

# Objective Measurement of Physical Aspects of Meat Quality

Howard J. Swatland\*

## Introduction

Biochemistry, histology, physiology and statistics are the dominant objective methods used by meat scientists to investigate meat quality and these methods have brought us a long way in our scientific understanding of meat. However, apart from one aspect of rheology (empirical use of the Warner-Bratzler shear method), the biophysical aspects of meat have been rather neglected. Research on the physical aspects of meat quality is important for a number of reasons.

(1) Physical aspects of meat quality are very important commercially. Tenderness is an obvious example. In the PSE (pale, soft, exudative) condition, all three aspects of the condition are physical in nature.

(2) Although biochemistry may explain why something has happened (for example, why postmortem glycolysis occurs), the interaction of biochemical and biophysical aspects must be understood to explain the complete effect (for example, how a low pH causes meat to become pale).

(3) The physical aspects of meat quality lend themselves readily to objective measurement. Some objective methods of measurement are rapid, reliable and non-destructive and may be used to measure or grade meat quality under commercial conditions.

The purpose of this presentation is to provide a brief introduction to some of the physical aspects of meat quality that I have investigated using objective methods. Special consideration is given to the most difficult problem of all: taking a laboratory method and developing it for use on-line in the meat industry. I have no experience in the rapidly developing field of video image analysis of cut meat<sup>1</sup> and my presentation is restricted to methods, potential or already in existence, for measuring meat quality in intact carcass sides.

## On-Line Measurements

The ability to make on-line measurements of meat quality would greatly improve the efficiency of meat merchandising and processing for the general benefit of both producers and consumers. The idea has been around for a long time and a variety of different types of apparatus appeared some years ago. The Armour Tenderometer (Hansen, 1971) had a battery of needles to measure meat toughness. The Goefo<sup>2</sup> was a monochromatic reflectance meter with hand-held measuring heads that could be used on rib-eye areas. Although used

to some extent for research, such methods were not feasible for routine use. Research and development for the on-line measurement of meat quality was forgotten until the meat industry accepted automated measurements of back-fat depth as a reasonable method of predicting lean yield.

The apparatus to measure fat depth consists of two main working parts: firstly, a device to monitor the depth of penetration of the probe and, secondly, a system to detect the fat-lean boundary. Since the first part uses technology that has been available for many years, the creation of fat-depth graders depended upon the development of the second part. Infrared reflectance using inexpensive photodiodes has emerged as the most successful system for detecting the fat-lean boundary, but this required time for research, development, testing and selling the idea. It has taken a very long time for fat-depth graders, which in principle are very simple devices, to reach wide usage in the meat industry. This is a salient point to remember for anyone interested in the far more complex technology of adding meat quality measurements to existing methods of fat-depth grading.

Another point that should not escape notice concerns the role which we, as meat scientists, have in the general environment of science and industry. Although meat scientists have certainly contributed to knowledge in the basic sciences, most of us take our ideas and methods from the basic sciences and apply them to meat. Thus, when we come to a topic such as the on-line measurement of meat quality, we may find the pool of basic knowledge worth applying to be rather inadequate. From an empirical or pragmatic perspective, our response to this dilemma might be to exploit existing technologies, such as the use of multivariate statistical analysis of infrared reflectance data gathered with a fiber-optic probe. There is a complete package of optoelectronic hardware and statistical software already available<sup>3</sup> and it might be relatively simple to develop methods to measure intramuscular lipid or protein content on intact carcasses. However, if we wish to do more than this, to measure more profound aspects of meat quality and to understand what we are doing, we have a long way to go. This, I believe, is why basic research on the physical aspects of meat quality is important. The great difficulty is that funding agencies for basic research generally will not support basic research on meat quality because it is already goal-oriented, while funding agencies for applied research are often only interested in research with a short-term economic or political pay-off.

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## On-Line Possibilities

We are all aware that meat quality means different things to different people, depending on whether they are producing, processing, selling or consuming the product. Relative to the on-line measurement of carcass meat quality, and taking a broad approach to consider present and future possibilities, some of the major properties that we might wish to measure are listed in Table 1.

Without getting side-tracked into considering meat quality per se, a few comments on Table 1 are needed. The point of the exercise is not to create a definitive list of the parameters of meat quality, but to scan through a typical list to see what possibilities might exist for on-line measurement.

With meat color, the basis of measurement is straightforward (spectrophotometry) and the items of interest in the muscle and the fat are very similar.

With fluid status, the muscle and fat differ fundamentally. With an intact muscle deep in the carcass, how might we predict whether fluid will be rapidly lost as soon as the muscle is cut or, at the other extreme, whether the muscle will be able to bind additional water when it is cut? Soft or semi-fluid fat is sometimes a commercial problem but, in this case, does the measurement of fat fluidity require a special technique? A spring-loaded on-line probe for the measurement of fat softness has been developed by Eric Dransfield at Bristol (Anon., 1987).

Structural properties are measurable on excised samples of meat (with varying degrees of reliability). For firmness-softness, it is likely that a transducer that could be used to measure the muscle could also be used for the fat. Tensile strength is the underlying basis of meat tenderness evaluation (Voisey, 1976), even though we still talk of shear-testing. There are immense differences between the structural properties of muscle and fat. For firmness-softness, there are dozens of potential methods we might use since strain-gauge technology is easily available off-the-shelf, but what about fascicular size? Turkey producers might like to produce turkey breasts with the fascicular texture of chicken breast.

**Table 1. Aspects of meat quality to measure on-line.**

PROPERTY	MUSCLE	FAT
Color	Myoglobin content	Carotene content
	Residual hemoglobin	Residual hemoglobin
	Paleness-darkness	Translucency
Fluid status	Water holding-binding	Melting point
Structural	Tensile strength	Layer adhesion
	Firmness-softness	Firmness-softness
	Fascicular size	
	Gristle content	
Chemical	Marbling fat	Volatile substances
	Flavor components	
	Residues	
Pathological	Muscle degeneration	Adipose pathology
	Parasites	
	Microbiological status	

Could it be measured in some way to facilitate progress towards this goal? The coarse fascicular structure of beef from bulls is often regarded as an undesirable trait. Could it be measured objectively in some way? Gristle content and tensile strength are often related, but if the two could be isolated, we might be able to separate the contributions of sarcomere length and connective tissue to meat toughness.

Chemical aspects of meat quality are varied. Looking at what is presently available, the measurement of protein:triglyceride ratio is probably measurable at present with off-the-shelf infrared technology. Looking to the future, one may envisage the combination of gas chromatography and probe technology. We might start with a probe for boar taint and finish with the on-line prediction of cooked meat taste.

