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Trichinella spp. control in modern pork production systems

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ABSTRACT

Infection with *Trichinella* spp. from pork and other sources has been a major public health concern in many parts of the world. This review describes the progression of processes followed to protect consumers from exposure to this parasite. Testing programs for pigs, as required by some countries, have been important in reducing the risk of exposure from commercial pork products. However, improvements in pork production systems in the past several decades, including high levels of bio-security in confinement production systems, have also contributed to major reductions in the occurrence of this parasite in pigs and pork products. International guidelines and regulations have codified requirement for controlled management or controlled housing that prevents risk of exposure of pigs to *Trichinella* spp. Adhering to these requirements, with appropriate documentation, eliminates the need for individual carcass testing for domestic consumers as well as for purposes of trade. Pigs not produced in controlled housing systems should be subject to testing to confirm absence of *Trichinella* spp. infection.

1. Introduction

This manuscript is a review with some opinion and is intended to describe changes in the requirements for assuring public health safety from the risk of *Trichinella* spp. in pork. While historical testing has proven effective for reducing human disease, modern pork production systems have been equally or more effective in eliminating the risk of trichinellosis from commercial pork. While regulations have been updated based on scientific findings and expert opinions, further review of regulatory requirements is necessary for rationale and equitable approaches to trade requirements.

2. Background

Trichinellosis, a human disease resulting from infection with larvae of the genus *Trichinella*, is one of the oldest, and for some periods of time, one of the most well-known and widely-feared foodborne illnesses. The history of *Trichinella* spp. control began >150 years ago following the elucidation of the life history of the parasite and its association with eating raw or undercooked pork. Details of these discoveries are described by Gaeta and Bruschi (2021),

The life history and routes of transmission of *Trichinella* spp. are relatively simple among the parasites affecting humans (Pozio, 2007; Gamble et al., 2007). Further, the risks for human exposure from pork and pork products are limited, and, on the surface, seemingly easy to prevent (Gamble et al., 2000; Gamble et al., 2019). Nevertheless, human infection from pork was common in many countries for much of the 19th and 20th centuries, and significant outbreaks still occur today in some regions (Murrell and Pozio,

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2011).

As an example of how serious the risk of *Trichinella* spp. infection was, cadaver surveys performed in the United States in the 1930's (Wright et al., 1943) found worms in the musculature of almost 1 in 5 humans. While the historical levels of infection have long since been controlled and, due to factors including the sanitary systems used in modern pork production, it does point out why, in the late 1800's and the first half of the 1900's, *Trichinella* spp. were considered a serious health issue and a real concern for consumers of fresh pork.

Because of the morbidity and mortality resulting from human trichinellosis, the threat of acquiring worms from pork caused an aversion to this source of meat. Even today, the presence of fresh pork products on restaurant menus lags far behind that of poultry and beef. Even when served, pork is still frequently overcooked, despite the absence of risk of possible *Trichinella* spp. infection in many parts of the world.

Among the major impacts of *Trichinella* spp. in pork were requirements restricting trade. For example, U.S. pork was prohibited in Greece, Italy and Portugal (1879), Germany, Spain (1880), Denmark (1888), Austria, France, Hungary, Turkey and Romania (1889), among other countries (Campbell, 1983). Many of the testing and post-harvest processing requirements for *Trichinella* spp. continue to play a role in trade agreements (OIE, 2021; European Community, 2015).

As noted, control of *Trichinella* spp. has historically been performed by testing at slaughter or by post-slaughter processing using methods of cooking, freezing or curing. Testing at slaughter will be reviewed here and a full discussion of post-slaughter mitigations can be found in Noeckler et al. (2019). This review will then address the development of measures for assuring the safety of pork relative to *Trichinella* spp. by following management practices that prevent possible exposure to this parasite during pork production.

