23 Mathematical modelling in meat processing

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Introduction

Processing meat into products frequently involves comminution and blending operations which may be followed by a heating stage to cook or stabilise the product. The variables which give individual products their distinctive character are numerous. Species, age of the animal, cut and composition of the meat, are to some extent controllable, as are addition of water, salt, polyphosphates, nitrite and spices, all of which have important roles in product quality. Factors less readily controllable are events associated with slaughter, chilling, conditioning and frozen storage, and those attributable to live animal stress causing gross differences in meat structure. Variation in quantity and quality of ingredients and severity of process are likely to affect yield, nutritional value, shelf life and the physical and sensory characteristics of the product. Hence, accurate prediction of the consequences of the events associated with carcass treatment and product composition could result in improvements in processing procedures and increased economic efficiency.

To study some of these interactions, the colour, shear and cooking loss, of a meat product were used to create mathematical models. The principal advantage of using models in such mixture experiments is that they provide estimates of the properties of the entire system from only a limited number of observations (Cornell, 1973). In practice, there is usually a specific area of interest within the system which can be defined. Models based on linear equations take no account of interactions; inclusion of square terms are necessary for two way interactions and cubic terms for those within the boundary of the model. A comparatively simple but elegant solution using polynomial models for 3 component mixtures (Plackett, 1963) was devised by Sheffé (1963). The basis for this special cubic model is a simplex centroid design of a symetrical arrangement of points in a triangle. It has the property that the coefficients of the model can be calculated even though the major constituents in the mixture are themselves mixtures. Examples of such models are illustrated for food formulations by Hare (1974) and their use fully discussed by Cornell (1981).

This paper reports the results of three specific objectives which were: (a) to assess the effectiveness of the special cubic model (Sheffé, 1963) for mixtures of the three main components of meat products, i.e. muscle, fat and water, (b) to test the effect of structure changes in the raw meat by varying the post-slaughter chilling regime, (c) to quantify the interactive effects of modifying salt and polyphosphate concentrations, especially on water holding and texture properties, using a central rotatable design (Cochran and Cox, 1957). This design requires only a small number of observations and is particulrly suitable for studying the effects of addition of minor quantities of components in a system.

Experimental

Materials The meat used was from shoulders of heavy hogs purchased locally and slaughtered at the Meat Research Institute.

Chilling Regimes Immediately after slaughter and dressing, the shoulders were removed from the warm carcasses, deboned and vacuum packed in nylon-polyethylene laminate bags and chilled by immersion in tanks of water. The left shoulders, designated "fast" chilled, were held for 2 hours at 15°C and then transferred to 0°C (ice-water mixture) for >20 hours. The right shoulders, "slow" chilled, were maintained at 35°C for 5 hours, transferred to the 15°C tank for 18 hours and finally brought down to 0°C in ice-water. For "hot" processing, meat was removed from shoulders and processed before the pH of the muscle reached 6.0.

Processing The meat was trimmed of excess fat and gross connective tissue, cut into small pieces, mixed and then ground in a single pass through an 8 mm plate in a Hobart Mincer. Pork backfat was similarly ground through an 8 mm plate.

Homogenates of meat, fat and water, with the appropriate levels of sodium chloride, sodium tripolyphosphate and sodium nitrite dissolved in the added water, were blended using a Robot Coupe R2 Food Processor. Each 1 kg mix was blended for a total of 60 sec at 3000 rpm divided into three periods of 15 sec, 30 sec and 15 sec intersperced by manual mixing to ensure uniform homogenisation. Two batches were then combined under vacuum in a Winkworth Mixer for 3 min to withdraw entrained air. The mixture was stuffed into 55 mm diameter fibrous casings and clipped into 3 sausages, 120 to 150 mm in length. These were held at +1°C, until cooked in fan circulated moist air at 80°C for 1 h in a Rapidaire Cooker,and then cooled to 0°C. The sausages were weighed before and after cooking, and after discarding the casing and removal of surplus liquid.