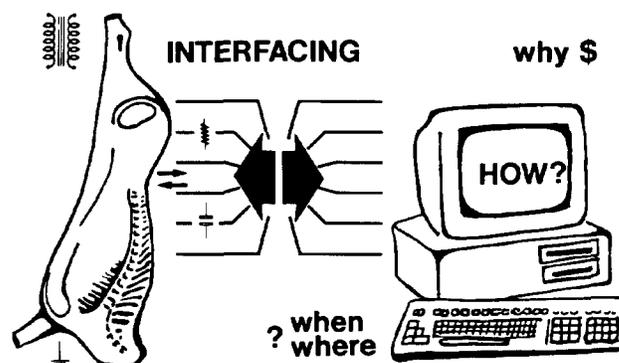
Finally, since meat inspection is already an established form of on-line quality control, some thought should be given to automating this, where possible, and adding it to the on-line measurement of meat quality. With the successful ongoing revolution in automated methods in microbiology, might it be possible to measure parasites and microbes in intact meat carcass?

Knowing little about microbiology, and even less about chromatography, I can offer no insights into how these latter aspects might develop and I leave the development and evaluation of chemical probes, such as the Pegasus system for measurement of nucleotide degradation by hydrogen peroxide polarography<sup>4</sup> to my more knowledgeable colleagues.

## Interfacing

On one hand, we have an intact meat carcass that may be hot, wet and moving while, on the other hand, we have a digital computer into which we wish to enter information on the meat quality of the carcass. Thus, immediately, we see that the key element to the on-line measurement of meat quality is the *interface* (Fig. 1). How can we connect the carcass to the computer to achieve our objective? At present, the meat quality data that we might produce on-line are processed by digital electronics and, perhaps, communicated by fiber optics. In my own research, commencing in the late 1970's, it seemed reasonable to start with relatively

Figure 1



<sup>4</sup>Microfresh, Pegasus Biotechnology, P.O. Box 319, Agincourt, Ontario, Canada M1S 3B9.

simple interfacing possibilities, and to consider how analog mechanical, electrical and optical signals might be interfaced fairly directly to a digital computer.

### Indirect Interfacing

The level of postmortem reflex activity probably has a major effect on the rate of postmortem glycolysis (Bendall, 1973) and so might be used to predict the development of PSE pork in carcasses. When I was working on the physiology of animal slaughtering, I could see little hope for using electromyography on an on-line basis. However, it was feasible to collect information on the electrical stunning of pigs and to use a load cell in the shackling chain (Fig. 2; Swatland, 1983a). The load cell gives information on the rate of exsanguination, the hot carcass weight and the degree of postmortem reflex activity. As the carcass is moved, the load cell provides information on the development of rigor mortis combined with the setting of adipose tissue as the carcass temperature declines (the recoil pattern differs between soft and rigor carcasses). Carcass temperature would be relatively easy to assess indirectly by infrared emittance.

### Electrical Properties of Meat

Most of the work in this field has been undertaken on pork. In Britain in the 1920's and 1930's, what we would now call dark, firm, dry (DFD) pork became a problem when the shipping of pigs by rail to new centralized abattoirs replaced local slaughtering. In traditional curing methods, the penetration of curing ingredients by diffusion is poor in DFD pork and leads to serious problems in the center of the ham. Banfield (1935) hit on the idea of measuring the penetration of curing salts by testing the electrical resistance of the meat. This led

to the discovery that the resistance of fresh pork was quite variable. Perhaps his original thought was simply that DFD hams were drier and would, therefore, have a higher resistance than wetter, normal hams.

The resistance of biological tissues cannot simply be determined from Ohm's law using a direct current because the current causes battery-like effects at the junctions of the metal electrodes with the tissue. An alternating current is used to avoid this effect (polarization) and so measures impedance rather than resistance. With Banfield's (1935) original apparatus, which used a bridge circuit to balance the impedance of the pork against a known impedance (primarily resistive impedance), the null point was found subjectively, using earphones to listen to the residual current.

Banfield (1935) was then faced with many of the logistical problems that are still with us today. Having found, in the laboratory, how to measure objectively the fluid status (PSE-normal-DFD) of pork, the next problem was how to make such measurements under industrial conditions. The key problems were, and still are:

- (1) portability,
  - (a) weight or size,
  - (b) rugged construction,
  - (c) water-resistance,
  - (d) power supply,
  - (e) simplicity,
  - (f) speed of measurement,
- (2) measurement,
  - (a) standardization,
  - (b) sensitivity,
  - (c) accuracy,
  - (d) repeatability,
    - (i) internal error,
    - (ii) sample variance,
  - (e) degree of objectivity.

His solution was to adapt a hand-cranked soil ohmmeter (50 Hz, 92 mA, 80 V; regulated by a slipping clutch mechanism) for use in the abattoir. Quite probably, he or his technician were able to jot down their readings from an analog meter in a laboratory notebook.

Each of the above points could easily be expanded to many pages if this was a text-book rather than a short lecture. Most of the points are common sense, or will be familiar to anyone with experience with scientific instrumentation. All of the points, however, have hidden aspects. Let us take power supply as an example. The shackle or gambrel that supports the carcass is generally grounded via the overhead rail system. So too is one wire of the mains-supply. Thus, an off-the-shelf instrument such as a typical impedance meter with a mains power supply cannot be used to probe a hanging carcass without some modification with respect to the grounding of the carcass and (or) the instrument. Even though abattoirs typically have humid ambient conditions, a hanging carcass soon develops a substantial static charge that complicates the matter still further. Thus, an internal battery power supply has much to offer and has the added advantage of safety for the operator.

The logical development of Banfield's (1935) discoveries may be followed through the several reports that this group at Cambridge published up to the outbreak of war in 1939 (Bendall and Swatland, 1988). In our search for the general principles of on-line quality measurement, let us move forward to the present time. Research on the electrical properties of pork was resumed in the 1980's (Swatland, 1980a,

Figure 2

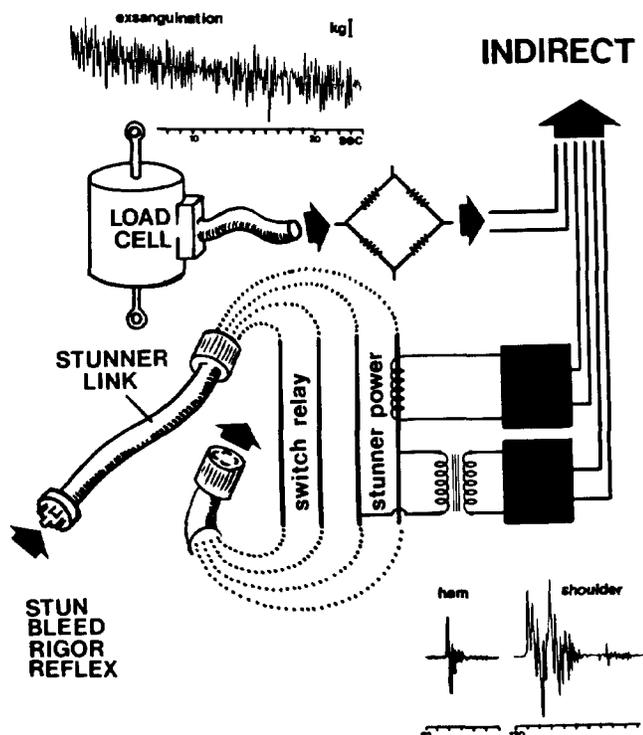
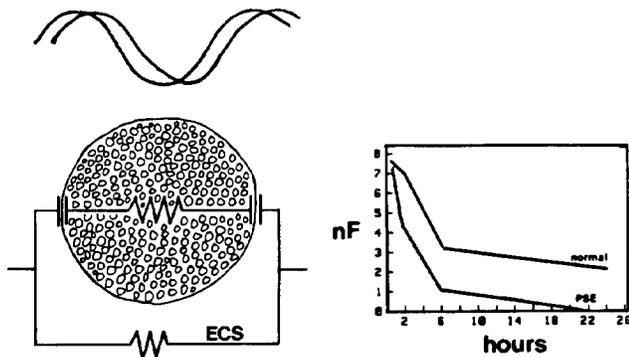