3. Control of *Trichinella* in pork by testing

3.1. Direct testing

While practiced extensively in many countries, testing of individual pig carcasses for *Trichinella* spp. infection by direct, visual means has seen limited advancements over the 150 years of practice. The original method of compressing small pieces of porcine muscle between two glass slides and examining under a microscope was incredibly time consuming. Nevertheless, this method, which is known to reliably detect infections of three (3) or more larvae per gram of tissue (Noeckler and Kapel, 2007), was an effective means of preventing serious human disease. Of equal importance, detecting heavily infected carcasses had the advantage of removing infected meat from possible re-introduction to pigs when fed waste products.

The single major advancement in the direct detection of *Trichinella* spp. in pig musculature was the development of the pooled sample (magnetic stirring) digestion method (Zimmermann, 1967). This test combined the ability to test multiple samples by digestion in acidified pepsin. While positive samples could not be tracked initially to an infected carcass, positive samples could be re-tested in smaller batches. Where infection rates were low and few infections found, this method especially saved countless hours of time and expense.

As a direct method, and with proper technical training, the artificial digestion method has absolute specificity and with the advent of molecular methods can pinpoint species or taxa of *Trichinella*, possibly assisting in epidemiological investigations. While specificity is high, sensitivity is not, at least for low-level infections. Studies report that to achieve a sensitivity of close to 100%, infections must be at a level of 3–5 larvae per gram of tissue (Gamble, 1996, 1998, 1999; Noeckler and Kapel, 2007). This assumes testers are well trained and follow strict quality assurance protocols. In this way, testing identifies infected carcasses that are most likely to cause clinical human disease if meat is not processed by cooking, freezing or other methods known to inactivate *Trichinella* spp. larvae.

Slaughter testing of pigs, as required by most veterinary authorities, cannot be said to prevent human exposure to *Trichinella* spp. Rather, the goal of testing is to prevent clinical human disease (Van Knapen, 2000). It is often cited that human disease can result from ingestion of a meal of infected meat containing one (1) larva per gram of tissue or greater. While this is only supported by limited studies (Teunis et al., 2012), if this is an accurate assessment, then given the sensitivity of the pooled sample digestion method, is likely that carcasses harboring a parasite burden of <3–5 larvae per gram of tissue are not detected and may be passed for human consumption. It is not possible to know what these numbers might be, but in areas where *Trichinella* spp. infection occurs in pigs, it is clear that risk of human exposure remains even when slaughter inspection is performed.

3.2. Alternatives to direct testing

Much effort has gone into finding more cost-effective methods for testing pork for *Trichinella* spp. infection. While a variety of serological methods have been used to detect antibodies directed at *Trichinella* spp., with the advent of enzyme-linked immunosorbent assay (ELISA) (Ruitenberg et al., 1976) this method was suggested as a possible alternative to digestion testing.

Various forms of ELISA and related antibody binding methods such as Western blotting, when used with specific antigens (culture-derived, monoclonal-purified, recombinant or synthetic) (Gamble and Graham, 1984; Gamble et al., 1983, 1988, 1997; Gómez-Morales et al., 2012; Cuttell et al., 2014), have proven to be extremely useful for purposes of surveillance and as an alternative to invasive procedures for confirmation of human infection. While ELISA would be a cost-effective alternative, issues precluding use of this method for individual carcass testing purposes include inadequate sensitivity and specificity. The extent of these inadequacies has been the subject of considerable study (Bruschi et al., 2019; Gottstein et al., 2009).

With respect to specificity, some reports have suggested serologic cross-reactivity with other parasites in pigs; however, proper preparation of excretory-secretory (ES) antigens by short-term cultivation in a minimal media provides good specificity when used in the ELISA (Gamble et al., 1988; Bruschi et al., 2019). In contrast, the antigenic components of crude extracts or excretory secretory preparation that are not produced properly under these short-term culture methods, or that may have contamination with metabolic products from bacterial or fungal contamination, do not perform adequately. Similarly, ES products that are affinity-purified with specific monoclonal antibodies or recombinant or synthetic antigens bearing the same dominant epitopes (Bruschi et al., 2019) appear to perform without significant cross reactivity but with lower sensitivity than that of ES antigens. Reports of false positive results are one reason serology is not acceptable as a slaughter test. Requirements for any positive serology result would include retesting by a direct method to confirm or reject that result.

