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Title: The welfare risks and impacts of heat stress on sheep shipped from Australia to the Middle East

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PII: S1090-0233(16)30159-9
DOI: http://dx.doi.org/doi: 10.1016/j.tvjl.2016.09.011
Reference: YTVJL 4884

To appear in: *The Veterinary Journal*

Accepted date: 29-9-2016

Please cite this article as: Clive Phillips, The welfare risks and impacts of heat stress on sheep shipped from Australia to the Middle East, *The Veterinary Journal* (2016), http://dx.doi.org/doi: 10.1016/j.tvjl.2016.09.011.

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Review

The welfare risks and impacts of heat stress on sheep shipped from Australia to the Middle East

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Highlights

- Australia sends about two million sheep to the Middle East annually
- Mortality rates on board are increased during the northern hemisphere summer
- Mortality appears due to a combination of heat stress, salmonellosis and inanition
- The risk posed by heat stress and means of mitigating the risk are reviewed

Abstract

This review considers the welfare issues confronting sheep due to heat stress on board ships undertaking long distance voyages. Sheep engage behavioural and physiologic mechanisms to attempt to mitigate heat stress, but the evidence from Australian shipments from 2005 to 2014 is that mortality approximately doubles when sheep are transported from Australia in winter to the Middle East in summer. Much of this increase has been attributed to salmonellosis and inanition, but this may have been mistaken for, or exacerbated by, heat stress. The Australian government's estimate of the heat stress threshold of sheep is substantially higher than that observed under simulated live export conditions, which leads to an underestimate of the importance of heat stress in sheep on voyages where mortality is high. Improved temperature monitoring on ships and the creation of both a robust model of the impact of increased temperatures on sheep morbidity and mortality, and a heat stress scale for sheep would assist in understanding and addressing this welfare concern. The high risk to sheep exported from Australia during summer in the Middle East is sufficient to warrant consideration of restriction of trade during this period.

Keywords: Animal welfare; Heat stress; Live export; Sheep; Ship

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Introduction

Australia exports approximately two million sheep annually, 98% of which go to the Middle East[1]. The transition from the southern to northern hemisphere means those animals experience a large change in temperature within two weeks, from temperatures as low as 0^{o} C immediately prior to boarding at Portland[2] to temperatures of 40^{o} C and above in the Middle East (Pal and Eltahir, 2016). Voyages leaving Australia during the southern hemisphere winter and entering a northern hemisphere summer pose a particularly high risk to sheep, which may derive from their susceptibility to heat stress (Norris and Richards, 1989) and/or a natural reduction in appetite of the sheep in the fat deposition phase during the second half of the year (Higgs et al., 1991). Sheep are particularly at risk of heat, rather than cold, stress because of the large amount of heat generated by the fermentative digestion of their feed by micro-organisms in the reticulorumen. Furthermore, large amounts of heat and moisture are generated within a ship by the high stocking density of livestock, as well as heat generated by the ship's engine (Caulfield et al., 2014). Many of the sheep are sent from Australia for the Eid al-Adha festival of sacrifice, currently in mid-September, but advancing by 10 days each year, which will bring the timing of the voyages close to mid-summer in the Middle East.

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[1] See: Livecorp Sheep Statistics. www.livecorp.com.au/industry-information/industry-statistics/sheep-statistics (Accessed 27 September 2016).

[2] See: Weather2. www.myweather2.com/City-Town/Australia/Victoria/Portland/climate-profile.aspx?month=6 (Accessed27 September 2016).

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The mechanisms used by individual sheep to mitigate heat stress are well known for land-based farming systems, but this review considers the risks of heat stress to sheep on ships and the impacts on their welfare.

General animal responses to heat stress

Research using a rat model demonstrates that the early stages of heat stress are characterised by tachycardia and increased blood pressure, with the latter falling in severe heat stress (Quinn et al., 2014). Ultimately multi-organ failure is responsible for mortality during heat stroke, including, in particular, myocardial infarction, renal tubular necrosis and nephrosis, and acute liver necrosis (Quinn et al., 2014). Renal dysfunction has been detected in sheep subjected to thermal conditions similar to those experienced by sheep transported from Australia to the Middle East (Stockman et al., 2011).

Temperature sensors are located in the skin, buccal cavity, spinal cord and hypothalamus, relaying information to the preoptic area of the hypothalamus, the main centre for temperature regulation (Beatty, 2005). In some species, high ambient temperatures are accompanied by a cranial arterio-venous difference in blood temperature which protects brain function (Vesterdorf et al., 2011). As an example this protective function, heating of the preoptic area and rostral hypothalamus artificially leads to rapid cessation of eating in goats, supporting thermostatic control of feed intake (Bianca, 1965).

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During heat stress, the core body temperature of animals increases and humans at least report unpleasant sensations (Parkinson et al., 2016). In humans, terminal heat stress is accompanied by central nervous system (CNS) disorders, including intracranial hypertension, delirium, convulsion and coma. Cattle are also reported to have neurologic signs in terminal heat stress (Beatty 2005). The events appear to be triggered by ischemic and oxidative damage to the hypothalamus (Chen et al., 2013). In non-terminal heat stress, pain and exhaustion are frequently reported (Sahu et al., 2013), as are hypothermia and continued production of the stress hormone corticosterone (Chen et al., 2013). There is some commonality in responses to heat stress between rodents and humans (Chen et al., 2013) and between humans and sheep (Damanhouri and Tayeb, 1992). The studies that have been conducted in sheep, particularly as models for heat stroke in humans, have demonstrated impairment of platelet function (Mohanty et al., 1997), as well as the beneficial effects of the muscle relaxant dantrolene and the opioid antagonist naloxone (Damanhouri and Tayeb, 1992).