Figure 3

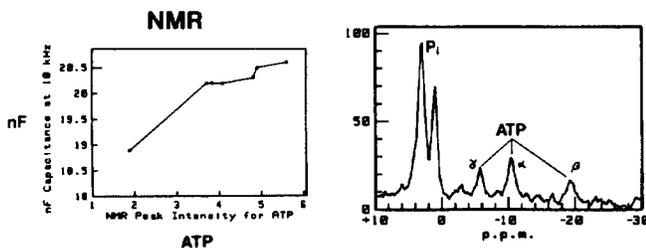
## CIRCUIT through FIBER



1980b, 1981c, 1982c, 1982d, 1986d). The work of Pftzner (1981), Pftzner and Fialik (1982) and Kleibel et al. (1983) has culminated in a commercially available system for the on-line detection of PSE pork<sup>5</sup>. The two main points are: (1) what is being measured, and (2) how to develop a suitable interface.

Fig. 3 shows how an AC current might move through meat. This circuit unit would be repeated many times in series and parallel. Capacitance probably originates from membranes separated by electrolytes (primarily plasma membrane and transverse tubules, but also perhaps from sarcoplasmic reticulum). Resistance is probably determined by the pattern of fluid partitioning between intracellular and extracellular (ECS) space. Impedance is the combination of both resistance and capacitance. Since resistance is strongly affected by temperature, the temperature must be measured in order to adjust impedance and resistance measurements to the same base. Capacitance is only slightly affected by temperature and may be used uncorrected to assess the status of the meat. Capacitance declines postmortem in all carcasses, but declines most rapidly in those with a rapid decline in ATP levels. Lactate may or may not have some effect on the postmortem decline in capacitance, but the relationship of ATP and capacitance is strong and easily detected, as in the nuclear magnetic resonance data summarized in Fig. 4 and in biochemical studies undertaken in collaboration with Thayne Dutson (Swatland and Dutson, 1984). A likely possibility is that ion pumps in the membrane became freely available to transmit a current when ATP is

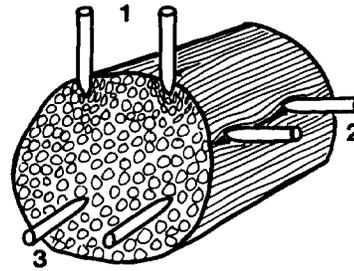
Figure 4



<sup>5</sup>MS-TESTER, Testron, Thimiggasse 23, A-1180 Wien, Vienna, Austria.

Figure 5

## ANISOTROPY



depleted, thus explaining why both PSE pork and dark-cutting beef have a low capacitance (Swatland et al., 1982).

Temperature is not only the only factor that causes problems with electrical measurements of meat. Meat is anisotropic (Fig. 5). Although raster electrodes and multiple electrode methods have been widely used in the biomedical field, the apparatus developed so far for on-line testing of meat uses two electrodes (either needles or blades). There are three possible ways to interface a pair of electrodes with the meat. For example, in the situation shown in Fig. 5, position 2 gives a lower resistance than position 1. Experiments on the deformation of muscle fibers around sites of electrode insertion showed that position 2 made better contact with ECS. With a low parallel resistance, there is a lower voltage to charge any membranes, so that capacitance is also low in position 2. Apart from the difficulty of controlling the anatomical site and orientation of the probe interface, it is difficult to control the depth of penetration and to eliminate effects caused by shorting at the surface of a wet carcass.

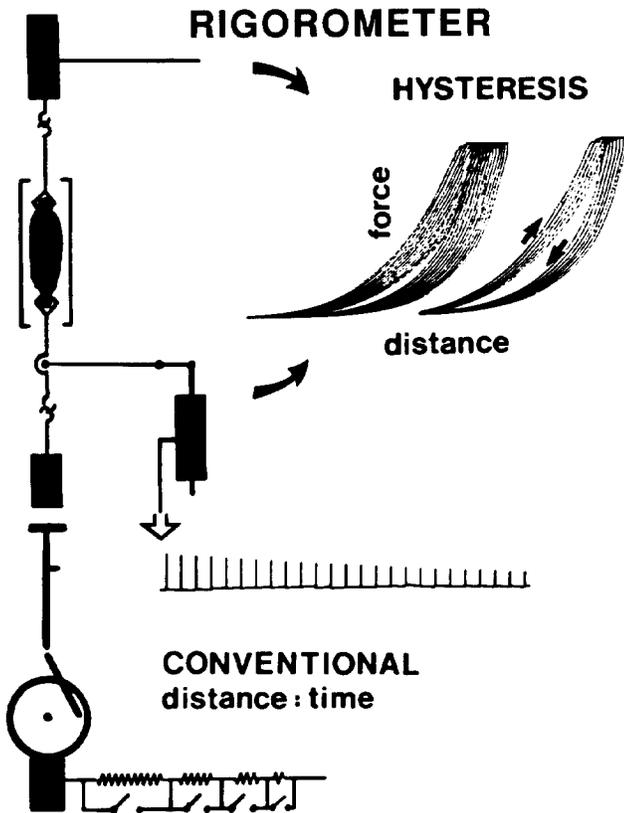
The value of electrical methods for the on-line measurement of pork quality is reviewed by Bendall and Swatland (1988). The short answer is that electrical methods are somewhat better than pH (probably because of easier penetration and standardization) but may not be suitable for populations in which severe PSE is relatively rare. With a relatively high incidence of severe PSE from pigs with porcine stress syndrome (PSS), however, the electrical method might be of value.

## Mechanical Methods

The Bate Smith (1939) rigorometer has evolved quite considerably in the hands of many research groups and the physical principles of the method have been clearly elucidated (Bendall, 1973). The method provides an excellent indicator of the state of rigor development and might be used to great advantage in industry when early rigor and sarcomere shortening are suspected of causing meat toughness. However, it is not an easy method to get working on-line. Sybesma (1966) developed a hand-held penetration rigorometer for on-line use. I strongly suspect, given modern instrumentation and robotic application, his principle could be made to work.