In contrast to direct testing methods like artificial digestion, the ELISA test is able to detect very low-level infections (reported to be as low as 1 larva in one of gram of tissue) (Gamble, 1998; Gamble et al., 1988,). However, this sensitivity depends on the infecting dose and the time after infection when the blood sample is taken. In pigs, when very large doses are ingested, antibodies can be detected as early as 7–10 days post-infection. In contrast, very low dose infections in pigs may not result in detectable antibodies for six weeks post-infection or longer. This dose-dependent antibody response can result in a diagnostic window of false negativity and is considered a major drawback to the use of serological methods for slaughter testing of individual carcasses. During this window of false negativity occurring 17 or more days after infection, parasites may be infective in the musculature in an infected host, but the host immune response has not yet produced antibodies detectable by ELISA or other antibody binding methods.

The importance of the diagnostic window of false negativity can be debated relative to the low sensitivity of pooled sample digestion testing known to be 3–5 larvae per gram of tissue (Noeckler and Kapel, 2007). In the case of serology, low-level infections would certainly be missed in pigs that became infected three to six week prior to slaughter. On the other hand, any pig with an infection level less than three larvae per gram would likely be missed by pooled sample digestion. Given the goal of "preventing clinical infection" in humans, the digestion method has continued to be the method of choice recommended by the scientific community and codified by regulatory documents.

Despite the drawbacks of using ELISA for assurances of food safety when testing individual carcasses at slaughter, it has proven highly useful for surveillance studies in pigs and a variety of other animals (Noeckler et al., 2004; Gómez-Morales et al., 2022).

3.3. Value of carcass testing

As discussed, while *Trichinella* spp. have been a major food safety issue in the past, the status of *Trichinella* spp. in pigs has changed significantly over time due to improvements in productions systems which essentially preclude risk of exposure of pigs to *Trichinella* spp.

In some countries where testing is, and has been routinely performed for many decades, *Trichinella* spp. infection is now essentially absent from commercial pork production (Pozio, 2014). Summary data from the EU (European Centre for Disease Prevention and Control, 2021) for the most recent reporting year (2019) found that no *Trichinella* spp. infections were recorded from routine slaughter testing of 72.8 million pigs raised under controlled housing (reported from 16 Member States). On the other hand, testing of 139.6 million pigs from non-controlled housing resulted in 218 positive pigs representing a prevalence of 0.0016%. Positive pigs were reported from Bulgaria, Croatia, France, Poland, Romania, and Spain. Non-controlled housing sourcing positive pigs was described as free-range and backyard husbandry in rural areas.

Slaughter testing, and post-slaughter processing methods have been important for protecting public health, where *Trichinella* spp. infection in pigs has been a significant risk. With the implementation of modern pig production systems, countries where routine slaughter testing has not been performed, have been able to achieve the same low levels of consumer risk as countries where testing has been routinely performed. For example, in the U.S., where no slaughter inspection has been performed, and, where consumption of pork averages 65–70 pounds per annum, human trichinellosis rarely occurs. In a five-year period from 2011 to 2015, a total of two cases of human infection (0.4/ year) could be traced to pork in a population of over 300 million people (Centers for Disease Control and Prevention (CDC), 2017).

Interestingly, much of the transformation of pork production practices was not specifically directed at controlling *Trichinella* spp. The introduction of garbage cooking laws in the United States were intended to control vesicular exanthema (1953–1954) and hog cholera (1962) (Zimmermann and Zinter, 1971; Zimmermann et al., 1973). Likewise, improvements in husbandry, including the introduction of confinement housing systems, generally occurred to improve the profitability of pig production without specific intention to prevent exposure of pigs to *Trichinella* spp.

