Predictive models for the shelf life of Australian vacuum-packed beef and lamb: development and evaluation

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Abstract

The Australian meat industry exports vacuum packed beef and lamb to more than one hundred markets, some of them involving containerised sea voyages of 40-50 days. On occasion, product may be subjected to temperature increase due to refrigeration problems, or to extended shipping times due to strikes or to delays in clearing the destination port, as happened in 2020 due to the Coronavirus pandemic. Such deviations in temperature and time have a pronounced effect on the shelf life of the consignment which, traditionally, has required sampling of the cargo for microbiological and sensory testing prior to making a disposition - adding to the loss of shelf life. In this study, we describes a predictive tool that provides rapid and accurate assessment of the product shelf life remaining for Australian vacuum packed beef and lamb cuts, based on their initial total bacterial count, and time:temperature parameters. The models were validated by independent data and have a bias factor of 1.02 and 0.90, and an accuracy factor of 1.10 and 1.11 when used for predicting the shelf life of beef and lamb cuts, respectively packed under vacuum. This indicates a good agreement between the observed and predicted shelf lives of VP and VSP cuts. The models will allow the Australian meat industry to manage their supply chains effectively and reliably to ensure high quality meat products with excellent shelf life.

1. Introduction

Since its first exports in 1880, Australia has developed a reputation for producing red meat with excellent shelf life, servicing markets, especially for chilled, vacuum-packed (VP) beef and lamb, to more than 100 countries (Small et al., 2012). Supply to distant markets means that Australian exporters are constantly challenged to minimise the loss of product quality (including shelf life) along different supply chains and to meet a wide range of shelf life-related specifications imposed by intended markets. For instance, China specifies a shelf life of 120 and 80 days from slaughter for vacuum packed beef and lamb/mutton cuts, respectively, while some Middle Eastern countries require at least 50% shelf life to remain when the consignment is landed (Huynh et al., 2016).

It has long been known that shelf life depends upon the degree of bacterial contamination at packing and the growth conditions: temperature, pH and oxygen permeability of the packaging film, of which temperature is considered the most important factor. Gill et al., (1988a) established the optimum temperature for storage of VP meat as -1.5±0.5°C, and also showed that small rises in temperature reduce shelf life significantly: at temperatures of 0°, 2° or 5°C, the storage life was reduced by about 30, 50 or 70%, respectively, compared with storage at -1.5°C (Gill et al., 1988b). For supply to distant markets it has become customary for exporters to specify that the shipping container set-point is -1.5°C.

Temperature abuse, defined by Mills et al., (2014) as warmer than 5°C during any stage of the cold chain, is onerous for the supplier, usually involves the need to evaluate the sensory and microbiological condition of the shipment in order to decide its disposition. Further, the time taken to unload the container, select and sample representative units, then await test results increases the likelihood that the contents might be deemed unfit for human consumption or to comply with importer specifications. A container of VP meat can have an insured value of USD200,000 and, as a means of improving the timeliness with which a disposition decision can be made, we propose a predictive model that rapidly and accurately predicts the remaining shelf-life of VP beef and sheep meat.

Previously, we assessed the microbiological and sensory qualities of VP beef and lamb cuts sourced from several Australian abattoirs through storage at temperatures ranging from 0°C to 8°C (Kaur et al., submitted for publication) in which it was found that total bacterial count and odour of the meat were suitable indicators for determining the shelf life of VP beef and lamb. Rates of quality deterioration as indicated by odour were found to correlate strongly with TVC growth rates across the storage temperature range, with beef and lamb cuts showing different but consistently parallel rate values. These findings indicated the feasibility of developing models for separately predicting the shelf-life of VP beef and lamb based on the growth of microorganisms and of presence of persistent odour as a function of temperature. To this end, we developed predictive models for the shelf life of Australian VP beef and lamb primals that encompass and extend from the results and models of Kaur et al., (submitted for publication). A number of previously published work datasets were used and supply chain trials conducted to evaluate the performance of the developed models in both simulated and real commercial supply chains.