Fig. 6 shows the start of an alternative path of development that might also be possible. The conventional output of the rigorometer consists of a series of distance displacements with time on the x-axis. Further information on the state of the sample may be added by incorporating a force

Figure 6



transducer in the sample support linkage. This enables the hysteresis area of the force-displacement relationship to be examined. Apart from valuable information on the rheology of the sample, this extra information reveals that the rigometer itself, when used over a period of time, causes microstructural damage. Histochemical studies on the rates of glycogen depletion in individual muscle fibers show that fibers deplete their energy reserves and develop rigor mortis one-by-one. Thus, the first fibers to lose their extensibility are easily disrupted by the rigometer. Following this, as larger numbers of fibers in rigor become detectable, electron

Figure 7

CARCASS RIGOROMETER

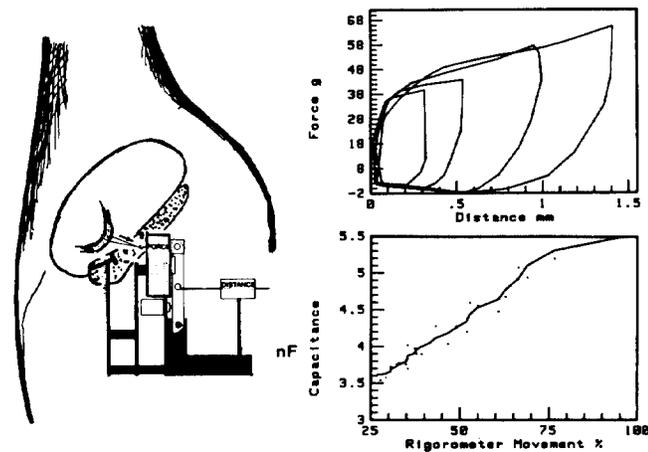
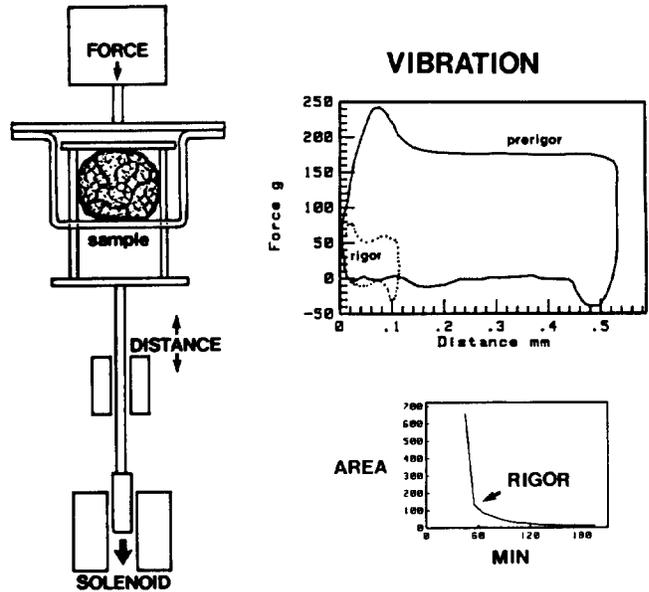


Figure 8



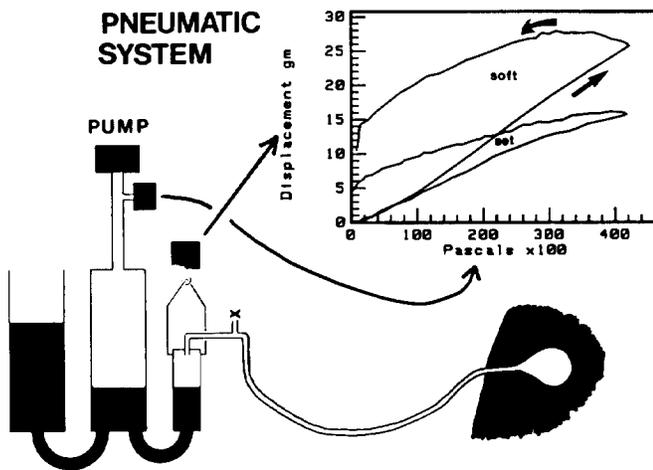
microscopy (EM) reveals considerable disruption in the transverse alignment of sarcomeres, with fibrous strands (desmin?) between the myofibrils being distorted (Swatland, 1985a). These problems with continuous testing need not be a problem in the on-line use of a rigometer where a single measurement would probably be made at a standardized time postmortem.

It is possible to attach a force-distance rigometer to the pubis of a split carcass, as shown in Fig. 7 (Swatland, 1985b). The apparatus tugs on a small slip of adductor muscle caught by a hook or a loop of thread. Rigor development may be followed by the decrease in size and change in shape of the hysteresis area or, with lesser information content, by the relative displacement. Both parameters are correlated with the decline in electrical capacitance. Temperature is again a problem when measurements are made in a meat cooler, since viscosity increases as temperature decreases.

An alternative configuration for the force-distance method of rigometry is to compress the meat sample (Swatland, 1987a; Fig. 8). The objective was to develop an on-line vibratory method for measuring softness, primarily in pork. The laboratory prototype for excised muscle samples showed that the hysteresis area could be measured asynchronously with a high-speed analog to digital converter, thus suggesting that a vibratory probe could be developed to probe carcasses on-line. Unfortunately, I was unable to obtain funding to take these experiments any further. As well as working at a low frequency, it might also be possible to use an ultrasonic method on-line, following the direction of Tamura et al. (1982).

Yet another possibility is the pneumatic rigometer (Swatland, 1986b; Fig. 9). A prototype was developed in an attempt to obtain rigor measurements deep inside the carcass instead of from superficial muscles. A small bulb made of soft, inelastic polymer is inflated after insertion deep into the carcass. The degree to which it inflates and pushes the surrounding tissue aside is monitored from the inflation pres-

Figure 9



sure and from the displacement of fluid (saline to avoid freezing at meat cooler temperatures) in the air-line outside the carcass. A major problem with this method when used continuously is that the tissue tends to rip progressively as the bulb is re-inflated. To some extent, this may be cancelled by re-standardizing the system at the start of each cycle (note the small release valve in the supply line). This would not be a problem with a single measurement at a standardized time postmortem.

### Optical Methods

MacDougall (1980) developed a monochromatic fiber-optic (FO) probe to measure PSE pork and dark-cutting beef and the system is now commercially available<sup>6</sup>. Other commercially available monochromatic systems have also been used in survey work (Bendall and Swatland, 1988) and a portable colorimeter is now commercially available for use on cut meat surfaces<sup>7</sup>.

An essential feature of any on-line optical probe that does not require the carcass to be ribbed is that some type of optical interface is inserted into a carcass muscle. The light source and photodetector may be miniature photodiodes that come into direct contact with the meat. Alternatively, the light source and photodetector may be in apparatus outside the carcass and their interface with the meat may be via optical fibers. With both configurations, we have the problem of deciding what to call the property that we are measuring.