Experimental design

(a) Sheffé model. The simplex for the meat (M), fat (F) and water (W) mixtures was an equilateral triangle with vertices Z1 (0.9M; 0.0F; 0.1W), Z2 (0.6M; 0.3F; 0.1W) and Z3 (0.6M; 0.0F; 0.4W). Concentrations of sodium chloride, sodium tripolyphosphate and sodium nitrite included in the final product were 2 per cent, 0.25 per cent and 200 mg kg^{-1} respectively, values representative of those found in commercial products such as cured luncheon meat. Sodium nitrite was added to eliminate possible problems associated with pigment oxidation. The minimum number of points to construct the special cubic model is 7 but this has the limitation that the design does not explore the interior of the simplex except for the centroid. Therefore a further 16 points were also measured to establish the reliability of the model. Of these, 12 were spaced symetrically within the triangle and the remaining 4 along the Z1 - Z3 edge because of the magnitude of the effects expected from incorporation of such a large amount of water at Z3. The design should provide sufficient observations for the adequacy of the fitted model to be tested by examining the sum of squares of the residuals due to lack of fit.

(b) Central rotatable model. The levels of sodium chloride and sodium tripolyphosphate used to model their interactive effects were 0 to 4 per cent and 0 to 0.5 per cent respectively. This design requires 13 points, 5 at the centre and 8 equally spaced around the circumference of a circle on the principal and star point axes. The centre of the circle was therefore identical to the centroid of the mixture triangle.

Colour The colour of the vacuum packed raw homogenates, after conversion of the pigment to nitrosylmyoglobin, and freshly cut surfaces of the cooked sausage were measured on a Hunter D25-9 Tristimulus Colorimeter fitted with a D25-A Optical Sensor. The instrument measures directly in tristimulus values X, Y, Z from which the psychological colour attributes lightness (L), hue angle (H^o) and saturation (S) can be calculated (Taylor and MacDougall, 1973). Four replicate measurements were made on the raw mixture through the Metathene X vacuum pouch and at 4 locations in each cooked sausage.

Texture The cooked sausages were cut into 1 cm thick slices on a Berkel electric meat slicer and shear was measured by the punch and die technique (Segars et al., 1975) on an Instron Universal Testing Machine. The hole in the shear plate was 2.00 cm in diameter with clearance of 0.005 cm and the vertical speed of the punch was 5.00 cm min^{-1}. Results are reported as N m^{-2} based on the maximum force required to shear the disc. The number of replicate shears per sausage was 4.

Results

The colour of the raw product after homogenisation was oxymyoglobin pink, but during and immediately after vacuum mixing it oxidised to the typical metmyoglobin grey brown colour of the first stage in curing (MacDougall et al., 1975). After vacuum packing and several hours storage the raw mixtures developed the nitrosylmyoglobin pink colour of cured meat; the low fat samples were translucent and bacon-like in appearance. Inclusion of fat in the raw mix considerably increased opacity and lightness. This agrees with the rationale of the Kubelka-Munk analysis of absorption and light scatter (Kubelka, 1948; MacDougall, 1983). If the low water sample with no added fat (Z1) is considered to have a given absorption coefficient (K) and scatter coefficient (S), dilution by fat will increase S and reduce K with consequent increase in reflectance (R); $K/S = (1-R)^2/2R$. The determined tristimulus value Y between Z1 and high fat sample Z2 were found to be in agreement with this concept. Dilution of Z1 to Z3 with water darkened the raw mixture which can be explained by its lower internal transmittance and dissipation of the scattered light within the material. On cooking, the range in colour appearance was considerably reduced due to increased scatter from denatured protein.

The consistency of the raw homogenate ranged from a semifluid gel with maximum inclusion of water to a stiff sticky paste with maximum added fat. The texture of the cooked sausage ranged from moist and spongy but still cohesive to rubbery and resilliant as would be expected with inclusion of salt and polyphosphate.

Efficiency of mixture model The three types of model, linear, square and special cubic were compared. Improvement as complexity of the model increased was assessed by the variance accounted for (VAC) by each regression equation. There was an improvement of 1 to 2 per cent VAC for each increase in complexity. For each attribute, except cooking loss, the VAC was from 80 to 95 per cent. The lower VAC for cooking loss, <60 per cent, was because of the inherent imprecision of the technique.