2. Materials and methods

2.1 Model development

2.1.1 TVC growth models

Data for specific growth rates of total bacterial count (TVC) on VP beef and lamb sourced from Australian abattoirs at different storage temperatures (ranging from 0°C to 8°C) were obtained from Kaur et al. (submitted for publication). To describe the effects of storage temperature on the rates of TVC growth, linear regression analysis was performed for each meat type (Ratkowsky et al., 1982) and the following model derived:

$$\sqrt{\mu_{\mathrm{TVC}}} = (a \times T) + b \tag{1}$$

where μ_{TVC} is the specific growth rate of TVC (in hours); *a* is the slope of the regression line; *T* is the temperature at which meat is stored (°C); and *b* is the regression coefficient. From Equation (1), the theoretical minimum temperature for TVC growth on VP beef and lamb was estimated by extrapolation of the regression line to $\sqrt{\mu_{\mathrm{TVC}}} = 0$.

2.1.2 Shelf life models

With the parameters obtained from Equation (1), shelf life could be predicted on the basis that spoilage of VP meat is mainly caused by microorganisms (Gill & Newton, 1979). Equation (1) can then be expressed as:

$$SL = [\frac{1}{a \times (T - T_{\min})}]^2 \tag{2}$$

where *SL* is the shelf life of VP primals (days); *a* is the slope of the regression line that corresponds to *a* in Equation (1); *T* is the temperature at which meat is stored (°C); and $T_{\min}$ is the minimum temperature where the rate of TVC growth is zero (*i.e.,* from Equation (1)). However, to account for the shelf life of Australian VP beef and lamb primals under ideal storage conditions as established by industry and research data (Phillips et al., 2012; Sumner

& Jenson, 2011) Equation (2) was modified to calibrate to the established shelf life of VP meat and is given as follows:

$$SL = [\frac{1}{a \times (T - T_{\min})} - c]^2 \quad (3)$$

where *c* is a factor that enables calibration to the established shelf life of VP beef and lamb. Equation (3) was further modified to predict the remaining shelf life by accounting for the observed initial TVC (at the time of packaging). This was achieved by calculating a correction factor that considers the established data for the initial TVC and the calculated TVC at the time of spoilage (Phillips et al., 2012; Sumner and Jenson, 2011). This correction factor was then incorporated to Equation (3) to predict the remaining shelf life ($SL_{\text{remaining}}$; day).

$$SL_{\text{remaining}} = [\frac{N_0 - (N_{\text{obs}}) + N_{\text{s}}}{N_{\text{s}}}] \times [\frac{1}{a \times (T - T_{\min})} - c]^2 \quad (4)$$

where N_0 is the initial TVC based on the established data of Phillips et al., 2012 (log CFU/cm^2); N_{obs} is the observed initial TVC (log CFU/cm^2); and N_{s} is the nominal population level on VP beef and lamb at the time of spoilage (log CFU/cm^2). The N_{s} value was estimated by extrapolation of the regression line of TVC data to the time at which spoilage occurs (Phillips et al., 2012; Sumner & Jenson, 2011).

2.1.3 Production of a model interface

Based on the developed Equations (1) and (4), a model interface was produced in MS ®Excel 2016 to predict the growth of TVC and the remaining shelf life of VP beef and lamb primals.

2.2 Validation of the developed models in commercial and simulated supply chains

2.2.1 Previous shelf-life trials

Relevant data for initial TVC, average storage temperature and observed shelf-life were collated from studies previously reported by Sakai et al., (submitted for publication) for VP beef, and Kaur et al., (2017) for VP lamb. Altogether, these studies provide 11 time:temperature based datasets for the shelf-life of Australian VP primals stored under either constant or dynamic temperatures.

2.2.2 Lamb primals, Australia- Middle East

The shelf-life of various lamb products was evaluated in a commercial supply chain. Lamb racks, boneless legs and bone-in legs were vacuum-packed, cartoned and shipped by sea from Australia to Bahrain where they were stored at approximately 0°C throughout the trials.

All trials were conducted with triplicate samples. The time:temperature profile of the samples was recorded by data loggers (TG-4080 Hastings Data Loggers, Australia) from an abattoir to storage in Bahrain. -

2.2.3 Beef primals and cuts, simulated trial Australia

A series of shelf-life trials were conducted at a beef processing plant in Brisbane, Australia to determine the shelf-life of various types of commercial products in a simulated domestic supply chain. These included VP rump roast with three ageing regimes (5, 20 and 69 days), and vacuum-skin-packed (VSP) rump streaks produced from VP primals after ageing for different durations product (30 and 57 days).

In a simulated supply chain, rump primals or roasts were aged in VP (at approximately 0°C) for different durations. Both aged and non-aged products, except for VP rump roast were cut into steaks and packed in different packaging systems as appropriate. All products were then subjected to different steps in a simulated supply chain: transferring to and storing in a distribution centre storage, and transferring to a retail display for different durations and at different temperatures as experienced in a domestic supply chain. In addition, conditions that simulate consumer's practices e.g. consumers home journey and storage in their fridge were included.