Heat stress responses in sheep

The heart rate of sheep increases in response to the requirements for additional blood flow to the lungs to support hyperventilation (Cezar et al., 2004). In cattle at least, core body temperature also fluctuates more widely than usual (Beatty et al., 2006, 2007). Sheep reduce their activity levels, lie down for prolonged periods, and have little appetite (Black et al., 1994). Lying helps to reduce heat load by providing a ready conduit for the heat to the floor, which has greater conductivity than air (Silanikove, 2000). Stress levels increase in extreme heat stress, as evidenced by increased blood cortisol concentration in sheep exposed to 35-44 ^{o}C for 35 days, to approximately three

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times basal levels within a week, progressing to four times basal levels within 2-3 weeks (Indu et al., 2015). This indicates prolonged distress when exposed to chronic heat stress (Silanikove, 2000). Similarly, adrenaline, noradrenaline and ACTH are increased in sheep in hot conditions (Cwynar et al., 2014).

As heat stress increases, the heat loss mechanisms in sheep change from passive loss, via radiation, conduction and convection, to active heat loss, mainly via vasodilation in the extremities (especially the legs and ears) and panting, but also via sweating, if there is only a small amount of wool cover (Marai et al., 2007). Sheep also attempt to spread their hind legs, assuming stocking densities allow this, thereby exposing the highly vascularised skin under their flanks and increasing heat loss through convection[3]. Tongue lolling, or extrusion of the tongue from the buccal cavity, has been observed in heat-stressed sheep on ships (Black et al., 1994). Tongue lolling increases both heat loss from the tongue and air inspiration.

Panting, or breathing rates over 40 breaths per minute (bpm), in sheep becomes common when maximum dry bulb temperature (DBT) reaches 26 ^{o}C (Silanikove, 2000), a temperature which is usually exceeded by the end of voyages from an Australian winter to a Middle East summer (Fig. 1). Panting accelerates air passage over the nasal turbinates, protecting the brain from rising body temperatures. Sheep are a species where high ambient temperatures are accompanied by a cranial arterio-venous difference in blood temperature (Vesterdorf et al., 2011). Under extreme conditions,

[3] See: Experimental methods for evaluating herbage P.107 http://www.archive.org/stream/experimentalmeth00camp/experimentalmeth00camp_djvu.txt (Accessed 27 September 2016)

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panting to increase heat loss raises respiration rate from the basal rate of 25-30 bpm up to 300 bpm, according to Silanikove (2000). The maximum respiration rate is suggested to be approximately 320 bpm by Turnpenny et al. (2000), similar to the 300 bpm measured by Hales and Brown (1974). At high heat loads breathing converts to a deep form of panting which has a lower respiration rate of about 166 bpm and results in air exchange into the deeper parts of the lungs (Hales and Brown 1974). Interestingly, McCarthy, a live export veterinarian reported that a transition from rapid breathing to low rate panting occurs at a rate of 220-240 bpm[4]. These conclusions are consistent with the findings of Stockman (2006) that, in thermal conditions experienced during transport of sheep from Australia to the Middle East, the mean respiration rate increased from 50 to 207 bpm, with individual sheep reaching 250 to 300 bpm. Whilst the mean respiratory rate did not differ between two consecutive heating periods, separated by 2.5 days, there was a transition to open mouth panting with reduced respiratory rate in the second heating period. On the days before open-mouth panting, the sheep were observed to have a wrinkled top lip with increased nasal secretions (Stockman et al 2011), which could be a warning sign. A consequence of prolonged panting is respiratory alkalosis (Stockman et al., 2011); however, this rapidly disappears on return to normal temperature (Stockman et al., 2011).

If air temperature (DBT) exceeds body temperature, normally 38.3-39.9^{o}C, the cooling effect of ventilation is reduced or eliminated; at this point, severe heat stress is usually evident (Mahjoubi et al., 2015). Wet bulb temperature (WBT) includes

[4] See: Pilot Monitoring of Shipboard Environmental Conditions and Animal Performance. www.livecorp.com.au/LC/files/ca/ca8fa4fb-c775-4e21-8af8-60cddc2f2170.pdf. (accessed 27 September 2016)

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humidity, and is a more accurate measure of the likelihood of heat stress than DBT. The Australian government has defined the heat stress threshold for sheep as the maximum ambient WBT at which heat balance of the deep body temperature can be controlled using available mechanisms of heat loss. According to the Australian government, the heat stress threshold for adult Merino sheep is 30.6°C[5], however this is not supported by industry research (Maunsell, 2004) suggesting that the heat stress threshold may range from 26 to 30 °C and research by Stockman et al (2011), who recorded increase core body temperature of adult Merino wethers at 26-28°C. It may be that the rate of change of ambient temperature may influence the temperature at which the core body temperature begins to increase, since ship mortality data suggest that sudden increases are associated with a rapid rise in mortality (Norris and Richards, 1989).

