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Bovine cysticercosis and taeniosis: The effect of an alternative post-mortem detection method on prevalence and economic impact

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In Europe, bovine cysticercosis (BCC) is detected by routine meat inspection (MI) at the slaughterhouse. The prevalence of BCC in Belgium based on MI is estimated at 0.23%. MI has a known low sensitivity for animals with localised infections and alternative detection techniques should be considered.

A mathematical scenario-analysis model was built to determine the current prevalence of BCC in Belgium based on MI results combined with results of dissection of the predilection sites (PS) and the B158/B60 Ag-ELISA on serum of 614 carcasses found negative on MI. Additionally, the impact of the introduction of the B158/B60 Ag-ELISA at slaughter on the prevalence of BCC and taeniosis and on the economic impact related to *Taenia saginata* was estimated for Belgium. Data for estimating the economic impact were gathered from multiple sources within the meat and human health sectors and included value loss for infected carcasses, inspection costs, carcass destruction costs, cattle insurance costs and costs related to taeniosis (consultation physician, drugs and laboratory test).

The model estimated the current prevalence of BCC to be 42.5% (95% CI: 32.4–60.7%) and the sensitivity of the MI for viable and degenerated cysticerci at only 0.54% (95% CI: 0.37–0.71%). A total of 213,344 viable cysticerci (95% CI: 122,962–386.249) were estimated to be present in the infected carcasses in one year and only 408 (95% CI: 356–464) of these were present in the carcasses detected at current MI. The annual number of human taeniosis cases is estimated at 11,000 by using the sale numbers of niclosamide in Belgium. Implementation of the Ag-ELISA at slaughter (Se = 36.37%; Sp = 99.36%) would greatly reduce the prevalence of BCC to 0.6% and the number of taeniosis cases to 89 in year 10.

Unfortunately, the accompanying resulting increase in costs for the animal owners, slaughterhouses and the insurance company, would be extremely high in the first years. Cattle owners would suffer losses of up to €21 million in the first year after implementation of the Ag-ELISA (compared to an annual loss of €3.5 million in the current situation), slaughterhouses of €10 million (compared to €200,000 currently) and the insurance company of almost €6 million (compared to €2.3 million profit currently). Therefore, implementation of the Ag-ELISA might not be feasible and other options for controlling *T. saginata* should be investigated.

1. Introduction

Taenia saginata (beef tapeworm) is a zoonotic tapeworm causing an important economic impact for the meat sector worldwide (Wanzala et al., 2002; Scandrett et al., 2009; Jansen et al., 2018b). The adult stage can be found in the intestines of the human final host (taeniosis) after consumption of raw or undercooked beef infected with viable *T. saginata* larvae. Viable cysticerci consist of a transparent capsule with an invaginated scolex. Cysticerci undergo degeneration, followed by calcification when they die. Bovine cysticercosis (BCC) includes both animals with viable and/or degenerated/calcified cysticerci (Murrell et al., 2005).

In Europe, diagnosis of BCC is based on official meat inspection (MI) (EC regulation 854/2004). Incisions are made into the heart and the masseter muscles and the oesophagus, tongue, diaphragm and visible muscle surfaces are visually inspected during MI. Carcasses diagnosed with BCC, either with viable or degenerated cysts, need to be frozen or condemned, depending on the number of cysticerci detected. The estimated prevalence of BCC in Belgium, based on MI, is 0.23% (FASFC, 2012, 2013, 2014, 2015, 2016), yet official figures for prevalence tend

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to be underestimations, as MI is known to have a low sensitivity (Kyvsgaard et al., 1990; Dorny et al., 2000; Eichenberger et al., 2013; Jansen et al., 2017, 2018a). BCC leads to important economic losses, especially for cattle owners, due to the value loss in infected cattle found positive on BCC during MI and that are condemned or need to be frozen (Jansen et al., 2018b).

The current meat inspection technique is not sufficiently capable of detecting the highest priority meat-borne risks for humans today (*Salmonella*, verotoxigenic *Escherichia coli* (VTEC) and *Campylobacter*). For detection of BCC, a new, risk-based meat inspection system has been suggested in which animals or herds with the highest risk of harbouring cysticerci are targeted (Alban, 2016). The system proposed by the European Food Safety Authority (EFSA) in a scientific opinion (EFSA, 2013), aimed to combine several preventative and control measures at farms and abattoirs and focussed on the high priority hazards. As incisions into organs and lymph nodes may increase the risk of cross-contamination with high-priority bacteria, the new system reduces this manual handling to a minimum. A study in the UK, looking into the transfer to visual only inspection, found that the risk for human tapeworm infections would increase (Hill et al., 2014). A risk-based meat inspection system would focus on a categorisation of farms and cattle according to risk for BCC based on Food Chain Information (FCI; e.g., epidemiological intelligence data, farm risk status, or post-mortem findings from animals previously sent to the abattoir) and could include known risk factors for BCC, such as age, gender, production type and history of BCC cases on the farm. Sadly, the current FCI system in the EU is lacking adequate and standardised indicators and does not provide sufficient information for modern meat inspection (Blagojevic et al., 2017). A Codex Alimentarius document has been developed providing guidance for governments on the application of risk-based measures for the control of *T. saginata* in cattle (WHO, 2014). MI is currently being reviewed by the EU Commission, based on the scientific opinion of EFSA (EFSA, 2013) and several studies showing a low risk in young cattle that are raised indoors (Calvo-Artavia et al., 2013; Dupuy et al., 2014; Marshall et al., 2016). The EU Commission is currently negotiating a regulation in which cattle raised indoors and slaughtered before the age of 20 months, are exempt of incisions into the masseter muscles (personal communication European Livestock and Meat Trades Union (UECBV)).