Each trial was conducted with at least triplicate samples. The time:temperature profile of the samples was monitored through the trials using five data loggers (TG-4080 Hastings Data Loggers, Australia).

2.2.4 Quality assessment

An appropriate number of packs of each product types (beef and lamb) were assessed on the day of packing and throughout the supply chain for sensory evaluation and/or microbiological analysis (total viable counts, TVC).

2.2.4.1 Sensory analysis

At each sampling point, each pack of samples was evaluated for its odour attribute by a trained sensory panel comprising of at least five members. Specifically, packs were opened and left for 10 min before panellists assessed their odour sensory quality. Assessment of odour was based on a 3-point categorical hedonic scale as follows: 0 = strong sour odour/off odour; 1 = moderate sour odour/moderate off odour; and 2 = fresh meat odour/very slight sour odour.

2.2.4.2 Microbiological analysis

Enumeration of total bacteria was performed on cuts at the time of vacuum packing. For beef samples a surface section from the longest length of the cut was aseptically excised (25 ± 2.5 g). Meat pieces were combined with 225 ml of buffered peptone water (BPW, CM1049, Oxoid Ltd., Australia) in a sterile stomacher bag and stomached for 1 min. Serial dilutions were prepared as necessary in BPW as required and aliquots (0.1 ml) of plated onto the surface of Tryptone Soy agar (TSA, CM0129, Oxoid Ltd., Australia).

For lamb samples, a surface area measuring 200 cm^2 was swabbed with a sterile sponge (Whirl-Pak Speci-Sponge, Nasco, USA), prewetted with 25 ml of Phosphate Buffer Saline (BR0014G, Oxoid Ltd., Australia). Swabs were hand massaged in the sample bags for 30 seconds to release the bacteria into suspension. Suspension (1 ml) was serially diluted in 0.1% bacteriological peptone water (LP0037, Oxoid Ltd., Australia) as required and aliquots plated onto Petrifilm aerobic count plates (3M Microbiology Products, St. Paul, MN) according to the manufacturer's instruction.

TSA and Petrifilm plates were incubated at 20 ± 1°C for 5 days aerobically, colonies were counted and reported as the mean log CFU/g or log CFU/cm^2 of the replicates (± standard deviation).

2.2.5 Determination of the shelf life

The shelf-life of each product type was determined from odour assessments described above. Specifically, products that were rated as 'marginal – smell off' were considered as commercially unacceptable and the time taken to reach that endpoint was recorded as the shelf life of the product. Due to the variability of product characteristics even within the same trial, the shelf life was determined when at least one of the replicates were rated as unacceptable at any given time point and subsequent time points.

2.2.6 Comparison between observed and predicted growth

The shelf-life of each product type were estimated using the developed predictive models based on initial TVC, and time:temperature history in the supply chain.

The performance of the developed models to predict the shelf-lives of VP red meat was evaluated using the methods described by Ross (1996). Bias and accuracy factors for the models were calculated from observed and predicted shelf lives (days) of each meat type.

3. Results and Discussion

There have been several models developed to predict the shelf life of particular products, most of which have remained a research tool rather than an effective industrial application. This is mainly because: i) the models were based on observations in well-controlled laboratory environments with microbiological media rather than complex food environments such as on meat; and ii) mode models validated under static temperature conditions rather than temperature fluctuations as occur during storage and distribution of foods (McDonald & Sun, 1999).

To develop effective spoilage models for Australian VP primals, a comprehensive study was conducted to determine the microbiological and sensory qualities of meat as they relate to spoilage (Kaur et al., submitted for publication). That study, congruent with previous studies, indicated a robust temperature dependency of spoilage rates of VP beef and lamb primals as reflected by the different rates of microbial growth (Gill et al., 1988b; Kaur et al., 2017; Sumner & Jenson, 2011). However, due to differences in meat biochemistry (especially glycogen and lactic acid contents), beef (pH 5.5-5.8) tends to have a lower pH than lamb (pH 5.6-6.8) (Carse & Locker, 1974). Such differences affect the growth of bacteria, with growth rates being faster on VP lamb than VP beef, with consequential effects on shelf life, necessitating the development of two independent models to predict the shelf life of each through the supply chain.