4. Alternatives to testing or processing for assuring pork safety

With the absence of positive results in many countries after many years of *Trichinella* spp. testing in commercial pigs, scientific experts and veterinary authorities have looked for alternatives to testing. Chief among the motivations to do so is the cost incurred by individual carcass testing. Pozio (1998) estimated that the cost of testing within 15 EU member states in 1998 was roughly $570 M USD per annum. Beginning in the 1990's regulatory authorities considered several approaches.

4.1. Free regions

Regulatory standards published by the World Organisation for Animal Health (OIE) initially proposed to recognize countries or regions that met certain standards to be "free" countries or regions relative to *Trichinella* spp. infection in pigs (OIE, Terrestrial Animal Health Code, Article 3.5.3.2, 8th edition, 1999 (out of print); OIE, Terrestrial Animal Health Code, Article 8.13.2, 19th edition, 2010 (out of print)).

According to these OIE standards, “a country or zone may be considered free from *Trichinella* spp. infection in domestic swine when: trichinellosis is a notifiable disease and there is in force an effective disease reporting system shown to be capable of capturing the occurrence of cases.” Further, the country or zone must demonstrate that “it has been ascertained that *Trichinella* spp. infection does not exist in the domestic swine population of the country or zone under consideration” as established by the regular surveillance of the swine population using an approved testing procedure. Testing must include five years of data from a serological survey of slaughter pigs showing absence of infection at a design prevalence of 0.01% followed by subsequent negative serological surveys of the sow population at a design prevalence of 0.2%. Alternatively, the country or zone could demonstrate that *Trichinella* spp. infection had not been reported in the domestic swine population for at least 5 years and that susceptible wildlife species and sow populations were also surveyed with negative results.

Following the OIE guidelines, Commission Regulation (EC) No 2075/2005 (European Community, 2005) provided requirements for an exemption from *Trichinella* spp. examination if the fattening pigs derived from a region where the risk of *Trichinella* spp. in domestic pig was officially recognized as negligible. Under EU regulations, Belgium and Denmark met the established criteria.

As early as 2000, the International Commission on Trichinellosis published recommendations stating that it is not possible to recognize geographic regions as free from *Trichinella* spp. (Gamble et al., 2000):

> “The ICT does not endorse any programme for assuring pigs to be free from *Trichinella* based on geographic boundaries such as a region, state or country (e.g., OIE *International Animal Health Code*, Article 2.2.9.3)”.

The ICT believed that absolute and ongoing freedom cannot be assigned based on territorial boundaries. This opinion was later supported by other expert bodies. The EC Scientific Committee on Veterinary Measures relating to Public Health (European Commission, 2001) stated:

> “Previously, the designation of *Trichinella*-free areas had been proposed, in recognition of the rare occurrence of *Trichinella* infections in modern pig farming in EU Member States. However, the presence of *Trichinella* in rodent and wildlife populations cannot be prevented by conventional measures, and thus infected rodents remain a source of possible infections for all pigs (and other animal species). Therefore, *Trichinella*-free areas can neither be achieved nor be maintained.”

The same Committee further stated that, “a certification system for modern pig farms, which takes sufficient precautions to guarantee a negligible risk for *Trichinella* spp. infections, should be considered.” This guidance was consistent with recommendations of the International Commission on Trichinellosis (Gamble et al., 2000). A provision for *Trichinella*-free countries and regions was subsequently deleted from OIE guidelines and EU regulations (European Community, 2015), although status remained in force for select countries (Belgium and Denmark).

4.2. Certifying absence of risk during pork production

The concept of documenting the absence of risk for *Trichinella* spp. infection on the farm, has been under discussion since the 1990's (Gamble et al., 2000; Van Knapen, 2000), and, with the modernization of pork production systems, this approach became more feasible for broad application in the pork industry. Pork production under a Hazard Analysis Critical Control Point (HAACP) system, applying critical controls to risks of *Trichinella* spp. exposure, allows for prevention of exposure where risk may exist.