For a number of years, I have been using the term "reflectance." Although the light that is returned to the photometer after being transmitted and scattered is clearly not simple reflectance (or even sterance), I did not dare to propose an alternative name. An anonymous reviewer recently directed me towards an ideal answer to this problem which is to use the term interactance, as proposed by Conway et al. (1984). I have no idea whether this term will achieve general recognition, but I suggest that we should use it until a better alternative becomes available. It is quite likely that interactance spectra are unique to the type of optical interface that is used.

Following the approach taken by MacDougall (1980), I became interested in using fiber optics for spectropho-

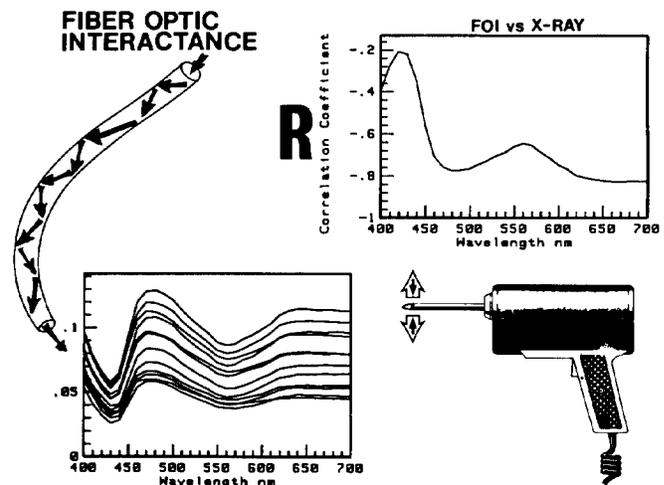
tometry (Swatland, 1982a). The objective of using a number of different wavelengths instead of a monochromatic measurement was to broaden the range of potential on-line applications, as in the following list.

- (1) To attempt to improve on monochromatic measurements of light scattering (PSE-DFD).
- (2) To measure myoglobin content in relation to veal grading (Swatland, 1985d,e).
- (3) To detect muscle abnormalities, such as deep pectoral myopathy in turkeys (Swatland and Lutte, 1984).
- (4) To measure the carotene content of fat, as undertaken subjectively in the Canadian beef grading system (Swatland, 1987i, 1988d).
- (5) In further processing, to monitor meat color during cooking procedures (Swatland, 1983b, 1987b).
- (6) In further processing, to monitor color changes in curing meat with nitrite (Swatland, 1988e).
- (7) To measure the ratios of Type I and III collagen by their fluorescence.

Since research on the measurement of triglyceride content using infrared (800 to 2500 nm) was already a well-established field (Norris, 1984), I centered my efforts on the range from 300 to 800 nm and attempted to develop a computer-controlled system that would be capable of working at different levels of tissue structure from intact steaks and carcasses down to the level of meat microstructure (Swatland, 1988f). Progress was made on all the proposed applications listed above, but only a few general points will be considered here.

In developing a commercial system for the on-line measurement of meat color, I was most fortunate in being able to work with Ken Butt<sup>8</sup> who had already developed a portable xenon-flash and photodiode array spectrometer (Swatland, 1986c). Equipped with a fiber optic probe, this unit (which is called the Colormet) provides 31 wavelength readings from 400 to 700 nm in a couple of seconds. Fig. 10 shows a typical

Figure 10



<sup>6</sup>TBL Fibre-optics Group Ltd, Torbay Works, Hunslet Road, Leeds LS10 1AT, UK.

<sup>7</sup>Minolta Corporation Head Office, Meter Division, 101 Williams Drive, Ramsey, NJ 07446.

<sup>8</sup>Metron Instruments Inc., P.O. Box 13246, Station A, St. John's, Newfoundland, Canada.

set of spectra that might be collected from pork loins with a range from mild-PSE to mild-DFD. When undertaking research with the goal of industrial implementation, it is important not to work on samples with a range greater than that which will be found commercially. Apparatus that has been standardized using regressions from correlations found in a population with a wide range (as in the comparison of pork from PSS and stress-resistance pigs) may not be of much use when used routinely on commercial populations with a smaller range. As is evident in Fig. 10, the reflectance of mild-PSE muscles is higher than that of mild-DFD muscles. The interactance spectra shown in Fig. 10 are related to conventional reflectance spectra by a cubic function of wavelength plus an additive constant.

Research, undertaken in collaboration with Professor Barry Millman and students Leo Diesbourg and Tom Irving of the Department of Physics at the University of Guelph, has been directed at confirming relationships between interactance and myofilament spacing measured by x-ray diffraction. Like others in the field, I was concerned that paleness by itself might not be a very reliable indicator of the potential exudate and suitability for secondary processing. With the subjective evaluation of PSE pork, it is certainly possible to find cases where muscles are pale but not exudative and vice versa. For a while, it appeared that paleness, softness and exudate might not be as closely related as was generally thought. With the hindsight of having spent several years measuring PSE with objective methods, I now think that these problems originate from the non-linearity of subjective evaluation coupled with our inability, subjectively, to separate light scattering from myoglobin concentration. With objective methods of measurement, paleness and exudate (interactance and fluid distribution) appear to be closely related. The situation with respect to softness has not yet been clearly established.

A combination of techniques has been used to study the fluid status of pork (Fig. 11; Diesbourg et al., 1988; Irving et al., 1989; Swatland, et al., 1989). The lateral separation of myofilaments was measured by transmission EM (Swatland and Belfry, 1985) and by x-ray diffraction, the intercellular space was measured by differential interference contrast (DIC) microscopy of frozen sections (unfixed, unstained, and

dry-mounted) and the potential exudate was measured by high-speed centrifugation. Interactance measured with the Colormet provided a valid but complex method of predicting the water distribution. The subject is too complex to consider here, but a few essential points may be of interest. X-ray diffraction measurements indicated that TEM measurements were negative biased (by shrinkage during processing). The experimental evidence was consistent with the classical theory of water holding in meat. Thus, as the pH declined postmortem, negative electrostatic repulsion between myofilaments decreased and the myofilament lattice shrunk laterally (detected by x-ray diffraction and TEM). Fluid was lost from between the myofilaments, first to the sarcoplasm (where it was detected by TEM), and then to the spaces between the fibers (where it was detected by DIC). The ECS in PSE pork may be much greater than previously realized.

As a result of empirical testing on groups of pork loins with widely different pre-slaughter treatments, it was found that the 400/700 nm interactance ratio provided a more reliable index of paleness than did interactance at 700 nm (Swatland, 1988a). This prompted an investigation of the physical basis of light scattering in pork using a FO goniophotometer (Swatland, 1988b; Fig. 12). The optical properties of meat were found to be even more strongly anisotropic than its electrical properties, a feature that had also been detected earlier with FO probes (Swatland, 1986a). Wavelength-related scattering was found with a perpendicular interface but not with a parallel interface. With the perpendicular interface, low wavelengths had greater scattering (lesser transmittance) than high wavelengths and this was neatly summarized by the 400/700 nm ratio.