3.1 Development of predictive models for the shelf-life of Australia VP primals

Using the relevant data of Kaur et al, (submitted for publication), we applied the square root model of Ratkowsky et al., (1982) to describe the effects of storage temperature on the rates of TVC growth on VP beef and lamb in accordance with Equation (1). Table 1 shows the model parameters for different meat types. As expected, these parameters (a and T_{min}) differ between meat types, reflecting the differences in their biochemistry (*i.e.,* meat pH as described above).

With the parameters (a and T_{min}) obtained above, predictive models for the shelf life of VP beef and lamb were developed in accordance with Equation (2). However, such models could not be used to specifically predict the remaining shelf life of Australian VP meat (*i.e.,* as defined in Equation (4)). This requires a number of factors (*i.e.,* N_0, N_s, and c) to be determined based on previous data for the shelf life of VP meat produced in Australia. VP beef and lamb with the initial TVC of approximately 3.0 log CFU/cm^2 (*i.e.* N_0, the initial TVC) typically have an acceptable shelf life of 160 and 90 days when stored at -0.5°C, respectively, as determined by odour assessment (Phillips et al., 2012; Sumner & Jenson, 2011). Using these values, the extrapolated N_s value was estimated to be 11.4 log CFU/cm^2 for beef and 11.0 log CFUcm^2 or lamb, whereas the *c* value (the factor required for calibration to established shelf lives) was 0.21448 and 0.49728 for VP beef and lamb, respectively. These, taken together, allow Equation (4) to be 'calibrated' (after inclusion of correction factors) to predict the remaining shelf life of Australian VP beef (Equation (5)) and lamb (Equation (6)) as follows:

$$SL_{\mathrm{remaining}} = [\frac{3.0 - (N_{\mathrm{expt}}) + 11.4}{11.4}] \times [\frac{1}{0.01964 \times (T - -4.45861)} - 0.21448]^2 \quad (5)$$

$$SL_{\mathrm{remaining}} = [\frac{3.0 - (N_{\mathrm{expt}}) + 11.0}{11.0}] \times [\frac{1}{0.01986 \times (T - -5.54856)} - 0.49728]^2 \quad (6)$$

The developed models were incorporated into a software tool (implemented in MS ®Excel) that allows prediction of the growth of TVC and calculates the remaining shelf life of VP beef and lamb primals in cold chains, (*see* Supplementary File 1). To use this tool, the user selects the product type (beef or lamb), enters the starting TVC, and a time:temperature profile, typically collected by a temperature datalogger. The tool then predicts the TVC growth profile and remaining shelf life of the product based on assessment of predicted growth and odour kinetic responses.

3.2 Shelf-life data for model validation

In Table 2 are summarised the shelf-life data (n=11) obtained for various beef and lamb products in both simulated and actual commercial supply chain (*i.e.* at fluctuating temperatures) (Kaur et al., 2017; Sakai et al., submitted for publication). These include TVC at the time of packaging, average storage temperatures and the observed shelf lives. The data were then used to evaluate the performance of the developed models.

A series of trials was also conducted to provide additional data for the shelf life of Australian beef and lamb products in a commercial supply chain. In Table 3 are summarised the data for all product types (n=15), including TVC at the time of packaging, average storage temperature and the observed shelf lives (ranging from 37 to 85 days).

3.4 Performance of predictive models

The predictive models for VP beef and lamb shelf life were evaluated for their performance by comparison with independent data not used to generate the models. The MS ®Excel-based tool as described above was then used to predict the shelf life of different meat products based on their time:temperature history and initial microbial counts. The observed *vs.* predicted shelf lives (days) of each product are shown in Tables 2 and 3.

The bias and accuracy factor analyses of Ross (1996) were used to assess the performance of model predictions of shelf life compared with the observed data. Ross (1996) reported that the bias factor serves as a measurement index for the average variation between the predicted and observed values, whereas the accuracy factor is used to estimate the accuracy of an established model. Bias and accuracy factor values of 1 indicate a perfect agreement between observed and predicted values. In this study, the models were found to have a bias factor of 1.02 and 0.90, and an accuracy factor of 1.10 and 1.11 when used for predicting the shelf life of beef and lamb in VP and/or VSP, respectively. These observations indicate a good agreement between the observed and predicted shelf lives of VP and VSP cuts. The models systematically underpredict the shelf life of VP meats with approximately 10% deviation, providing 'fail-safe' predictions, and it is noted that an over-prediction of time to spoilage was also noted by Albrecht et al., (2019), Bruckner et al., (2013) and Tang et al., (2013) for their shelf life predictive models for poultry and pork meat.