Nutritional requirements of sheep for maintenance increase exponentially during heat stress as a result of the energetic cost of heavy panting (Ames and Ray, 1983; Silanikove, 2000). The increased requirement occurs in conjunction with reduced feed intake, which itself reduces the heat generated by rumen digestion (Morand-Fehr and Doreau, 2001). The latter is typically about 50% of the energy consumed (Torrent and Johnson, 2001). As feed intake is reduced, it is possible that heat stressed sheep experience hunger associated with a nutrient deficit, although reduced thyroid hormones may concurrently dull appetite (Silanikove, 2000).

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[5] See: Australian Government Department of Agriculture Mortality Investigation Report 46 www.agriculture.gov.au/Style%20Library/Images/DAFF/__data/assets/pdffile/0003/2364213/mortality-investigation-report-46.pdf (accessed 27 September 2016)

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Long periods of heat exposure have cumulative effects on ruminants. In cattle, subcutaneous temperature increased over seven days of consistent heat stress (Beatty et al., 2006). Evidence of the inability of sheep to cope with prolonged, repeated exposure to heat stress in simulated shipboard conditions was provided by Caulfield et al. (2014), who noted that a second exposure of sheep to high temperatures by Stockman et al. (2011) induced a greater increase in core body temperature than the first.

Estimating the risk of heat stress on livestock shipments

Heat stress measures

Heat stress risk increases with both temperature and humidity. Risk has been well documented for cattle, in particular, as a function of these two factors, and combined into a temperature: humidity index (THI)[6] (Sparke et al., 2001; Lowe et al., 2002). To the author's knowledge, THI does not appear to have been investigated in sheep and validated with stress measurements. A relationship between THI, DBT and humidity has been reported by Marai et al. (2007), but it is unclear whether this is derived from empirical measurements with sheep:

$$THI = DBT - ([0.31 - 0.31\ RH]\ [DBT - 14.4])$$

where DBT is the dry bulb temperature (^{o}C) and RH is relative humidity in %.

There are other complex thermal comfort indices that incorporate radiation, wind speed, air temperature, partial vapour pressure and black globe temperature (Barbosa and Silva, 1995). However, two simpler scales for heat stress are based on

[6] See: Meat and Livestock Australia Tips and Tools Feedlots Heat Load in Feedlot Cattle https://futurebeef.com.au/wp-content/uploads/Heat-load-in-feedlot-cattle.pdf. (Accessed 27 September 2016)

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respiration rates (bpm): low: 40–60, medium - high: 60–80, high: 80–120, and severe heat stress: > 200 (Silanikove, 2000); and mild 120-140, moderate 140-180 and severe > 180[4]. Because respiration rate increases initially then decreases with advancing heat stress, simple respiration rate monitoring is inadequate as a measure of heat stress. Silanikove's scale is based on a review of the literature and in particular observations by Hales and Brown (1974), who subjected sheep to elevated temperatures in controlled conditions. McCarthy's scale[4] is based on shipboard observations and is contained in a report to the live export industry. Whilst the two scales are similar in their attribution of severe heat stress, Silanikove concluded from their controlled elevation of temperature and water vapour pressure that moderate heat stress exists at lower respiration rates than that suggested by McCarthy following shipboard observations[4]. Neither study validated the stress responses, for example with cortisol measurements (Cwynar et al., 2014), and these stress descriptions appear to be somewhat arbitrary, at least at all levels up to severe, with the exception that McCarthy's scale[4] additionally requires that the sheep are observed to be drooling at all heat stress levels (mild, moderate and severe). The severe level was probably determined by both authors to be a typical level for slow, deep panting during extreme heat stress. The McCarthy scale[4] may have been influenced by the desirability of minimising evidence of heat stress in sheep for the live export industry, in terms of demonstrating good sheep welfare. Turnpenny et al. (2000) considered that moderate heat stress only commences above 270 bpm, using data reported by Hales and Brown (1974). McCarthy[4] advocated using a qualitative panting scale, in conjunction with his respiration rate scale described above, to determine heat stress. In this, moderate heat stress has to be accompanied by occasional open mouth panting and severe heat stress

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by both open mouth panting and drooling and/or tongue extension from the buccal cavity. A panting scale for cattle used by Gaughan et al. (2008) also includes the presence of foam from the mouth. There is a need to develop an effective measure of heat stress in sheep that is validated with physiological stress measures.

High WBT and respiration rate have been identified by many stakeholders in the Australian live export industry as key animal welfare measures on ship (Pines et al., 2007). This suggests that heat stress is believed by stakeholders to be a significant welfare problem. However, onboard veterinarians note that it is difficult to count respiration rate accurately[4]. Nevertheless, there has been no attempt by industry to develop a comprehensive and validated heat stress scoring system in sheep that is appropriate to live export situations.

The Australian Standards for the Export of Livestock[7] require a daily report to the Australian government to be prepared by an accredited stockperson or, if present, an accredited veterinarian, which includes a daily characterisation of the respiratory character of the livestock on board as normal, panting or gasping. The lack of clarity on what is meant by 'panting or gasping' further supports the case for the development of a validated heat stress scale for sheep.