Alternative techniques to detect BCC should be considered and currently, these techniques include meat inspection with application of additional incisions in the heart muscle and several serological techniques (Juranek et al., 1976; Kyvsgaard et al., 1990; Lopes et al., 2011). A recent study on Swiss cattle showed a doubling of infected carcasses detected by making six additional incisions in the heart (Eichenberger et al., 2011).

Serological techniques have been developed to detect specific antibodies (Ab) or antigens (Ag) related to the presence of BCC. Ab-detecting techniques detect both viable and degenerated/calcified cysticerci (or past infections). Several Ab-detecting tests with varying performance have been developed, depending on the type of coating antigen used (Ogunremi and Benjamin, 2010). Ag-detecting techniques specifically demonstrate the presence of viable cysticerci (Wanzala et al., 2002). Ag-detecting tests could thus demonstrate that carcasses are free of viable cysticerci (containing none or only degenerated cysticerci) and could approve these carcasses for human consumption without being a food safety issue and restrict the value losses for the meat sector.

In a previous study on Belgian cattle, we looked into the ability of the B158/B60 monoclonal antibody-based Ag-ELISA to detect infections. This test proved to be the best alternative detection technique for use at slaughter, compared to enhanced meat inspection and excretory/secretory (ES) antibody ELISA (Jansen et al., 2017). The current study evaluates and compares the effect of the MI and the B158/B60 Ag-ELISA as post-mortem detection techniques for BCC in Belgian slaughterhouses, on the prevalence of BCC and taeniosis and the cost-effectiveness of both techniques, by using a scenario-analyses model.

2. Materials and methods

2.1. Sampling design

Sampling and laboratory testing of adult cattle at slaughter have been described in detail in Jansen et al. (2017). In brief, sampling was conducted weekly in three consecutive Belgian slaughterhouses during three consecutive 10-month periods between 2012 and 2015. Samples consisted of a collection of the predilection sites (heart, tongue, masseter muscles, oesophagus and diaphragm) and a blood sample. The SANITEL ear tag number (Belgian system for computerised management of the identification, registration and control of livestock) and MI result was noted. All MI-positive carcasses ($N = 101$) and a random selection of MI-negative carcasses were sampled ($N = 614$). Predilection sites were completely dissected making 0.5 cm thick slices (dissection PS) and the number and stage of all cysticerci was recorded. The B158/B60 Ag-ELISA was performed as described by Dorny et al. (2002).

Additionally, to determine the specificity of the Ag-ELISA, serum samples of 154 first-grazing season calves were collected from 11 commercial cattle farms. These animals had been grazing on pastures for one grazing season and had been exposed to common parasite species that may cause cross-reactions (Jansen et al., 2017).

2.2. Model

A model was written in the R programming language (R Core Team, 2014), combined with C++ for comparing the impact of post-mortem detection techniques at the slaughterhouses on (1) the prevalence of bovine cysticercosis and taeniosis and (2) the economic impact of the parasite in Belgium.

2.2.1. Modelling prevalence of BCC and taeniosis

2.2.1.1. Current situation. The model used the prevalence based on MI together with data collected during this study (Jansen et al., 2017) to estimate the current true prevalence of BCC in Belgium when the tests (MI, dissection of the PS and Ag-ELISA) are performed in parallel. Additionally, the model estimates the number of viable cysticerci present in the infected carcasses. The model is explained in Fig. 1 and Table 1.

The negative binomial distributions (NB_1 and NB_2) in the model are fitted as follows. For the carcasses positive on MI and those positive on the dissection of the PS, the number of cysticerci found in the predilection sites is known. By combining results from several experimental infections (Kyvsgaard et al., 1990; Soares et al., 2011, as well as personal communication; experimental infections P. Dorny/S. Gabriël, unpublished results), we estimated that on average 23.9% of all cysticerci in a carcass locate in the predilection sites. The number of cysticerci in the predilection sites of each carcass was divided by 0.239 to adjust for the rest of the carcass. A negative binomial distribution was fitted over all numbers of cysticerci for both MI-positive (NB_1) and PS positive (NB_2) carcasses. The negative binomial distribution for truly positive carcasses after performing Ag-ELISA was fitted using NB_2 together with β_3, but not allowing zero viable cysticerci in an ELISA-positive carcass.