This experiment prompted a number of others. The objective was to study the microstructural sources of light scattering in meat. With a moderate range from mild-PSE to mild-DFD (avoiding low pH's where precipitation of sarcoplasmic proteins may occur; Bendall, 1973), there are two leading possibilities. Light scattering may occur:

- (1) at the surfaces of muscle fibers or fasciculi separated by a large ECS, or,
- (2) within the myofilament lattice.

As yet, I have only had time to work on the second possibility.

Figure 11

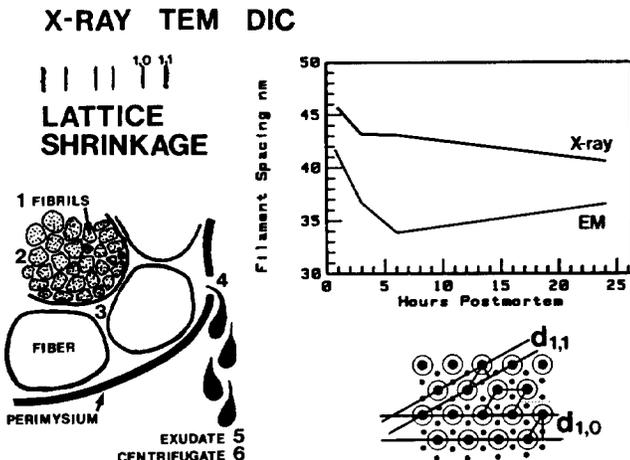


Figure 12

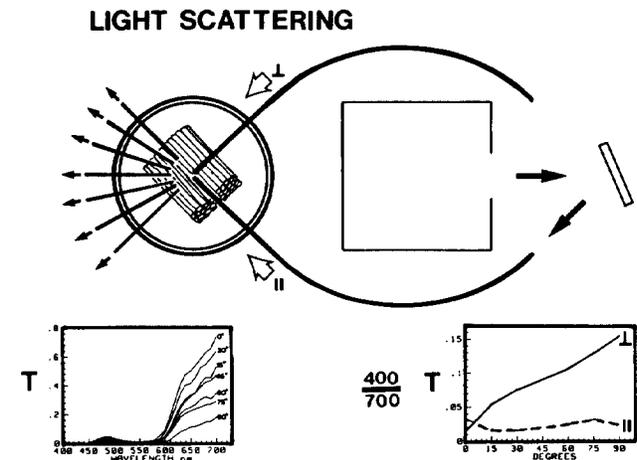
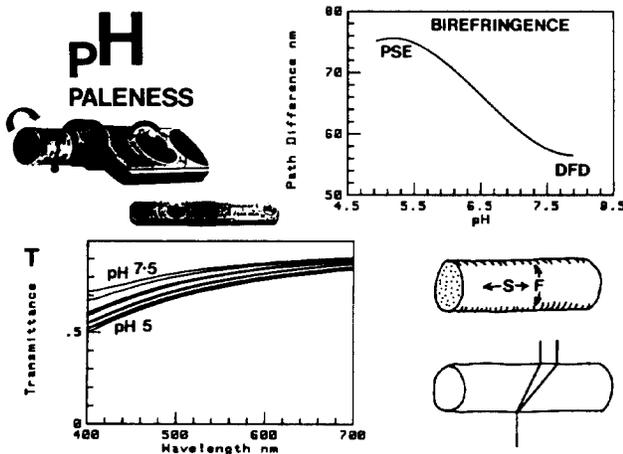


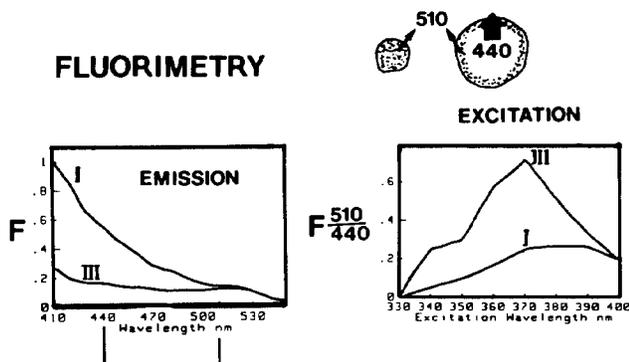
Figure 13



Using polarized light microscopy, it was shown that the birefringence of myofibrils in isolated muscle fibers was affected by pH. Fig. 13 shows the apparatus that is needed for the Desenarmont method to measure the optical path difference of a birefringent structure. In addition to a substage polarizer (not shown), a quarter-wave plate and a graduated rotary analyzer are added to the microscope in tube slots that should be provided on a research microscope. There are two possible light paths through the myofibril lattice, either along (slow optical axis) or across (fast optical axis) the long axes of the myofibrils. At present, it looks as if the speed of light is decreased in the slow axis by a decrease in pH so that the fibrils scatter more light. This was tested by measuring the transmittance of individual muscle fibers. Transmittance was decreased as pH was decreased. In both experiments, the results were reversible. The results also supported the use of the 400/700 nm ratio (or any similar ratio) to measure light scattering in meat in heterogeneous populations. Monochromatic measurements may be quite adequate with homogeneous populations.

Wavelength-related scattering creates a limitation on the use of fluorescence in the measurement of the ratios of Types I and III collagen (Swatland, 1987c,d,e,f,g,h, 1988c). On exposed connective tissue fibers or meat surface, Types I and III collagen have different fluorescence emission spectra (Fig. 14). I doubt whether this is because of their differences in amino-acid composition. The effect might be related to

Figure 14



fiber diameter and quenching. The quenching or fading of autofluorescence is generally quite rapid and appears to proceed from the surface to the core of a fiber. Thus, large diameter (Type I) collagen fibers maintain a pre-quenching emission spectrum from their deep cores much longer than do small diameter (Type III) collagen fibers. When initially exposed to UV light, fibers of both sizes have a similar emission spectrum (a Type I pattern).

On cut surfaces of muscles or on plates of ground beef, the 510/440 nm ratio of fluorescence emissions provides a sensitive (although non-linear) detector for the presence of particles of Type I collagen gristle. Fortunately, elastin (which is even tougher than Type I collagen) behaves in the same way as Type I collagen while adipose tissue (which confers tenderness) has a Type III emission pattern, so the method is not spoiled by the presence of elastic or adipose tissue. The peak excitation wavelength to detect Types I and III collagen is around 370 nm which is a region of the spectrum easily available with a mercury arc or black-light fluorescence tube. As may be seen in Fig. 13, however, penetration at 370 nm will be poor because of scattering. At present, therefore, I can only get this method to work properly on cut surfaces. However, it might be possible to develop a probe method. In-going and out-going optical fibers would have to be closely situated and software would be required to integrate the flashes of interactance as the moving probe came into contact with Type I collagen or elastin. Unfortunately, I have not been able to obtain funding to develop such a probe. Potentially, this method might revolutionize beef grading since we might be able to measure the sizes and numbers of Type I collagen fibers directly instead of guessing the animal's age.