Risk of exposure to high temperatures and heat stress

[7] See: Australian Standards for the Export of Livestock (Version 2.3) 2011 and Australian Position Statement on the Export of Livestock. www.agriculture.gov.au/SiteCollectionDocuments/animal-plant/animal-welfare/standards/version2-3/australian-standards-v2.3.pdf (Accessed 27 September 2016)

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A model for heat stress risk assessment has been used by the Australian live export industry since 2003. This has been reviewed in an industry report[8] and by Caulfield et al (2014). The model estimates heat stress risk from predicted: (1) WBT en route and at destination port for the time of year; (2) mortality rate at this WBT, adjusted for animal factors, live weight, body condition, coat type, and acclimatisation; and (3) ship factors, such as ventilation rate and stocking density (the latter can be varied in the event of the mortality risk being too high). Although based on scientific principles, the model has been criticised for the limited database utilised, for using unaudited vessel ventilation data, and for not being validated against actual performance data[8] (Caulfield et al., 2014). For example, open decks are subject to widely varying ventilation, depending on wind speed and direction. Without calibrating the model for differences between open and closed decks, it is not possible to know what wind speed at sheep level is produced by a specific ventilation rate[4].

The model assumes that a 2% (or lower) risk of 5% (or higher) mortality rate is acceptable. The acceptability of this limit depends on public opinion, with high mortality events being used by advocacy groups to draw attention to the ethics of the trade, e.g. by RSPCA Australia (Phillips, 2015). Ferguson et al.[8] state that the climatic parameters used for establishing the model, in particular the range of WBT experienced at its establishment in the early 2000's, may not be appropriate in the future. A regional climate change model has predicted particularly large temperature increases in the Arabian Gulf, sometimes to above a WBT of 35 ^{o}C (Pal and Eltahir, 2016). The

[8] See: Livecorp meat and Livestock Australia Review of the Livestock Export Heat Stress Risk Assessment Model (HotStuff). www.livecorp.com.au/LC/files/a3/a3a29b97-183c-4aad-8b6c-c90fb526dd06.pdf (Accessed 27 September 2016)

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Australian government estimates that the WBT at which mature Merino sheep will die is 35.5^{o}C[1]; however, the Australian live export industry suggests that hyperthermia occurs at temperatures 'approaching or exceeding 30 ^{o}C' WBT[9].

Temperatures on board live export shipments often increase during voyages, which in the extreme can cause an exponential elevation in core body temperature and respiration rate that indicate a failure to cope and potentially result in death of the sheep (Caulfield et al., 2014). Interpretation of shipboard temperature associations with mortality would be aided by more accurate measurement of thermal conditions on ships. Temperatures may be under-reported by several degrees by ship veterinarians, who are employed by the exporting companies (Caulfield et al., 2014). Furthermore, temperatures may not be recorded at the hottest time of the day, and are often noted in the morning in preparation for a midday meeting with the captain (personal communication, Dr Lynn Simpson). Thermal data loggers have been tested on live export shipments and could provide useful information to link to mortality events[4]. Whatever monitoring method is used, determining the appropriate location and number of sites is crucial and requires further research.

On livestock ships, temperatures may remain relatively constant throughout the day. On land, livestock experiencing heat stress during the day alter their behaviour to be active at night when it is cool, including feeding and oestrous behaviour. This opportunity is less available to sheep on ships because of the limited reduction in

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[9] See: Livecorp, Meat and Livestock Australia, Veterinary Handbook for Cattle, Sheep and Goats. www.veterinaryhandbook.com.au/Diseases.aspx?id=46&diseasenameid=116&speciesid=-1&syndromeid= (Accessed 29 September 2016)

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temperature at night, especially on closed decks. Sheep on open decks reliant on natural ventilation are at high risk when there is no crosswind, which is most likely to occur in port. Ships may adopt a zigzag pathway to increase the crosswind[4], but this is not possible in narrow waters. These factors exacerbate the heat stress risk above the level expected on land. Allowing cattle access to cool temperatures for just 3-6 h at night allows them the opportunity to lose the previous day's accumulated heat load (Silanikove, 2000; Sparke et al., 2001). Although sheep have a higher surface area to weight ratio and, therefore, greater potential to lose heat, compared to cattle (Brody, 1944), their coat has significant insulating properties (Beatty et al., 2008). Australian standards (ASEL, 2011) place restrictions on the export of sheep with wool more than 25 mm long; however, hair sheep, such as those of the Awassi breed, are not subject to such restrictions.

On voyages from Australia to the Middle East, WBT may exceed 30 ^{o}C (Caulfield et al., 2014). Recommended maximum DBT for transporting sheep has been estimated as 25 ^{o}C, based on mathematical modelling of the species' requirements for space to move, and ventilation and heat losses (Randall, 1993). Some areas of the ship are prone to high temperatures such as those near engine and boiler rooms, heated fuel tanks or under the top deck. While Australian government regulations require that, where ambient temperature exceeds 22 ^{o}C, any temperature increase in adjacent livestock space is less than 3 ^{o}C[10], compliance with this is not known. Temperature

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[10] See: Australian Government Australian Maritime Safety Authority Marine Order 43 (Cargo and cargo handling — livestock) 2006 in effect under the Navigation Act 2012

www.amsa.gov.au/vessels/standards-regulations/marine-orders/documents/MO43-modcomp-130729Z.pdf (Accessed 27 September 2016)

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mitigation is only likely to be available for sheep in the outer pens on open decks, due to some limited exposure to the colder night air. The greatest risks for open deck sheep that have no mechanical ventilation occur when the ship is stationary or when there are no cross winds.