Improvement from increase in number of observations, assessed by examining the sum of squares of the residuals, showed that the largest improvement was generally from 7 to 13 observations; in some cases there was negligible improvement from >13 observations. Clearly, more precise models will be constructed by increasing observations, but this has to be related to the experimental effort involved. For some situations, 7 observations will suffice.

Meat, fat, water model

(a) Fast chilled muscle. Models of raw and cooked lightness, shear and weight loss, based on 23 points and constructed from the "fast" chilled material, are shown in Figure 1. Raw lightness (L) ranged from 45 to 61 which is visually equivalent to 16 per cent of the difference between black and white. The direction of the contours clearly confirm the massive effect of increase in opacity and scattered light from fat and the lesser effect of added water on increasing translucency. Cooked product L ranged from 56 to 64, that is half that of the raw. Although the contours follow the same general direction as the raw, the modifying influence of added water on L is partly reversed. Z1 is now smaller than Z2, the opposite of raw. The reason for this can be explained by the difference in the relative contribution of the K and S coefficients before and after protein denaturation on cooking; Z2 is darkest raw because of the extra water increasing internal transmittance, whereas it is the lighter cooked because of lower pigment concentration and high scattering opacity.

Weight loss on cooking was affected by the fat content of the raw mix and to a lesser extent by the quantity of added water. The loss of liquid was small compared with the water added, illustrating the effective binding properties of salt and polyphosphate (Offer and Trinick, 1983). The wettest point Z3, with 40 per cent water, lost only 6 per cent on cooking.

Shear decreased predominantly with added water and to a lesser extent with added fat. The value halved from 62 to 24 N m^{-2} 10^3 from Z1 to Z3 along the water edge of the triangle but only to 46 at Z2 on the fat edge. The direction of the shear contours was opposite to that of raw and cooked L indicating that texture could not be predicted by measuring product colour.

(b) Muscle Structure. The effects of altering muscle structure on the models, either by extremely slow chilling or by hot processing were less marked than expected. The most important effect of slow chilling was an overall increase in weight loss, especially at Z3 where it more than doubled. Hot processing did not reduce weight loss on cooking and only resulted in small changes in shear, but both raw and cooked lightness was higher than the slow or quick chilled which may be the result of possible differences in the emulsification properties of muscle with high pH.

Salt, polyphosphate model The centre of the rotatable model was chosen to be identical to that of the mixture triangle. Shear for both centres was identical (45 N m^{-2} 10^3) with only a small displacement of the 5 per cent weight lost contour. The overall raw lightness range of the mixture set was darker but this does not invalidate interpretation of the circle. The models are shown in Fig. 2.

The range in raw L was 6 units, that is the effect of salt and polyphosphate on the light reflecting properties at the centre of muscle, fat and water is equivalent to half the range generated by the entire mixture triangle. L increased with salt concentration, decreased with polyphosphate to 0.3 per cent and then increased. On cooking these measured differences in L virtually disappeared. However there were obvious visual differences in cooked appearance related to salt concentrations. Above about 1 per cent salt freshly cut surfaces were cohesive and shiny, but approaching zero salt they lost their sheen and became matt as the structure lost its resilience and became crumbly.

The models also clearly demonstrate the interrelationship of salt and polyphosphate on both texture and water loss on cooking. The range in shear from <20 to >50 N m^{-2} 10^3 was similar to the range of the entire mixture triangle, whilst weight loss decreased from 20 per cent to near nil as salt increased. The interactive effect of polyphosphate with salt is seen in the slope of the contours for both shear and weight loss. For example, at 1 per cent salt, the addition of 0.1 per cent polyphosphate increases shear by 10 N m^{-2} 10^3 and decreases water loss by about 4 per cent, that is an effect equivalent to about 0.5 per cent salt.