Production practices that “prevent” exposure to *Trichinella* spp. are relatively simple, being based on eliminating opportunities for exposure of pigs to meat that could contain *Trichinella* spp. larvae (Gamble et al., 2000, 2007, 2019). Mitigating risk during production is accomplished as follows:

- Housing pigs in structures that incorporate architectural and environmental barriers to prevent entry of rodents and wildlife.
- Maintaining effective rodent control programs outside and inside pig buildings
- Adhering to good feed manufacturing standards and hygienic on-farm feed storage
- Prohibiting feeding of animal waste products
- Requiring good hygiene practices including prompt removal of dead animals and effective storage and disposal of waste
- Assuring introduction of new animals only from facilities with similar hygienic standards

For pig production facilities that follow the aforementioned standards, pigs may be considered to be free from risk for *Trichinella* spp., or more commonly in recent guidelines and regulations, to have a negligible risk for exposure to *Trichinella* spp.

An early application of principles of prevention of exposure to *Trichinella* spp. during pig production was the U.S. Trichinae Certification Program (Miller et al., 1997; Pyburn et al., 2005). This program emphasized auditing of good production practices that documented the absence of risk factors for exposure pigs to *Trichinella* spp. in including aspects of feed security and rodent and wildlife exclusion. As part of the audit requirements, farms were required to maintain accurate records of animal movement, animal disposal, and rodent control logs. Further, it provided for education of veterinary practitioners who were responsible for conducting regular audits of farms seeking and maintaining *Trichinella*-free certification. Finally, it provided guidance on verification testing of pigs produced by *Trichinella*-free certified farms.

In a similar manner, EU Commission Regulation No. 2075/2005 (European Community, 2005), allowed for exemption from slaughter inspection for a holding (production site) or categories of holdings that were recognized as free from *Trichinella* spp. For individual holdings and categories of holdings, requirements included compliance with principles of good production practices including no outdoor access and regular audits of these practices. The EU directive went further to require two years of slaughter testing after compliance with good production practices and a risk-based wildlife monitoring program (unless no *Trichinella* spp. infection had been reported in the prior 10 years).

While the U.S. Trichinae Certification Program and the EC 2075/2005 were both based on good production practices that preclude exposure of pigs to sources of *Trichinella* spp., they differed in the requirement for a history of testing before recognition of status and the requirement for testing wildlife (required by the EU, but not by the U.S.). The U.S. Trichinae Certification Program ultimately was not successful due to lack of incentives to perform independent audits specifically for this program. While an economic analysis by the U.S. pork industry demonstrated a lower cost for certification as compared with testing, routine slaughter testing for *Trichinella* spp.is not performed in the U.S. and therefore was not a cost that would be offset for producers or slaughter facilities.

5. Guidelines for negligible risk

Over the last decade, guidance and requirements for *Trichinella* spp. control have continued to be refined based on the principles of good management and controlled housing.

5.1. OIE guidelines

Current OIE food safety standards allow countries to define their commercial pigs as having a “negligible risk” for *Trichinella* spp. infection (see Annex A, World Organisation for Animal Health (OIE, 2021), Chapter 8.17) when meeting certain standards. The purpose of this risk classification is to ensure consumer health and standardize requirements for international trade. Exported pork originating from a herd classified as negligible risk should not be subject to any testing or processing mitigations (e.g., freezing, cooking or individual carcass testing) for *Trichinella* spp.