Heat stress risk is increased by the inability of sheep to avoid hot areas in the ship, because the official space allowance is low (0.26 m^2 for a 28 kg sheep to 0.32 m^2 for a 51 kg sheep[11]). These space allowances are less than the Australian minimum requirements for sheep in feedlots or sheds (at least 0.5 m^2/head for a wether [12] [13] [14]), but more than those for land transport (0.19 m^2 for a 28 kg sheep to 0.25 m^2 for a 50 kg sheep[15]). Land transport is shorter in duration than long haul sea voyages, hence tighter stocking is accepted. However, the only research to investigate stocking density on live export voyages failed to include any voyages to the Middle East in their summer (Phillips and Petherick, 2014). As a result, the relationship between heat stress and stocking density has never been investigated appropriately in long haul sea transport.

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[11] See Australian Standards for the Export of Livestock (Version 2.3) 2011 and Australian Position Statement on the Export of Livestock p.90. www.agriculture.gov.au/SiteCollectionDocuments/animal-plant/animal-welfare/standards/version2-3/australian-standards-v2.3.pdf (Accessed 27 September 2016)

[12] See: Primary Industries Standing Committee Model Code of Practice for the Welfare of Animals, The Sheep 2nd Ed. PISC Report 89. https://ablis.business.gov.au/ACT/resource/COP290.pdf (accessed 29 September 2016).

[13] See: Australian Standards for the Export of Livestock (Version 2.3) 2011 and Australian Position Statement on the Export of Livestock p.63.

www.agriculture.gov.au/SiteCollectionDocuments/animal-plant/animal-welfare/standards/version2-3/australian-standards-v2.3.pdf (Accessed 27 September 2016).

[14] See: Australian Animal Welfare Standards and Guidelines. www.animalwelfarestandards.net.au (Accessed 27 September 2016).

[15] See: Australian Animal Welfare Standards and Guidelines Edition One Version 1.1 21 September 2012. www.animalwelfarestandards.net.au/files/2015/12/Land-transport-of-livestock-Standards-and-Guidelines-Version-1.-1-21-September-2012.pdf. (Accessed 27 September 2016).

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Since the industry has not appropriately investigated, documented and researched heat stress on live export voyages, the only logical conclusion is that voyages to Middle East summer are an extreme animal welfare risk. An independent report to the Australian government on live export from Australia to the Middle East[16] recommended that: “There must be a continuation of the current industry investment in rigorous research and development programs on the suitability of different types of livestock for export: - in the meantime exports should be banned in circumstances where the available evidence indicates that the risks of adverse outcomes are predictably high”. This supports the case for prohibiting the voyages to the Middle East summer.

Mortality and morbidity resulting from heat stress effects on sheep transported by ship

Mortality

The suffering caused by exposure to heat stress is significant. Many sheep experience heat stress without dying, but as mortality is the only welfare measure that is publicly available regarding shipboard ‘performance’, it is relevant to investigate seasonal variation and compare on-board mortality rates with those on land. Mortality rates for sheep are increased on board ship compared with the mortality rate on land (mean equivalent daily mortalities for sheep are 0.10 % on ship versus 0.007 % on land, i.e. 14 x higher for ship) (Phillips, 2015). Mortality usually increases as voyages from

[16] See: Livestock Export Review Final Report A Report to the Minister for Agriculture, Fisheries and Forestry. www.agriculture.gov.au/SiteCollectionDocuments/animal-plant/animal-welfare/trade/export-transport-review/keniry_review_jan_04.pdf (Accessed 27 September 2016).

the southern hemisphere to the Middle East progress (Black et al., 1994). At high DBTs of 40-42 ^{o}C, each degree increase in temperature can be extremely detrimental to sheep survival (Sejian et al., 2013).

The mean monthly mortality from national livestock export industry shipboard performance report data (377 voyages over 9 years) is summarised in Fig. 2. The figure demonstrates a pronounced increase in mortality of all classes of sheep exported during the southern hemisphere winter/spring. More specifically, mean mortality monthly rates depicted from November 2005 to the present show a distinct increase between June and October, with the highest rate in August. Increased mortality in the second half of the year has been recognised in the annual national livestock export industry shipboard performance reports, most recently[17]. Early reports contained a Research Summary that gave the main causes of sheep mortalities as a persistent inappetence, salmonellosis inanition (PSI) condition, accountable for about 75 % of all sheep deaths[18]. Heat stress was acknowledged to be an occasional risk factor. No attempt was made in veterinary reports on ‘salmonellosis’ in export sheep to differentiate observed gross and histopathological lesions with those caused by hyperthermia (Curran, 2013). This may be related to the lack of studies of pathology of hyperthermia in sheep.

The PSI condition is commonly accompanied by adrenal gland hypertrophy indicating the association of stress (Higgs et al., 1993). Any analysis of the effects of

[17] See: Livecorp Meat and Livestock Australia Final Report Project code: W.LIV.0288. www.livecorp.com.au/LC/files/e7/e776991c-918e-401d-bb0f-5c0de31f1463.pdf (Accessed 27 September 2016).

[18]See: Livecorp National livestock export industry shipboard performance report 2008.

www.livecorp.com.au/research-development/reports/national-livestock-export-industry-shipboard-p-%286%29 (Accessed 27 September 2016).