The model further estimated the sensitivity of the MI for the detection of positive carcasses by dividing the simulated number of MI-positive carcasses by the total number of positive carcasses, and for viable cysticerci by dividing the simulated number of viable cysticerci in the MI-positive carcasses by the total number of viable cysticerci.

The model was run 100,000 times to estimate the total number of carcasses with BCC and the number of viable cysticerci present in these carcasses.

2.2.1.2. Comparison of detection techniques. The current number of taeniosis cases was estimated by the sale numbers of niclosamide (Yomesan®) (10,991 patients/year), since this is the prescribed drug for taeniosis in Belgium (Jansen et al., 2018b). The 'transfer-to-human'

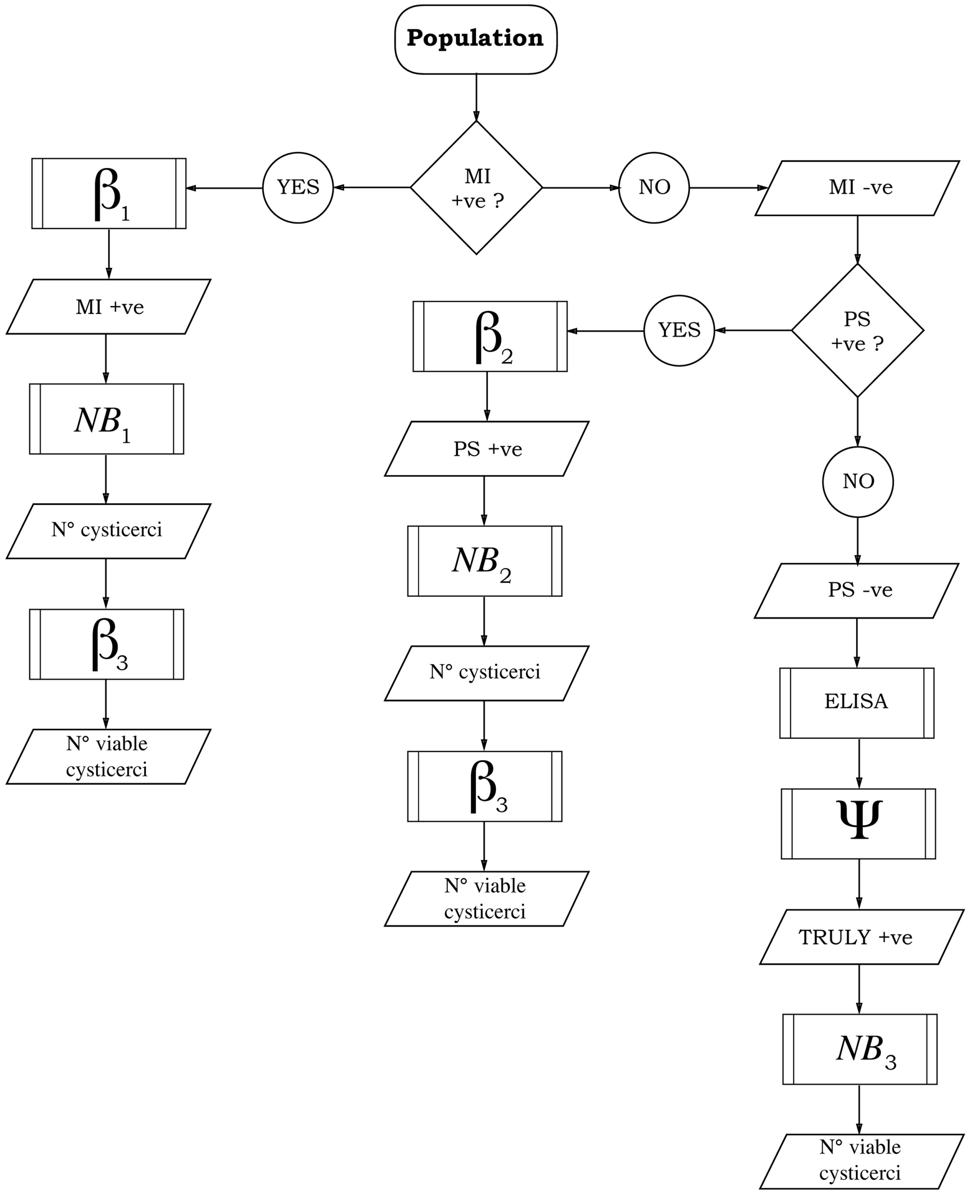

Fig. 1. Diagram explaining the model: parallel performance of three detection techniques of BCC to determine the true prevalence of BCC in Belgium. Population, number of slaughtered cattle per year; MI, meat inspection; PS, dissection of the predilection sites; ELISA, antigen ELISA; + ve, positive on test; − ve, negative on test; TRULY + ve, carcasses found positive on ELISA, corrected for sensitivity and specificity; β, beta distribution; *NB*, negative binomial distribution.