The negligible risk production standards of the World Organisation for Animal Health (OIE, 2021, Annex 1) address the risk factors for exposure of pigs to *Trichinella* spp. as described previously. Compliance with these production standards eliminates risk of exposure to *Trichinella* spp. if it were present in the environment. The standards include:

- Adhering to good feed manufacturing and storage practices
- Maintaining an effective rodent control plan
- Preventing access of pigs to wildlife
- Documenting an effective hygiene program for removal and disposal of deceased pigs
- Documenting animal movement into and from the production site, including new animals only from controlled management herds

The production standards described by the World Organisation for Animal Health to support negligible risk management of pigs are consistent with other described production practices for controlled management/controlled housing, including recommendations of the International Commission on Trichinellosis (Gamble et al., 2019), EU Directives (European Community, 2015), and national standards such as the Danish Product Standard (http://www.pigresearchcentre.dk/~/media/Files/DANISH/DANISH%20produktstandard/Produkt_Standard_UK.ashx) and U.S. Pork Quality Assurance (PQA) Plus® (http://porkcdn.s3.amazonaws.com/sites/all/files/documents/PQAPlus/V2.0/TrainingAdults/PQAPlusEducationHandbookVersion2.0.pdf).

Once negligible risk herds have been established, according to the World Organisation for Animal Health, these herds may be combined into groups or compartments. A compartment of pigs that meets the controlled mangement production standards must meet two additional metrics for classification as negligible risk:

- the absence of *Trichinella* infection in the compartment has been demonstrated by a surveillance program that takes into account current and historical information including slaughter testing results;
- a subsequent program of audits of all herds within the compartment is in place to ensure compliance with conditions of controlled management

For compartments, Article 8.17.4, the World Organisation for Animal Health (OIE, 2021) poses other specific prerequisites for a compartment of negligible risk which address traceability, reporting and communication, all of which are important for documenting possible breakdown of a controlled management compartment. Article 8.17.4 goes on to state the requirements that the Veterinary Authority 1) has knowledge of, and authority over, all domestic pigs, and 2) has current knowledge of the distribution of susceptible species of wildlife.

European Union regulations (European Community, 2015) regarding *Trichinella* spp. essentially mirror those of the World Organisation for Animal Health. Testing of individual pigs is not required if animals originate from a herd or compartment of negligible risk. Prior to recognition of negligible risk status, domestic pigs from production sites applying controlled housing must have demonstrated absence of infection by three years of testing a sampling (10%) of market pigs or all sows and boars. Alternatively, absence of infection can be documented by testing that has demonstrated absence of infection in the pig population at a prevalence of <1 per million animals. As described by the World Organisation for Animal Health, risk-based audits must be performed on production sites applying controlled housing. Further consistent with an option described in the Codex guidelines (see below), a surveillance program may be used to monitor the population of pigs originating from controlled housing to verify absence of infection.

5.2. CODEX guidance on negligible risk (CAC/GL 86–2015)

The Codex Alimentarius provides guidelines "intended for use by government risk managers and industry in the design of food control systems" and "could be used when judging the equivalency of different food safety measures ………… for international trade purposes".

In describing measures to prevent *Trichinella* spp. infection in domestic pigs, CAC/GL 86–2015 (Codex, 2015) refers to the OIE Terrestrial Animal Health Code. Codex guidance further states that "with the establishment of a negligible risk compartment ……… the competent authority may provide derogation from specific post-slaughter controls" (e.g., individual carcass testing).

After establishing a negligible risk compartment for *Trichinella* spp. according to Chapter 8.17 of the OIE Terrestrial Animal Health Code, the Codex states that public health protection to avoid *Trichinella* spp. contaminated meat from going into commerce can be assured by:

- a review of evidence, in particular from audits of herds, demonstrating compliance with the conditions as described in Article 8.17.5 of the OIE Terrestrial Animal Health Code; or
- a risk-based slaughter surveillance program that takes into account information from historical testing results and is supplemented by regular review of information from audits of herds within the compartment; or
- a slaughter surveillance program incorporating current testing data demonstrating that prevalence of infection does not exceed 1 infected carcass per 1,000,000 pigs slaughtered with at least 95% confidence.