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heat stress on sheep in live export must consider the interrelationship between PSI and heat stress. PSI is reported to account for approximately 75 % of mortality in the live export of sheep from Australia to the Middle East[19]. Higgs et al. (1993) found that the excretion of *Salmonella* spp. increased over the duration of voyages from Australia to the Middle East, which they attributed to the developing inanition. However, extrapolating from research in humans and other animals, heat stress may exacerbate PSI. During heat stress increased cutaneous blood flow is accompanied by reduced splanchnic blood flow, and the resultant oxidative and nitrosative stress in an ischemic environment enables bacteria to cross the tight junction barrier from the gut lumen into the systemic circulation (Leon and Helwig, 2010). The increased gut epithelial permeability also increases the likelihood of endotoxin leakage. It has been hypothesized that this can contribute to multi-organ system dysfunction, since endotoxaemia ensues if the endotoxins cannot be neutralised by the liver, macrophage activity, antibodies or high-density lipoproteins (Lim et al., 2007). The resultant cytokine release and inflammatory response can lead to systemic coagulation and haemorrhage, necrosis, apoptosis and multi-organ failure (Lim and McKinnon, 2006). Current models of heat stroke based on clinical observations of humans and other animals propose that, following migration of endotoxins into the circulatory system, the activation of the immune cells and cytokines promote inflammation and drive the clinical symptoms of heat stroke more than the hyperthermia (Lim and McKinnon, 2006; Lim et al., 2007). Furthermore, evidence from animal models suggests that controlling the endotoxaemia protects against heat stress, and conversely a pre-existing

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[19] See: Meat and Livestock Australia Final Report Project Code: LIVE123 www.livecorp.com.au/LC/files/4f/4f560cff-2c64-4da1-b64d-7bab541e866a.pdf (Accessed 27 September 2016).

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inflammation compromises heat tolerance (Lim et al., 2007). Thus, in monogastric animals at least, heat stress is associated with reduced immunocompetence. In ruminants, the survival of *Salmonella* spp. in the rumen is enhanced by low feed intake (Brownlie and Grau, 1967). Therefore, as most sheep are exposed to *Salmonella* spp. in the feedlot, during the voyage or both, it is possible that the combination of heat stress and the PSI may enhance mortality. Curran (2013) has contended this proposed synergism to suggest that heat stress on live sheep exports has been misdiagnosed as PSI, citing the similarity of clinical effects in the intestine observed post mortem.

Morbidity

Given the marked physiologic and behavioural responses to heat, it is evident that heat stress results in considerable morbidity in sheep on ships. On land, heat stress in sheep has been reported when THI exceeds 22 (Marai et al., 2007), but in cattle, at least, homeostasis prevents elevation of rectal temperature until THI exceeds approximately 78 (Silanikove, 2000). The latter study identified four levels of heat stress in livestock: innocuous, aversive, noxious, and extreme. From the previous descriptions of the temperatures and behavioural responses, in particular elevated core body temperatures and respiration rates, it is clear that sheep on live export ships experience the two most severe levels.

Increased panting and sweating both use water vapour as a conduit for surplus heat, and the consequent loss of body water increases water requirements. In cattle it has been observed that voluntary drinking water intake may be doubled during heat stress (Beatty et al., 2006, 2007). Sheep congregate around the water troughs to meet

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their increased water needs during heat stress, and it may become more difficult for other sheep to reach the troughs. If sheep are unable to drink to requirements, dehydration ensues, which allows body temperature to increase (Silanikove, 2000), causing the profoundly negative emotion of thirst (Ogino et al., 2014), and increasing risk of heat stroke (Leon and Helwig, 2010). Increased water intake leads to increased urination, which can result in deficiencies in sodium and potassium (Beatty et al., 2006). Water temperature may exceed 40 ^{o}C when live export sheep arrive in the Middle East, leading to reduced ability to control body temperature by drinking (Savage et al., 2008; McKinley et al., 2009).

Sheep remain on solid floors on ships. The accumulating excreta is desiccated into a dry, friable powder by the high ship ventilation rate. Over a journey of typical duration, the depth of the powder builds up to approximately 10 cm (Pines and Phillips, 2011). However, with the increased ratio of urine to faeces during heat stress, exacerbated by the associated reduced feed intake, there is a risk that the excreta will turn into slurry. This in turn can increase humidity in the ship's environment, which increases WBT and exacerbates heat stress. High humidity in inhaled air reduces an animal's capacity to expel moisture and, hence, body heat, during expiration (Liu and Li, 2009). The risk of these occurrences will be exacerbated during periods of limited air flow on open decks, which rely in part on natural ventilation as opposed to the lower, enclosed decks, which rely solely on forced air ventilation.

Conditions on board ship, especially high humidity and high stocking density, limit the opportunity for sheep to mitigate the effects of heat stress. At high

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temperatures on one voyage from New Zealand to Saudi Arabia, sheep attempted to move to the well ventilated parts of each pen, especially around ventilators, or to the feed trough (Black et al., 1994). In so doing, it was observed that smothering occurred as they struggled over sheep that were lying down (Black et al., 1994). Movement in areas with a slurry of excreta was noted to be particularly difficult (Black et al., 1994). It was also observed on this voyage that sheep plunged into other sheep to get access to better ventilated areas. The consequence was commonly death by suffocation, which represented the largest cause of mortality on that one voyage in which heat stress occurred (Black et al., 1994).