probability (η_τ) was estimated by the model by dividing the number of taeniosis cases by the number of viable cysticerci entering the food chain (the number of cysticerci passing inspection undetected estimated by the model). This factor thus covers all handling of the meat prior to consumption (e.g. freezing or cooking) from the moment the beef leaves the slaughterhouses onwards. We assume that consumption of one viable cyst will lead to one tapeworm. Throughout the model, this probability is assumed to remain stable. It is also assumed that carcasses with generalised infection will be detected with or without a specific inspection technique, as the lesions are clearly visible.

Four scenarios of detection techniques at slaughter are compared in this study: (1) MI, (2) Ag-ELISA, (3) a combination of MI on all carcasses, followed by Ag-ELISA on carcasses negative on MI and (4) no inspection for BCC. An additional beta-distribution was included in the model to simulate the number of Ag-ELISA positive carcasses (56) amongst the randomly selected MI-negative carcasses (614) for scenario two and three. It was opted to only use the MI-negative carcasses since these were selected at random and on the contrary, all MI-positive carcasses were sampled. The error due to this decision is minimal as prevalence based on MI is very small.

Starting from the previous estimates made in the model, the number of rejected carcasses, the number of undetected viable cysticerci that pass the inspection and the number of human infections were estimated for each scenario (Table 2).

2.2.1.3. Long-term effect. The long-term effect of the different scenarios was estimated for a period of 10 years, assuming a linear relationship between the number of bovine cysticercosis and taeniosis cases and a constant 'transfer-to-human' probability (η_τ). Calculations are explained in Table 3.

The number of infected carcasses in year i was calculated using the number of undetected viable cysticerci in the previous year ($i - 1$) since cysticerci need to infect humans and the adult tapeworm needs to produce eggs, before these cysticerci can lead to new infected cattle. We therefore assume that infected cattle from year i arise from viable cysticerci from year $i - 1$.

Table 1
Table explaining the model: parallel performance of three detection techniques of BCC to determine the true prevalence of BCC in Belgium.

Parameter	Value	Explanation
Population	511,528	Average annual number of animals slaughtered[a]
β_1	B(1169, 510,361)	Beta distribution for 1168 MI-positive carcasses[a, b]
β_2	B(145, 471)	Beta distribution for 144 PS-positive[b] in 614 MI-negative tested
Ψ	$PS^{-}\left[\frac{\frac{\mathrm{Bin}[PS^{-}, p(ELISA^{+})]}{PS^{-}} + \mathrm{Sp} - 1}{\mathrm{Se} + \mathrm{Sp} - 1}\right]$	Truly positive carcasses in 470 MI-PS-negative carcasses
PS^{-}		Number of MI-negative PS-negative carcasses *i.e.* Population $\times (1 - \beta_1) \times (1 - \beta_2)$
$ELISA^{+}$	B(41, 431)	Beta distribution for 40 ELISA-positive[b] in 470 PS-negative tested
Se ELISA	B(8, 14)	Beta distribution for 7 ELISA-positive in 20 carcasses with viable cysticerci
Sp ELISA	B(155, 1)	Beta distribution for 154 ELISA-negative in 154 first-grazing-season animals tested
NB_1	NB(2.25, 7.89)	Negative binomial distribution for number of cysticerci in a MI-positive carcass[c]
NB_2	NB(3.48, 6.49)	Negative binomial distribution for number of cysticerci in a MI-negative PS-positive carcass[d]
β_3	B(21, 393)	Beta distribution for 20 viable cysticerci in 412 detected cysticerci
NB_3	NB(14.06, 2.87)	Negative binomial distribution for number of viable cysticerci in an ELISA-positive carcass[e]

[a] Source: Federal Agency for the Safety of the Food Chain.
[b] MI, meat inspection; PS, dissection of the predilection sites; Ag-ELISA, antigen ELISA.
[c] Computed from own observations, using both MI-positive carcasses and cysticerci burdens found during predilection site dissections, and assuming 23.9% of the cysticerci being found in the predilection sites (see main text for references).
[d] Computed from own observations, using PS-positive carcass data, and assuming 23.9% of the cysticerci being found in the predilection sites (see main text for references).
[e] Computed using NB_2 and β_3.