The scattering of light by the microstructure of meat makes it difficult if not impossible to use polarized light for the on-line testing of carcass meat quality. Optical methods to measure sarcomere length can be developed quite easily in the laboratory to work on one or two isolated muscle fibers. So far, however, I have not been able to get such methods to work on intact muscle. Perhaps others may have more success. Like fluorescence, polarization provides an extra set of optical possibilities that may have a great future for on-line probing of meat quality.

### Need for Basic Research

In summary, it appears to me that the objective measurement of meat quality is a promising subject for research since it may be possible to develop techniques of measurement, grading and quality control that would be of use industrially. However, apart from a couple of easy methods, such as measuring meat paleness, we are still a long way from that goal. To use the words of Bruce Marsh last year (Marsh, 1988), "There is nothing inherently wrong with trial-and-error methodology, which has produced wondrous advances in many fields; but when, year after year, it proves of no avail, we must recognize that empiricism has reached its limit." With the on-line measurement of meat quality, empiricism is not even going to take us as far as it has in other fields, and the subject is not going to go anywhere without our having a better grasp of the microstructural and biophysical changes that occur in meat postmortem.

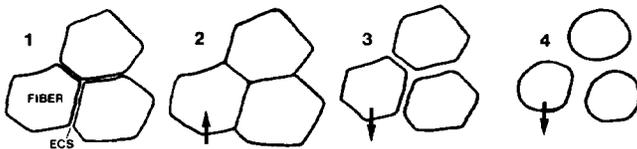
To illustrate this point, let us consider what for many in

industry might be the number one objective for on-line quality measurement – to predict the ultimate level of PSE from a measurement at around 45 minutes postmortem (when carcasses could be sorted after slaughter). Apart from the fact that some PSE is late developing and has not revealed itself by 45 minutes (Swatland, 1981a; Swatland, 1988a), there are transient changes around this time in the sign of both electrical and optical predictors of PSE. Although, ultimately, capacitance decreases and interactance increases, capacitance may show a transient increase and interactance may show a transient decrease around this time in intact pork carcasses (Swatland, 1985c). Fig. 15 shows my working hypothesis to explain this effect.

In the live muscle there is a slight ECS (which has been exaggerated in Fig. 15). Research with TEM, x-ray diffraction, DIC and centrifugation confirms that the ECS eventually increases (from 1, to 3 and 4 in Fig. 15) and this is consistent with the ultimate decrease of capacitance and increase of

Figure 15

## CHANGE IN ECS



interactance. However, at some time soon after slaughter, some muscle fibers may take up fluid osmotically from the ECS to cause the transient effect (2 in Fig. 15). Perhaps this occurs because of an increase in osmotic pressure associated with glycogenolysis. The problem is difficult to investigate biochemically because adjacent fibers may be going in opposite direction with respect to glycogen depletion or resynthesis, as has been shown histochemically (Swatland, 1981b). Compounded with variation in carcass temperature, interface anisotropy, anatomical error in probing the carcass and the considerable intermuscular variation in physical properties that exists (Swatland, 1982b), this transient effect is yet another reason why it is difficult to predict meat quality from a single measurement at 45 minutes postmortem.

Electrical and optical methods for the prediction of the ultimate degree of PSE in intact sides of pork generally become progressively weaker as they are used at earlier times. As our methods improve, however, the prediction of the ultimate degree of PSE from a measurement soon after slaughter becomes progressively better and better. With testing under commercial conditions, Fortin (personal communication) recently found that Colormet interactance at 690 nm at 60 minutes postmortem was correlated with subjective color scores at 24 hours,  $r = -0.52$ . Thus, we have just about reached the point at which prediction soon after slaughter may be accurate enough to be of value in some situations. Who knows what the future may hold? Considerable improvements might be possible if we understood more about the biophysical aspects of postmortem muscle metabolism.

## References

- Anonymous, 1987. Soft fat and the consumer. *Meat Bull.* Feb., 1987, pp. 10-13.
- Banfield, F.H. 1935. The electrical resistance of pork and bacon. Part 1. Method of measurement. *J. Soc. Chem. Ind. Trans. Comm.* 54:411T.
- Bate Smith, E.C. 1939. Changes in elasticity of mammalian muscle undergoing rigor mortis. *J. Physiol.* 96:176.
- Bendall, J.R. 1973. Postmortem changes in muscle. In: *The Structure and Function of Muscle*, Vol. II, 2nd edition. Ed. by Bourne, G.H. Academic Press, New York. Chapter 5.
- Bendall, J.R.; Swatland, H.J. 1988. A review of the relationships of pH with physical aspects of pork quality. *Meat Sci.* 24:85.
- Conway, J.M.; Norriss, K.H.; Bodwell, C.E. 1984. A new approach for the estimation of body composition: infrared interactance. *Am. J. Clin. Nutr.* 40:1132.
- Diesbourg, L.; Swatland, H.J.; Millman, B.M. 1988. X-ray diffraction measurements of postmortem changes in the myofilament lattice of pork. *J. Anim. Sci.* 66:1048.
- Hansen, L.J. 1971. U.S. Patent 3,602,038.
- Irving, T.C.; Swatland, H.J.; Millman, B.M. 1989. X-ray diffraction measurements of myofilament lattice spacing and optical measurements of reflectance and sarcomere length in pork. *J. Anim. Sci.* 67:152.
- Kleibel, A.; Pftzner, H.; Krause, E. 1983. Measurement of dielectric loss factor. A routine method of recognizing PSE muscle. *Fleischwirtschaft* 63:1183.
- MacDougall, D.B. 1980. Use of a fibre optic probe for segregating pale, soft, exudative and dark, firm, dry carcasses. *J. Sci. Food Agric.* 31:1371.
- Marsh, B.B. 1988. Mechanisms and strategies for improving meat tenderness. *Recipr. Meat Conf.* 41:113.
- Norris, K.H. 1984. Reflectance spectroscopy. In: *Modern Methods of Food Analysis*, Ed. Stewark, K.K., Whitaker, J.R. AVI Publishing Co., Westport, CT.
- Pftzner, H. 1981. Automatic dielectric loss factor analysis for the detection of tissue anomalies. *Vth Int. Conf. Electr. Bio-impedance*, Tokyo, paper 56.
- Pftzner, H.; Fialik, E. 1982. A new electrophysiological method for the rapid detection of exudative porcine muscle. *Zbl. Vet. Med. A.* 29:637.
- Swatland, H.J. 1980a. Anisotropy and postmortem changes in the electrical resistivity and capacitance of skeletal muscle. *J. Anim. Sci.* 50:67.
- Swatland, H.J. 1980b. Postmortem changes in electrical capacitance and resistivity of pork. *J. Anim. Sci.* 51:1108.
- Swatland, H.J. 1981a. Postmortem development of paleness in pork loins. *Can. Inst. Food Sci. Technol. J.* 14:147.
- Swatland, H.J. 1981b. Cellular heterogeneity in the response of beef to electrical stimulation. *Meat Sci.* 5:451.
- Swatland, H.J. 1981c. Electrical capacitance measurements on intact carcasses. *J. Anim. Sci.* 53:666.