The heat stress experiences of individual sheep will vary according to their position on the ship. If they are near the heat sources in the ship identified earlier they will have an increased ambient temperature. If they are near ventilation outlets they will experience greater cooling effects. At a local level, sheep ventilation will be impaired by the high stocking density adopted on ships. Sheep that can elevate their heads above other sheep are at a significant advantage (Black et al., 1994) as they are able to facilitate heat loss through their ears (Marai et al., 2007). Likewise, those that can reach water troughs are advantaged (Taylor, 1983). As there is limited sheep movement around pens (Pines and Phillips, 2013), many individual animals have little or no opportunity to mitigate the risk of heat stress, other than attempting to spread their legs as discussed previously.

Heat stress is promoted by the same conditions that increase volatilisation of ammonia, a noxious gas that causes considerable suffering under live export

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conditions, including reduced feed intake (Phillips et al., 2010, 2012). These conditions include high temperatures and high stocking density per volume of air space, such as in double-tiered decks. The possibility of synergistic effects between heat stress and ammonia has not been investigated and is worthy of study.

The impact of the heat load on sheep welfare on-board is therefore significant. As well as documented heat stress responses, it is clear that many voyages entail factors that both exacerbate the condition and increase the risk of it occurring. In addition, it may also generate behaviours that threaten the welfare of other sheep, such as plunging into and smothering other sheep, again potentially resulting in mortality. Australian space allowances appear small, in comparison with other long duration accommodation for sheep.

Conclusions

Evidence is provided that conditions on live export shipments regularly expose sheep to heat stress, which appears to be most severe for sheep transported from Australian winters to summer in the Middle East. There is limited information on how the industry addresses these concerns, and what parameters should be or are measured to determine the extent of heat stress. Industry has developed a heat stress risk model, but this requires further research before its effectiveness is known. There is an urgent need to develop both a THI and a panting scale for sheep that are properly validated with physiological measures. The similarity of clinical signs of heat stress and PSI suggest that detailed post mortems are required, at least on high mortality voyages. The contributing factors to heat stress in the export of livestock from Australia in winter to

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the Middle East in summer are broadly known: high temperature and humidity; reduced variation in circadian temperature; high stocking densities which increase heat production and limit opportunities for sheep to mitigate heat load effects; the presence of excreta and variable ventilation rates. However, relationships with heat stress are not adequately quantified, and investigations into the actual impact of each of these factors on heat stress on ships has been poorly investigated. Since voyages to Middle East summer are an extreme animal welfare risk and an independent report to the Australian government concluded that exports should be banned if the evidence is the risks of adverse outcomes are predictably high, there is a case for prohibiting these voyages.

Conflict of interest statement

The author of this paper has no financial or personal relationships with people or organisations that have inappropriately influenced or biased the content of the paper.

Acknowledgements

The author is grateful to Animals Australia for part-funding of this review. Two anonymous reviewers provided valuable comments.

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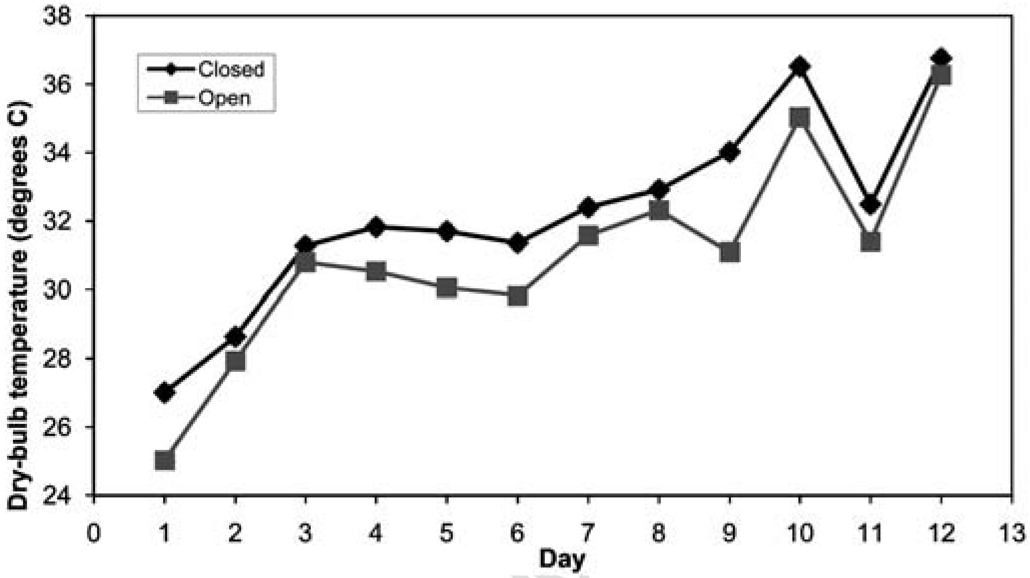
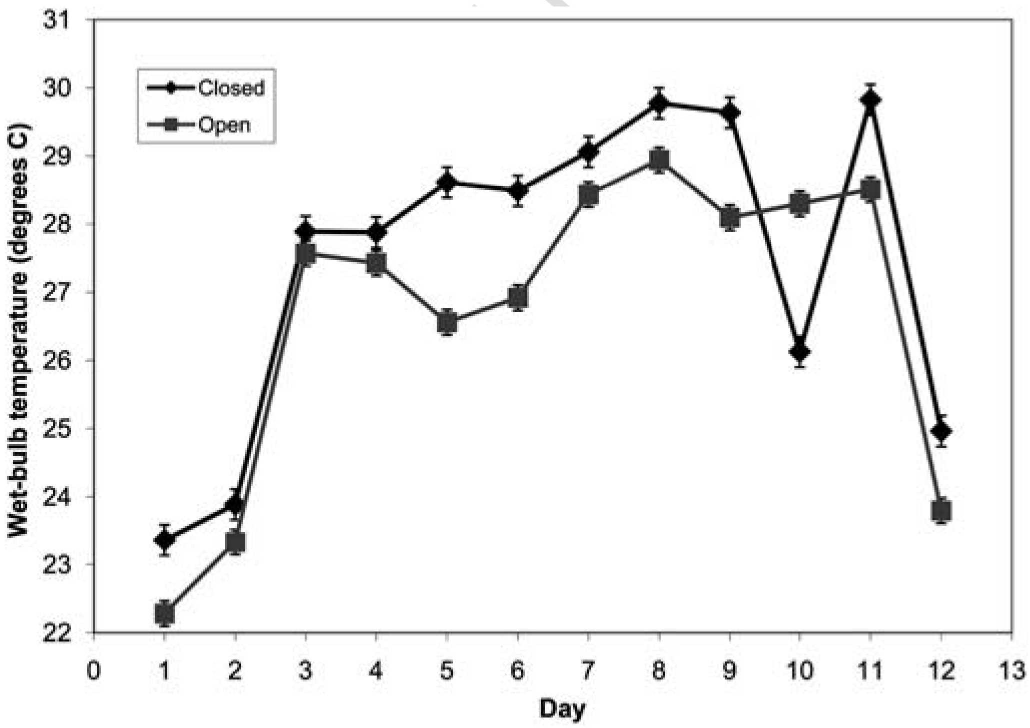
Figure legends