2.2.2. Modelling the economic impact of T. saginata

The yearly economic impact of *T. saginata* in Belgium has been estimated and the procedure was explained in detail in Jansen et al. (2018b). The current model performs the same calculations to determine the economic impact for all four scenarios: (1) MI, (2) Ag-ELISA, (3) a combination of MI on all carcasses, followed by Ag-ELISA on carcasses negative on MI and (4) no inspection for BCC. These calculations are based on the estimates for number of infected carcasses and viable cysticerci made in the first part of the model. In brief, for the animal sector, the model calculates (1) the average yearly value loss for carcasses with generalised (total value lost) and localised infections (40–70 percent value loss) based on real beef prices, (2) the cost for inspection, thus the cost for (a) the presence of an inspector during meat inspection (and/or the price of the Ag-ELISA), (b) for processing the infected carcasses and preparing them for shipment, and (c) for deboning of the localised infected carcasses, (3) the costs related to the destruction of the carcasses with generalised infections and (4) the costs related to the insurance fee that animal owners can purchase for BCC.

In Belgium, there is one official insurance company present for BCC. An estimated 30% (personal communication owner of insurance company) of slaughtered cattle are insured by this company prior to slaughter. Several slaughterhouses offer an unofficial insurance for BCC and approximately 5% of all slaughtered cattle are insured in the unofficial way.

The inspection cost is a fee, rated at 75€/hour, that slaughterhouses need to pay to the Federal Agency for the Safety of the Food Chain (EFSCA), for the presence of a meat inspector during inspection. For the scenarios including the Ag-ELISA, the inspection cost is calculated as follows. The cost of the Ag-ELISA was set at €1 per sample, based on the cost of the commercial version of the B158/B60 Ag-ELISA from ApDIA®, which is registered for use on human and pig serum samples, but not on bovine samples. For the scenario where only Ag-ELISA is used as detection technique (scenario 2), €1 is counted for every slaughtered animal, and added to the normal meat inspection cost which serves as

Table 2
Calculations made in the four scenarios for the number of rejected carcasses, the number of undetected viable cysticerci and the number of human infections.

Scenario	To be estimated	Method
1. MI	No. rejected carcasses	MI positive carcasses[a]
	No. undetected viable cysticerci	Total no. viable cysticerci – No. viable cysticerci in MI positive carcasses[a]
	No. taeniosis cases	No. undetected viable cysticerci × η_τ[b]
2. Ag-ELISA	No. rejected carcasses	binom(population, B(57, 559)) binomial distribution on total population using beta distribution for 56 ELISA positive in 614 MI negatives
	No. undetected viable cysticerci	Total no. viable cysticerci – viable cysticerci in ELISA positive carcasses (using NB_3)[c]
	No. taeniosis cases	No. undetected viable cysticerci × η_τ[b]
3. MI + Ag-ELISA	No. rejected carcasses	MI positive + binom(MI-negatives, B(57, 559)) binomial distribution on MI-negatives using beta distribution for 56 ELISA positive in 614 MI negatives
	No. undetected viable cysticerci	Total no. viable cysticerci – viable cysticerci in MI positive carcasses − viable cysticerci in ELISA positive carcasses (using NB_3)[c]
	No. taeniosis cases	No. undetected viable cysticerci × η_τ[b]
4. No. inspection for BCC	No. rejected carcasses	0 (no inspection, so no rejected carcasses)
	No. undetected viable cysticerci	Total no. viable cysticerci[a]
	No. taeniosis cases	No. undetected viable cysticerci × η_τ[b]

[a] Estimated in previous part of model.
[b] η_τ = probability of a person to become infected.
[c] See Table 1.

Table 3
Calculations made for the long-term effect in the four scenarios.

To be estimated	Method
No. undetected viable cysticerci in year i	Total no. of viable cysticerci in year $i-1$[a] × SR_{year1}[b]
No. human infections in year i	No. undetected viable cysticerci in year i × η_τ[c]
No. infected carcasses in year i	Total No. of undetected viable cysticerci in year $i-1$[a] × SI_{year1}[d]
No. rejected carcasses in year i	No. infected carcasses in year i × CF_{year1}[e]
No. undetected infected carcasses in year i	No. infected carcasses in year i − N. rejected carcasses in year i

[a] Estimated in previous part of model.
[b] $SR_{year1} = \frac{\text{No. undetected viable cysticerci in Scenario in question}}{\text{No. undetected viable cysticerci in Scenario 1}}$; standard reduction.
[c] η_τ = probability of a person to become infected.
[d] $SI_{year1} = \frac{\text{No. infected carcasses in Scenario 1}}{\text{No. viable cysticerci in Scenario 1}}$; standard infection.

an estimate for the collection of a blood sample in the slaughterhouses. For the scenario combining MI and Ag-ELISA, the total MI inspection cost is counted for all animals since all animals will undergo standard MI. The MI-negative carcasses will undergo an ELISA and for these animals the same calculations were done as for the scenario with only Ag-ELISA as detection technique and this is added to the MI inspection cost. Estimates for the cost of the laboratory technicians performing the ELISA's and the transport to the laboratories are not included in the model. The estimates will thus be underestimations. Carcasses that are found positive on Ag-ELISA will be frozen and not condemned, since carcasses with generalised infections will be detected at slaughter without a specific MI procedure. For the 'no inspection for BCC' scenario, there are no costs for inspection.