Development of the models here use the square root model of Ratkowsky et al., (1982) to predict the remaining shelf life of VP meats, consistent with other studies indicating microbial spoilage of foods can be described by the square root model (Kreyenschmidt et al., 2010; Mataragas et al., 2006). However, it should be noted that, in contrast to those studies, the developed models provide shelf life predictions based on the growth of TVC rather than that of a specific group of organisms (collectively known as 'specific spoilage organisms' or SSOs). This suggests that spoilage in VP meats might be facilitated by a complex phenomenon involving interactions among growing bacteria (*i.e.,* by community effects). Further investigation involving inoculation of specific bacteria into sterile meat to test for their spoilage capability is required to elucidate this.

From the above, the developed models were successfully validated to provide an accurate and reliable prediction of the shelf life of beef and lamb stored under vacuum packaging conditions. Such models can be readily adopted as a reliable decision-making tool in commercial supply chains for VP beef and lamb. This tool offers a cost-effective approach for the meat exporters to optimise and better understand their supply chains. Disposition of product affected by adverse events, such as temporary loss of refrigeration on the vessel or extended delivery times can be resolved speedily by using this tool.

4. Conclusion

This study provides "ready-to-use" models for predicting the shelf life of VP primals. The models were well-validated by independent data from commercially available products in both simulated and commercial supply chains. The use of the models by the Australian meat industry has already led to effective management systems for optimising and monitoring meat quality. At the time of writing the Coronavirus emergency has resulted significant volumes of product landed in many countries requiring extended storage at the port. and the tool has provided both the exporter and importer with a confident estimate of the shelf life remaining.

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Table 1.

Estimated values of the parameters of Equation (1) for the specific growth rate of TVC.

Product type	*a*	*b*	T_{min} (°C)[1]
VP beef	0.01964	0.08757	-4.45861
VP lamb	0.01986	0.11021	-5.54856

T_{min} is the theoretical minimum temperature and was estimated by extrapolation of the regression line to $\sqrt{\mu_{\mathrm{TVC}}} = 0$.

Table 2.

Summary of previously published data used for evaluation of the models for shelf life predictions.

Type of meat cut	Average storage temperature[a]	Initial TVC (log CFU/cm^2)[b]	Observed shelf-life (days)[c]	Predicted shelf-life (days)	Study
Vacuum-packed beef products					
Striploin	-0.47	1.91	140	159	Sakai et al., (submitted for publication)
Striploin	-0.44	1.91	140	158	
Chuck tender	1.45	2.47	90	81	
Chuck tender	2.27	2.47	90	63	
Chuck tender	1.54	2.47	90	83	
Striploin	2.22	1.54	70	75	
Striploin	1.98	1.54	70	83	
Striploin	2.21	1.54	70	75	
Striploin	2.34	1.54	70	72	
Vacuum-packed lamb products					
Bone-in hind shank	8.00	3.15	13	10	Kaur et al., (2017)
Bone-in hind shank	-1.20	3.15	124	122	

a. Average temperature from packaging to the end of the trials

b. Average TVC at the time of packaging

c. The time taken for each product to reach its end of shelf-life based on odour attribute.

Table 3

Summary of the data generated for different meat products in their supply chains and its comparison with the shelf life predictive models.

Type of meat cut	Packaging types[a]	Average storage temperature[b]	Initial TVC (log CFU/cm^2)[c]	Observed shelf-life (days)[d]	Predicted shelf-life (days)
Beef products					
Rump roast with 5-day aging	VP	3.97	1.03	60	56
Rump roast with 20-day aging	VP	3.03	1.03	70	75
Rump roast with 69-day aging	VP	1.04	1.03	85	90
Rump steaks produced from VP primals without aging	VSP	3.25	2.30	41	43
Rump steaks produced from VP primals after aging for 30 days	VSP	3.21	3.23	38	40
Rump steaks produced from VP primals after aging for 57 days	VSP	3.16	4.00	37	38
Lamb products					
Boneless legs	VP	1.36	0.12	103	88
Bone-in legs	VP	1.36	0.16	97	92
Racks	VP	1.36	0.07	94	92

a. VP = vacuum packaging; MAP = modified atmosphere packaging (75-82% O_2 and 18-25% CO_2); OW trays = over-wrapped trays; and VSP = vacuum skin packaging

b. Average temperature from packaging to the end of the trials.

c. Average TVC at the time of packaging.

d. The time taken for each product to reach its end of shelf-life based on odour attribute