Fig. 1. Dry and wet bulb temperatures on the closed and open decks of a typical voyage from Fremantle to Muscat (12 days) in July 2005 (Pines and Phillips, 2013)





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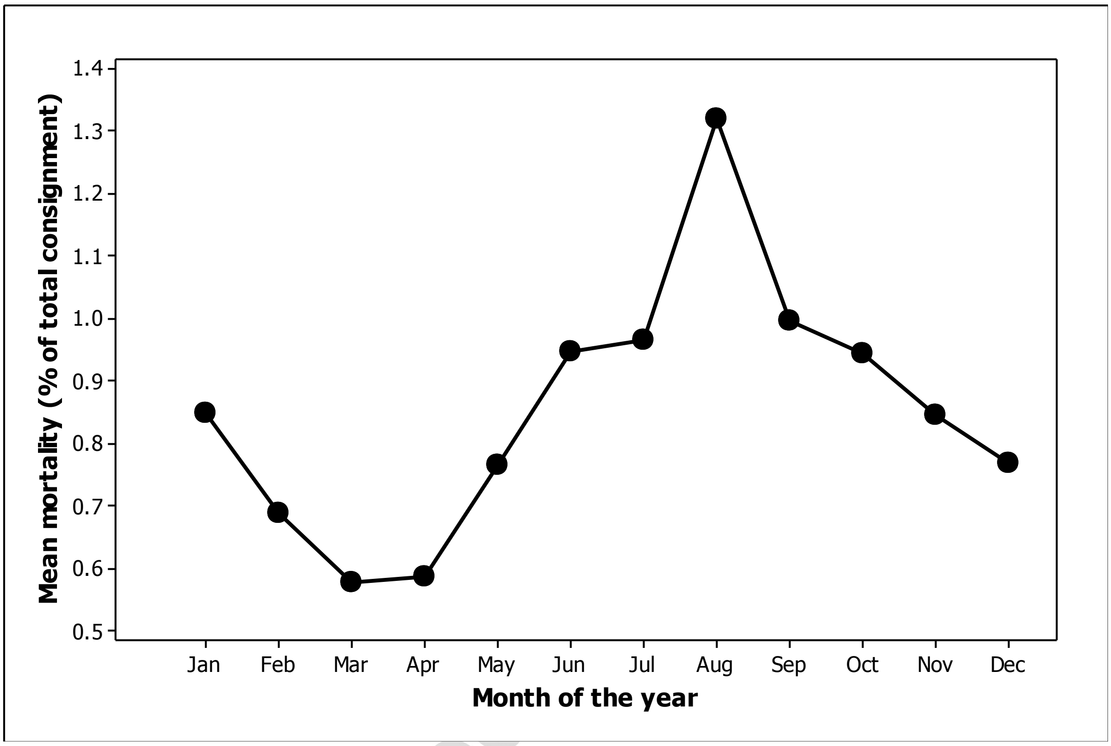
717 Fig. 2. Mean sheep mortality rate over the 12 months of the year for shipments exported

718 from Australia between November 2005 to November 2014 (data derived from

719 Australian Government, 2015[20])



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[20] See: All sheep (any class), exported from all Australian ports to a variety of destinations, but mostly in the Middle East. Australian Government Department of Agriculture and Water Resources, Live Animal Export Statistics Reports to Parliament. 2015. Sheep Export Voyages**.** http://www.agriculture.gov.au/export/controlled-goods/live-animals/live-animal-export-statistics/reports-to-parliament (Accessed 27 September 2016).