The model subdivides all calculated costs over the different parties involved: the animal owners, the slaughterhouses and the insurance company. The animal owners bare the costs related to the insurance and the value losses and destruction costs of uninsured animals. The slaughterhouses have an income generated by the unofficial insurance and costs due to the inspection fee and value losses and destruction costs of the unofficially insured animals. The insurance company generates an income through the official insurance fee, and is responsible for the value losses and destruction costs of the officially insured animals.

For the costs related to human health, the model assumed a worst-case scenario in which all patients consulted a physician, had a follow-up appointment to ensure successful treatment, and all physicians filed for a diagnostic test. The costs considered in the model are (1) the costs for the consultations (for patient and for health care sector), (2) the costs for drugs and (3) the costs for diagnostic tests.

3. Results

3.1. Modelling prevalence of BCC and taeniosis

3.1.1. Current situation

The model estimated the current prevalence of BCC in Belgium based on the parallel performance of the MI, the dissection of the PS and the Ag-ELISA (Table 4) at 42.5% (95% CI: 32.4–60.7%).

Table 5 shows the estimated test characteristics for MI and Ag-ELISA.

3.1.2. Comparison of detection techniques

The results for the number of rejected carcasses, the number of undetected viable cysticerci that pass the inspection and the number of human infections per year for the different detection technique scenarios ((1) MI, (2) Ag-ELISA, (3) a combination of MI and Ag-ELISA and (4) no inspection for BCC) are shown in Table 6. The annual 'transfer-to-human' probability (η_τ; the number of taeniosis cases divided by the number of viable cysticerci entering the food chain per year) was estimated at 0.05, meaning that one in 20 viable cysticerci that pass the inspection undetected will infect a human host and develop into a tapeworm.

Table 4
Estimated numbers of BCC positive carcasses and the total number of viable cysticerci they contain.

Detection technique	No. positive carcasses per year	No. viable cysticerci per year
MI (95% CI)	1,169 (1076–1265)	408 (356–464)
Dissection PS (95% CI)	120,111 (103,449–137,596)	33,424 (28,781–38,301)
Ag-ELISA (95% CI)	96,100 (47,518–189,064)	179,511 (88,708–353,148)
Total (95% CI)	**217,380 (165,938–310,708)**	**213,344 (122,962–386,249)**

Estimations based on the parallel performance of the meat inspection (MI), the dissection of the predilection sites (PS) and the Ag-ELISA (including 95% confidence intervals) on the total no. of animals slaughtered per year. Total = MI + Dissection PS + Ag-ELISA.

Table 5
Estimated test characteristics of MI and Ag-ELISA.

Test characteristic	Estimate (95% CI)
Se MI infected carcasses	0.54 (0.37–0.71)
Se MI viable cysticerci	0.21 (0.10–0.34)
Se Ag-ELISA	36.37 (18.14–57.02)
Sp Ag-ELISA	99.36 (97.65–99.98)

Sensitivity (Se) of meat inspection (MI) for all infected carcasses and for viable cysticerci, sensitivity (for current infection) and specificity (Sp) of Ag-ELISA.

Scenario 2 with the Ag-ELISA as detection technique at slaughter would lead to a 41.32% decrease in the number of viable cysticerci that can pass the inspection undetected each year, scenario 3 with both MI and Ag-ELISA to 41.43% decrease and scenario 4 using no inspection for BCC to a 0.19% increase.

3.1.3. Long-term effect

The annual number of infected carcasses, undetected infected carcasses, viable cysticerci in these undetected carcasses and taeniosis cases after prolonged use (10 years) of different detection techniques for BCC at slaughter are depicted in Table 7. Prevalence of BCC after using the Ag-ELISA as detection technique (scenario 2) for 10 years was estimated to be 0.6%.

3.2. Modelling the economic impact of *T. saginata*

Table 8 summarises the annual costs for cattle owners, the annual costs and income for the slaughterhouses and the insurance company and the annual costs related to taeniosis for the different scenarios after 1 year and after 10 years of using the Ag-ELISA as a detection technique.

Cattle owners have the highest cost due to the insurance fee for BCC. They further suffer losses when uninsured animals are found positive for BCC and need to be frozen or destroyed. The slaughterhouses suffer the same losses for the animals that are insured via the unofficial way, but have an income from the insurance fee. They are also responsible for the inspection costs. The insurance company gains the biggest proportion of the insurance fee and suffers losses amongst the insured animals.

Table 6
The number of rejected carcasses, undetected viable cysticerci that pass the inspection and human infections (including confidence interval) for the scenarios MI, Ag-ELISA, a combination of MI and Ag-ELISA and no inspection for BCC.

