based TTI in frozen pork. Smolander, Alakomi, Ritvanen, Vainionpää, & Ahvenainen (2004) & Vainionpää et al. (2004) determined the applicability of VITSAB®, Fresh-Check® and 3M Monitor® TTIs for monitoring the quality of MA packed broiler cuts at different temperatures and in comparison with several standard analytical methods, respectively. In both studies, TTIs were closely correlated with microbiological analyses of spoilage bacteria and were shown to be more effective than certain metabolic quality indices such as spoilage-associated volatiles, biogenic amines and organic acids.

In 1991 a UK survey (MAFF, 1991) indicated that 95% of respondents ($n = 511$) considered TTIs to be a good idea but indicated that substantial publicity or an educational campaign would be required for general use. It is likely that similar attitudes still apply today. Despite predictions for the full commercial realisation of TTIs, adoption has been very limited. However, given technological developments in recent years and greater consumer appreciation for the need for food safety monitoring (particularly in meat products), analysts believe that TTIs will inevitably find widespread commercial application in the food industry. The critical importance of maintaining proper storage temperatures for meat and poultry products throughout the distribution chain means that this sector of the food industry could be a major beneficiary from any such development.

### 3.3. Radio frequency identification tags (RFID)

RFID technology does not fall into either sensor or indicator classification but rather represents a separate electronic information based form of intelligent packaging. RFID uses tags affixed to assets (cattle, containers, pallets, etc.) to transmit accurate, real-time information to a user's information system. RFID is one of the many automatic-identification technologies (a group which includes barcodes) and offers a number of potential benefits to the meat production, distribution and retail chain. These include traceability, inventory management, labour saving costs, security and promotion of quality and safety (Mousavi, Sarhavi, Lenk, & Fawcett, 2002). Prevention of product recalls is also considered an important role of RFID technology (Kumar & Budin, 2006). RFID technology has been available for approximately 40 years although it's broad application to packaging is a relatively recent development.

At it's most basic level, an RFID tag contains a tiny transponder and antenna that have a unique number or alphanumerical sequence; the tag responds to signals received from a reader's antenna and transmits it's number back to the reader. While the tags are relatively simple, much better inventory information than barcode or human entry systems can be gained through tracking software. RFID tags have the advantage over barcoding in that tags can be embedded within a container or package without adversely affecting the data. RFID tags also provide a non-contact, non-line-of-sight ability to gather real-time data and can penetrate non-metallic materials including bio-matter (Mennecke & Townsend, 2005). RFID tags can hold simple information (such as identification numbers) for tracking or can carry more complex information (with storage capacity at present up to about 1 MB) such as temperature and relative humidity data, nutritional information, cooking instructions, etc. Read-only and read/write tags are also available depending on the requirements of the application in question.

Tags can be classified according to two types: active tags function with battery power, broadcast a signal to the RFID reader and operate at a distance of up to approximately 50 m. Passive tags have a shorter reading range (up to approximately 5 m) and are powered by the energy supplied by the reader (giving them essentially unlimited life).

Common RFID frequencies range from low ($\sim$125 kHz) to UHF (850–900 MHz) and microwave frequencies ($\sim$2.45 GHz). Low frequency tags are cheaper, use less power and are better able to penetrate non-metallic objects. These tags are most appropriate for use with meat products, particularly where the tags might be obscured by the meat itself and are ideal for close-range scanning of objects with high water content.

The costs of RFID are decreasing rapidly as major companies such as Wal-Mart, 7-Eleven and Marks & Spencers adopt the technology. At present, the cost of passive RFID tags ranges from approximately from \$0.50 to \$1.00. For the technology to be truly competitive analysts estimate that tags must cost less than \$0.05 (others below \$0.01) (Want, 2004). It is expected that tags will fall to the \$0.01 per-tag level after 2007 (Mennecke & Townsend, 2005). Initiatives to establish formal standards should also serve to reduce further the cost of RFID systems.

RFID is beginning to be used in a number of countries for tracing individual animals (mainly cattle) from birth to the processing plant. The key to individual animal traceability lies in the ability to transfer animal information sequentially and accurately to sub-parts of the animal during production. RFID-based tracking systems provide an automated method of contributing significantly to that information exchange (Mennecke & Townsend, 2005). At present, individually RFID tagged meat products are not available to the consumer, although the use of RFID tagging of meat cuts has extended, in one case at least, to the pig processing industry (http://www.flagshipfoods.co.uk/dalehead), from the individual pig to its' primal pieces, i.e. hams. Although the purpose of this tracking scheme is for quality control, employee accountability and precision cutting, and does not extend beyond the cutting room floor or provide information about the individual animal with the final product, it does exemplify the developing use of RFID technology within the meat industry. Although the implementation of intelligent packaging of meat products using RFID technology is still largely hypothetical, indications suggest it is unlikely to remain so for very much longer.

## 4. Conclusion

The ultimate incentive for deployment of any new technology is cost. The cost effectiveness of active and intelligent packaging devices is dependent on the perceived benefits derived from such systems. Producers must ultimately derive benefit from increased profit margins and consumers must derive benefit as 'utility' or satisfaction from economic exchange. Economies of scale suggest that the cost of many active packaging devices (scavengers, absorbers, emitters) or intelligent packaging devices such as oxygen sensors, TTIs or passive RFID tags are not currently or will not be a factor prohibitive to mass commercialisation. What little consumer-attitude information available seems to be positive towards such packaging concepts (Lähteenmäki & Arvola, 2003).

Changes in consumer preferences have led to innovations and developments in new packaging technologies. Active packaging is useful for extending the shelf life of fresh, cooked and other meat products. Forms of active packaging relevant to muscle foods include; oxygen scavengers, carbon dioxide scavengers and emitters, drip absorbent sheets and antimicrobial packaging. Recognition of the benefits of active packaging technologies by the food industry, development of economically viable packaging systems and increased consumer acceptance opens new frontiers for active packaging technology. Commercially, there is widespread use of oxygen scavengers in pre-packed cooked sliced meat products. Antimicrobial packaging is gaining interest from researchers and industry due to its potential for providing quality and safety benefits. Future research in the area of microbial active packaging should focus on naturally derived antimicrobial agents, bio-preservatives and biodegradable packaging technologies. The possibility of utilising additional active packaging technologies, as currently applied to other foodstuffs, for safe and effective storage of meat and meat products also merits investigation.

In order to address the present imbalance between potential and realisation of intelligent packaging concepts, a number of research gaps need to be filled. These include further modelling of the interactions between foods and microbes and their metabolites under dynamic storage conditions, better understanding of correlations between spoilage indication and sensory quality, effective incorporation of sensors and indicators into high-volume packaging processes, knowledge on the behaviour of intelligent packaging devices at all points of the storage and distribution chain and issues relating to sensitivity (including over-sensitivity) and reliability. Food manufacturers can ill-afford inaccurate extrapolations based on a limited knowledge base. Nor will they risk commercial investment in unproven technologies.

The potential advantages of intelligent packaging for muscle-based foods are many and varied. Apart from aspects of quality, safety, and distribution already outlined, intelligent packaging offers considerable potential as a marketing tool and the establishment of brand differentiation for meat products. Assuming intelligent packaging can effectively provide solutions to current producer and consumer problems, it appears likely that intelligent packaging systems for muscle-based food products will become more commercially viable and common-place in the years to come.

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