In addition to the above, epidemiological investigation of human trichinellosis cases to confirm that the source of the contaminated meat was not from a negligible risk compartment according to Chapter 8.17 of the OIE Terrestrial Animal Health Code should be conducted to the extent possible. Where applicable and available, slaughter and any other relevant testing data from outdoor pigs and wild animals can provide additional information on the conditions surrounding the negligible risk compartment and the potential for infection of animals within the compartment.

5.3. Auditing

To adequately assure compliance with the requirements of a negligible risk herd or compartment, it is necessary to monitor the process by auditing. According to the FAO/WHO (2020), auditing should be carried out following a risk-based approach that the veterinary authority perceives is adequate for protecting public health.

Auditing serves a variety of purposes for assuring compliance with requirements for general hygiene, animal welfare, disease prevention, and specific production standards required by pork packers and processors. In some cases, there are industry-wide standards such as the previously mentioned Danish Produkt Standards and the U.S. pork industry Common Swine Audit (https://porkcheckoff.org/certification-tools/producer-tools/common-swine-industry-audit/). Audits are typically conducted by third party auditors. For the purpose of using audit results to document controlled management and negligible risk for *Trichinella* spp., oversight, review and/or spot auditing for compliance is required of veterinary authorities.

There is flexibility in requirements for auditing among the various documents discussed here. The OIE (OIE, 2021) states that visits by approved auditors should be made periodically to verify compliance with good management practices and the frequency of inspections should be risk-based, taking into account historical information, slaughterhouse/abattoir monitoring results, knowledge of established farm management practices and the presence of susceptible wildlife. The Codex (Codex, 2015) provides auditing as an option for verifying negligible risk, stating "public health protection can be assured by a review of evidence, in particular from audits of herds, demonstrating compliance with the conditions as described in Article 8.15.5 of the OIE Terrestrial Animal Health Code". Likewise, the European Community (European Community, 2015) regulations state that "the competent authority shall ensure that audits are carried out periodically and the frequency of the audits shall be risk-based, taking account of the disease history and the prevalence, previous findings, the geographical area, local susceptible wildlife, animal husbandry practices, veterinary supervision and farmers' compliance".

Depending on the requirements of veterinary authorities, variations in practices among independent, contract, or integrated production systems, and the structure of auditing within those production systems (self-auditing, internal or contract auditing, third party auditing, etc.) the form and frequency of auditing may vary considerably. It is ultimately the responsibility of the veterinary authority to assure adequate compliance and oversight.

5.4. Other considerations for negligible risk compartments

The principles for establishment of negligible risk herds and compartments are based on implementation and maintenance of specific critical control points that preclude exposure of pigs to *Trichinella* spp. By maintaining and verifying these controls, other factors outside of the production system should not impact risk within the production system.

Historical testing and wildlife surveillance are largely irrelevant for risk mitigation when pigs are maintained under conditions of controlled management/controlled housing. The barrier to exposure is the production system employing specific control points for prevention of exposure to sources of *Trichinella* spp. These controls, when properly implemented, will work to prevent exposure irrespective of the level of infection pressure. Once a system of controlled management/controlled housing is in place, the status of pigs from a production system prior to the implementation of the controls is not reflective of the status under a documented system of controlled management/controlled housing.

Within a negligible risk compartment, continued testing is unnecessary, as it will not be adequate for the purpose of documenting absence of infection; determining true prevalence at a very low incidence would require testing all animals, which negates the goal of a negligible risk compartment. On the other hand, if the metric required is not absence of infection but infection below a level that poses negligible risk, as defined by Codex (Codex, 2015), (infection of <1/M pigs) then periodic testing could be justified.