	MI	Ag-ELISA	MI + Ag-ELISA	No. inspection BCC
No. rejected carcasses (95% CI)	1169 (1076–1265)	47,320 (36,295–59,626)	48,402 (37,350–60,753)	0 –
No. undetected viable cysticerci (95% CI)	212,935 (122,543–385,808)	124,951 (30,374–299,952)	124,707 (29,840–299,221)	213,344 (122,962–386,249)
No. human infections (95% CI)	10,988 (6323–19,908)	6448 (1567–15,478)	6435 (1540–15,440)	11,009 (6435–19,934)

Table 7
The annual number of infected carcasses, undetected infected carcasses, viable cysticerci in these undetected carcasses and taeniosis cases after 10 years of using the adjusted detection techniques at slaughter.

	MI	Ag-ELISA	MI + Ag-ELISA	No. inspection BCC
No. infected carcasses	217,380	3056	3009	220,739
No. undetected infected carcasses	216,211	2391	2339	220,739
No. undetected viable cysticerci	212,935	1757	1726	216,640
No. human infections	10,987	91	89	11,179

4. Discussion

The study compares the estimated prevalence of bovine cysticercosis and taeniosis and the economic impact caused by this parasite in Belgium under four different scenarios using different post-mortem detection techniques at slaughter: (1) routine meat inspection, (2) B158/B60 Ag-ELISA, (3) MI combined with Ag-ELISA and (4) no inspection for BCC.

The model estimates the prevalence of BCC in Belgium to be 42.5% (95% CI: 32.4–60.7%) (containing viable, degenerated and calcified cysticerci), based on a parallel performance of routine MI, dissection of the predilection sites and the Ag-ELISA and taking into account the estimated sensitivity and specificity of the Ag-ELISA. The carcasses with BCC contain on average 213,344 viable cysticerci in total, each capable of infecting a person if the beef containing the cysticerci is eaten raw or not well cooked. In the current situation, only 1169 infected carcasses get detected at MI, containing only an estimated 408 viable cysticerci. Sensitivity of the MI is therefore even lower than previously expected: 0.54% for all infected carcasses and 0.21% for viable cysticerci compared to 'less than 15%' (Kyvsgaard et al., 1990; Dorny et al., 2000; Eichenberger et al., 2013; Jansen et al., 2017). A similar result for prevalence (36%) had already been estimated from these data in a previous study (Jansen et al., 2017), without the use of a model. A recent study estimated the prevalence for Swiss cattle to be 15.6%, also much higher than the estimate based on routine MI (Eichenberger et al., 2013).

If the Ag-ELISA were to be implemented as a detection technique of BCC at slaughter (scenario 2), 41.32% less viable cysticerci would pass the inspection and consequently, less people would get infected. In turn, less infected people produce less eggs and this would lead to a decrease in the prevalence of BCC. On the long term, the model estimates prevalence of BCC to be only 0.6% after 10 years and, assuming a linear relationship between the prevalence of BCC and of taeniosis, the number of human infections drops to 91. A combination of MI and Ag-ELISA (scenario 3) does not improve these results enough to counter the additional costs (due to costs related to inspection). If carcasses are not inspected for BCC at slaughter (scenario 4), a slow increase in prevalence of both BCC and taeniosis would occur, but the difference with MI is not substantial. The long term predictions are made assuming that

Table 8
The annual costs related to the animal sector for the parties involved and for the health care sector for the different scenarios investigated. Estimates are based on the assumption that prices will remain stable over 10 years and that animal owners will keep insuring their cattle against BCC, even with a lower risk.

	MI	ELISA		MI + ELISA		No. inspection BCC	
		1 year	10 years	1 year	10 years	1 year	10 years
Cattle owners							
Value loss	−453,424	−18,022,874	−261,617	−18,434,787	−263,400	−8368	−8368
Destruction	−1370	−1370	−1370	−1370	−1370	−1370	−1370
Insurance	−2,954,061	−2,954,061	−2,954,061	−2,954,061	−2,954,061	−2,954,061	−2,954,061
Total	*−3,408,854*	*−20,978,304*	*−3,217,047*	*−21,390,217*	*−3,218,831*	*−2,963,799*	*−2,963,799*
Slaughterhouses							
Value loss	−34,879	−1,386,375	−20,124	−1,418,061	−20,262	−644	−644
Destruction	−105	−105	−105	−105	−105	−105	−105
Insurance	422,004	422,004	422,004	422,004	422,004	422,004	422,004
Inspection	−598,033	−8,897,460	−1,024,540	−9,477,596	−1,422,880	−1,125	−1,125
Total	*−211,013*	*−9,861,937*	*−622,766*	*−10,473,758*	*−1,021,243*	*420,130*	*420,130*
Insurance company							
Value loss	−209,272	−8,318,249	−120,746	−8,508,363	−121,569	−3862	−3862
Destruction	−632	−632	−632	−632	−632	−632	−632
Insurance	2,532,057	2,532,057	2,532,057	2,532,057	2,532,057	2,532,057	2,532,057
Total	*2,322,152*	*−5,786,825*	*2,410,679*	*−5,976,938*	*2,409,855*	*2,527,563*	*2,527,563*
Health care							
Consultation physician	−87,900	−51,580	−725	−51,479	−713	−88,068	−89,429
Drugs	−69,111	−40,554	−570	−40,476	−560	−69,244	−70,313
Health care system	−461,473	−270,793	−3,807	−270,266	−3,741	−462,358	−469,501
Diagnostic tests	−177,118	−103,933	−1461	−103,731	−1436	−177,458	−180,199
Total	*−795,602*	*−466,860*	*−6,563*	*−465,951*	*−6449*	*−797,128*	*−809,442*