Discussion

The results of this investigation confirm that mathematical modelling can be used to quantify the physical attributes in a meat product as affected by major variables in processing. The introduction of the technique in commercial practice would find immediate application in new formulations or creation of new products. Incorporation of modelling into least cost formulation procedures should result in a detectable and worthwhile improvement in product quality. At present, only a small number of economically important attributes are included in least cost formulations and little account is taken of the major quality attributes. Of the three objectives in this paper, that requiring most further work is associated with the properties of the raw meat. The "manufacturing quality" shoulder meat used was less susceptible to changes induced by chilling than was expected. A preliminary trial to assess the effects of stress susceptibility also resulted in little change. Shoulder meat from Pietrain pigs did not have the same pale, soft exudative character that obtains in the M. longissimus dorsi. It may be necessary, therefore, to use meat that would not normally be used for manufacturing products to model the effects of extremes of muscle structure.

The results reported are the preliminarly analyses of a larger set, for example, only the lightness attribute of colour is described. Modelling techniques will be used to relate the other psychological attributes of hue and saturation to product composition. Also, the existing mixture models are all based on initial composition; supplementary models need to be constructed on actual composition after processing.

Only one method of assessing the mechanical properties is reported and care must be exercised in interpreting shear contours as indicative of identical texture. Further work will attempt to model sensory assessment of texture to the mechnical properties.

An important finding in this work is the magnitude of the effects of salt and polyphosphate at one point relative to the meat, fat, water domain examined. How large the effects will be when modelled at the vertices of the triangle remains to be seen, but the results of modelling at the centre suggest that control of these minor ingredients has tremendous consequences on product quality.

The enormous potential of the use of modelling, demonstrated in the simple system used in this trial, will be tested in a more complex product, the British sausage, which has a minimum of 6 commonly used ingredients all with different physical and cost constraints. This will require the use of more complicated models.

The benefits of modelling in the meat industry in particular, and the food industry generally could be substantial. The increased understanding of the role of ingredients with minimum experimental effort could result in large savings.

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Figure 1 Models of the interaction of meat (M), fat (F) and water (W) on raw and cooked lightness, shear and weight loss in a meat product containing 2 per cent salt and 0.25 per cent sodium tripolyphosphate.

Vertices were: Z1 (0.9M; 0.0F; 0.1W)
Z2 (0.6M; 0.3F; 0.1W)
Z3 (0.6M; 0.0F; 0.4W)

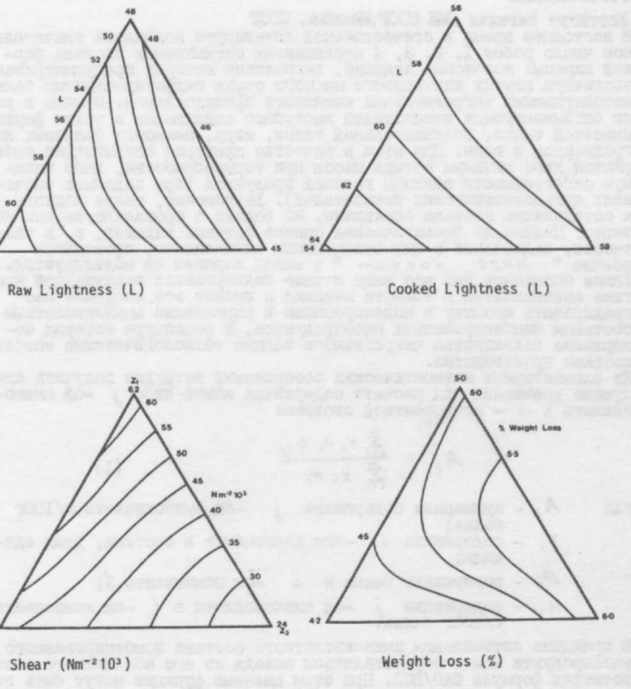

Figure 2 Models of the interaction of sodium chloride (NaCl) and sodium tripolyphosphate (TPP) on raw and cooked lightness, shear and weight loss in a meat product of composition 0.7 meat; 0.1 fat; 0.2 water.