The OIE requires the Veterinary Authority to have complete knowledge of *Trichinella* spp. susceptible wildlife (OIE, 2021, Chapter 8.17, Article IV, point 2). While the frequency of *Trichinella* spp. in wildlife may have value in the risk to pigs where structural barriers are not entirely effective, complete knowledge of infection in wildlife requires extensive testing of large numbers of mammals as well as some avian species. It is questionable as to the ability of countries to implement such surveillance; proper implementation of controlled management production systems prevents potential exposure to wildlife. Proper management, including effective biosecurity, documented by a robust auditing program, assures absence of risk of exposure to *Trichinella* during pig production (Alban and Petersen, 2016).

5.5. Assuring public health for pigs from non-controlled housing systems

While controlled management/controlled housing is fully effective in eliminating exposure of pigs to *Trichinella* spp., when properly implemented and maintained, pigs that are raised outdoors for all or part of the time, may have risk of exposure. Risk of exposure to *Trichinella* spp. remains when the security of production systems breaks down, and also exists for pigs (e.g., organic production) that are raised in an open environment where access to rodents and wildlife is uncontrolled. The risk of *Trichinella* spp. infection for pigs raised in outdoor farming systems is clear in all parts of the world (Bilska-Zajac et al., 2021; Malakauskas et al., 2007; Noeckler et al., 2004; Pozio et al., 2021).

In contrast to systems following controlled management, the degree of risk to pigs raised outdoors depends in great part on the infection levels in local wildlife, and this degree of risk is of substantial importance for 'organic' or 'green' pig producers, who provide products to consumers seeking meat from animals raised under natural conditions. An example of different risk levels for outdoor pigs was demonstrated by Noeckler et al. (2004) who tested pigs raised outdoors in Germany and Croatia. While all pigs raised outdoors in Germany tested negative, all outdoor farms from Croatia had pigs that tested positive for *Trichinella* spp. This observation points out the importance of understanding infection pressure from the wildlife population, as well as other management factors that contribute to risk (e.g., poor hygienic conditions), when controlled management is not practiced.

Further research is needed on outdoor production systems to define best practices and to validate management systems that might provide greater assurances for absence of risk.

6. Discussion

For a variety of reasons, including a long history of testing and other mitigations, as well as major improvements in the security of pig production systems, *Trichinella* spp. have become a very rare infection in domestic (commercial) pigs in many countries and is no longer a significant concern to consumers of fresh pork (Devleesschauwer et al., 2015). Changes in pork production that reduce or eliminate risk of pigs acquiring *Trichinella* spp. have had the same, or a superior, influence on reducing the prevalence of *Trichinella* spp. as have long standing testing programs. Thus, countries where pigs are reared under controlled management systems have achieved the same level of public health protections as countries where testing has been or continues to be applied to every carcass.

When pigs are raised in modern production facilities under conditions of controlled management, and these conditions are adequately documented, there is no reason to perform individual carcass testing. The conditions of controlled management/controlled housing have been adequately documented in various guidelines and regulations (International Commission on Trichinellosis, the World Organisation for Animal Health, the Codex Alimentarius, the European Union, and the Food and Agricultural Organisation of the UN).

As determined by Franssen et al. (2018), the estimated annual risk of human trichinellosis does not differ for pigs from controlled housing if they were tested or not tested. The authors state, "this means no cases [of human trichinellosis] per year irrespective of *Trichinella* testing. Thus, controlled housing effectively prevents infection and *Trichinella* testing does not contribute to food safety for this housing type."

Where controlled management is applied following the principles described previously, pork should be considered safe for human consumption without additional mitigations or requirements both in domestic and export markets.

The focus of this review has been limited to control of *Trichinella* spp. in pigs. Since *Trichinella* spp. have a wide range of hosts including mammals (e.g., wild boar, bear, walrus, horses, etc.), birds and reptiles, this parasite will continue to be a threat to humans who ingest meat from these animals. While some testing programs are in place for meat other than pork, for the most part, consumer protection relies on education regarding risks and proper method of preparation. This is particularly true for individuals and communities who rely on hunted meat sources.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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