- Swatland, H.J. 1982a. Fiber optic spectrophotometry and the wetness of meat. *J. Food Sci.* 62:957.
- Swatland, H.J. 1982b. Intermuscular variation in the physical properties of pork. *Can. Inst. Food Sci. Technol. J.* 15:92.
- Swatland, H.J. 1982c. Meat color of pork chops in relation to pH and adductor capacitance of intact carcasses. *J. Anim. Sci.* 54:264.
- Swatland, H.J.; 1982d. Evaluation of pH-related aspects of pork quality by capacitance measurements in an abattoir. *Can. J. Anim. Sci.* 62:725.
- Swatland, H.J. 1983a. Measurement of electrical stunning, rate of exsanguination, and reflex activity of pigs in an abattoir. *Can. Inst. Food Sci. Technol. J.* 16:35.
- Swatland, H.J. 1983b. Fiber optic spectrophotometry of color changes in cooked chicken muscles. *Poultry Sci.* 62:957.
- Swatland, H.J. 1985a. A computer-operated rigorometer for studying the development of rigor mortis in excised samples of pork and beef. *Can. Inst. Food Sci. Technol. J.* 18:207.
- Swatland, H.J. 1985b. Development of rigor mortis in intact sides of pork measured with a portable rigorometer. *J. Anim. Sci.* 61:882.
- Swatland, H.J. 1985c. Optical and electronic methods of measuring pH and other predictors of meat quality in pork carcasses. *J. Anim. Sci.* 61:887.
- Swatland, H.J. 1985d. Fibre-optic spectrophotometry of immature bovine skeletal muscles and the cellular distribution of myoglobin and succinate dehydrogenase. *Histochem. J.* 17:675.
- Swatland, H.J. 1985e. Measurement of veal color by fiber optic spectrophotometry. *J. Food Sci.* 50:1489.
- Swatland, H.J. 1986a. Post-mortem spectrophotometry of pork and beef using quartz optical fibres. *Meat Sci.* 17:97.
- Swatland, H.J. 1986b. Pneumatic measurement of post-mortem setting in pork carcasses. *Can. Inst. Food Sci. Technol. J.* 19:167.
- Swatland, H.J. 1986c. Color measurements on pork and veal carcasses by fiber optic spectrophotometry. *Can. Inst. Food Sci. Technol. J.* 19:170.
- Swatland, H.J. 1986d. Remote measurement of electrical capacitance in meat carcasses and the effect of frequency and temperature. *Comput. Electron. Agric.* 1:271.
- Swatland, H.J. 1987a. Measurement of postmortem changes in pork by high-speed compression hysteresis. *J. Anim. Sci.* 64:444.
- Swatland, H.J. 1987b. Fiber optic spectrophotometry of color intensity problems in raw and cooked turkey breasts. *Poultry Sci.* 66:679.
- Swatland, H.J. 1987c. Fluorimetry of gelatin by fiber optics. *Can. Inst. Food Sci. Technol. J.* 20:102.
- Swatland, H.J. 1987d. Fiber-optic reflectance and autofluorescence of bovine elastin and differences between intramuscular and extramuscular tendon. *J. Anim. Sci.* 64:1038.
- Swatland, H.J. 1987e. Fluorimetry of bovine myotendon junction by fibre-optics and microscopy of intact and sectioned tissues. *Histochem. J.* 19:276.
- Swatland, H.J. 1987f. Effect of excitation wavelength on the separation of Types I and III collagen by fiber optic fluorimetry. *J. Food Sci.* 52:865.
- Swatland, H.J. 1987g. Measurement of the gristle content in beef by macroscopic ultraviolet fluorimetry. *J. Anim. Sci.* 65:158.
- Swatland, H.J. 1987h. Autofluorescence of adipose tissue measured with fibre optics. *Meat Sci.* 19:277.
- Swatland, H.J. 1987i. Optical properties of white and yellow beef fat in relation to carcass grading. *Can. Inst. Food Sci. Technol. J.* 20:383.
- Swatland, H.J. 1988a. Selection of wavelengths at which to measure paleness in pork by fiber-optic spectrophotometry. *Can. Inst. Food Sci. Technol. J.* 21:494.
- Swatland, H.J. 1988b. Measurements of light scattering in normal pork using a fiber-optic goniophotometer. *J. Anim. Sci.* 66:2578.
- Swatland, H.J. 1988c. Autofluorescence of bovine ligamentum nuchae, cartilage, heart valve and lung measured by microscopy and fibre optics. *Res. Vet. Sci.* 45:230.
- Swatland, H.J. 1988d. Carotene reflectance and the yellowness of bovine adipose tissue measured with a portable fibre-optic spectrophotometer. *J. Sci. Food Agric.* 46:195.
- Swatland, H.J. 1988e. A brief study of the effect of nitrite on bologna coloration measured with a Colormet fiber-optic spectrophotometer. *Can. Inst. Food Sci. Technol. J.* 21:560.
- Swatland, H.J. 1988f. Effect of interface conditions on the optoelectronic measurement of carcass meat quality. *Comput. Electron. Agric.* 2:233.
- Swatland, H.J. 1989. A review of meat spectrophotometry (300 to 800 nm). *Can. Inst. Food Sci. Technol. J.* in press.
- Swatland, H.J.; Belfry, S. 1985. Post mortem changes in the shape and size of myofibrils from skeletal muscle of pigs. *Mikroskopie* 42:26.
- Swatland, H.J.; Dutton, T.R. 1984. Postmortem changes in some optical, electrical and biochemical properties of electrically stimulated beef carcasses. *Can. J. Anim. Sci.* 64:45.
- Swatland, H.J.; Lutte, G.H. 1984. Optical characteristics of deep pectoral myopathy in turkey carcasses. *Poultry Sci.* 63:289.
- Swatland, H.J.; Ward, P.; Tarrant, P.V. 1982. Electrical capacitance of dark-cutting beef. *J. Food Sci.* 47:686.
- Swatland, H.J.; Irving, T.C.; Millman, B.M. 1989. Fluid distribution in pork, measured by x-ray diffraction, interference microscopy and centrifugation compared to paleness measured by fiber optics. *J. Anim. Sci.* in press.
- Sybesma, W. 1966. Die Messung des Unterschiedes im Auftreten des Rigor mortis in Schinken. *Fleischwirtschaft* (6):637.
- Tamura, Y.; Hatta, I.; Matsuda, T.; Sugi, H.; Tsuchiya, T. 1982. Changes in muscle stiffness during contraction recorded using ultrasonic waves. *Nature* 299:631.
- Voisey, P.W. 1976. Engineering assessment and critique of instruments used for meat tenderness evaluation. *J. Texture Stud.* 7:11.