there is a linear relationship between the number of taeniosis and BCC cases and so the 'transfer-to-human' probability remains the same. In reality, this factor can vary with changing transmission dynamics.

The biggest hurdle for implementing the Ag-ELISA in slaughterhouses is the initial increase in the costs for the meat sector. All parties would suffer major losses in the first years of using Ag-ELISA as a detection technique (scenario 2 and 3). Losses for the cattle owners would increase to €21 million in the first year, mostly due to many additional animals that are not insured being found positive at inspection and that suffer a value loss between 40 and 70 percent. The same is true for the slaughterhouses, that will suffer more value losses amongst the unofficially insured cattle. On top of that, the inspection costs will increase with €8 million because all infected carcasses detected by Ag-ELISA need to be processed and deboned before freezing. As the need to control BCC originates from the losses this parasite causes to animal owners, implementation of the Ag-ELISA might not be feasible.

However, the estimations for the economic impact on the long term are first of all based on the estimations made by the model for prevalence levels on the long term. As stated before, it is possible that the 'transfer-to-human' probability is not a stable variable when transmission dynamics change. Furthermore, the estimations are based on the assumption that prices will remain stable within the sector but this is most likely not realistic. The insurance company will suffer a significant loss after 1 year of using the Ag-ELISA as a detection method (-€5,786,825), due to the many additional carcasses that will be condemned and need to be frozen before consumption. The insurance company will need to raise the average fee for the insurance, which is currently €16.5. To compensate the losses suffered (without making any profit), the insurance fee needs to increase to €37.7 per carcass in scenario 2 and to €38.9 in scenario 3. This would lead to a total annual cost for the cattle owners of €24,775,526 and €25,409,238, respectively. For the insurance company to make any profit, the fee needs to raise even more. On the other hand, when after several years fewer carcasses with BCC are detected in the slaughterhouses and the risk is greatly reduced, an insurance might become unnecessary and this cost could be omitted. In this case, the economic situation for animal owners will have improved compared to the current situation.

The commercial Ag-ELISA kit (ApDIA®) suggested, is only registered for the use on human and porcine serum samples and not yet for bovine serum samples. Using this test currently costs €1 per sample, but this price might decrease when the test is produced in bigger numbers. The model currently assumes that collection of a blood sample takes the same amount of time as current meat inspection and is also done by a licensed inspector. The model does not take into account the cost for the transport of the blood sample taken in the slaughter house, to the laboratory and the laboratory technician performing the ELISA. On the other hand, blood samples could be used for other purposes simultaneously (e.g. diagnosis of other diseases, hormones or antibiotics), reducing the cost directly related to BCC. A switch to ante-mortem detection using the Ag-ELISA is another possibility. Overall, several factors remain unknown concerning 10-year predictions for the costs related to BCC. Since we are unable to predict the behaviour and reactions of animal owners and the insurance company on the increased number of BCC positive carcasses, the estimates in Table 8 are simplified estimates based on current conditions.

The economic impact in scenario 4 where there is no inspection for BCC at slaughter, is lower compared to the impact in the first scenario, routine MI. Animal owners remain the ones suffering the biggest losses, while slaughterhouses would start making profit, due to the lack of an inspection cost and less carcasses suffering value losses. Again, these estimates are based on the costs involved in the current situation, but when there is no inspection for BCC, it might not be necessary to purchase an insurance for cattle, and this cost could be eliminated. Carcasses with generalised infections would still be detected, even without control, so value losses for these animals still exist. On top of that, the insurance also covers sarcosporidiosis (85 cases/year, personal communication FASFC). It is impossible to determine what part of the insurance fee is allocated to BCC and what part to sarcosporidiosis. Therefore, an insurance might remain advisable.

The economic impact on the human health sector decreases yearly in scenarios with the Ag-ELISA as detection technique, since the number of taeniosis cases will decrease immediately after implementation of a new detection technique. After only 1 year, costs are reduced to €466,860 compared to €795,602 in the current situation. After 10 years, total costs would be only €6563. But these numbers remain insignificant compared to the economic costs due to BCC in the meat sector.

It was chosen to consider the Ag-ELISA as an alternative technique, based on the results presented in Jansen et al. (2017) and because this test only detects actual infections with viable cysticerci. In Jansen et al. (2017), a comparison was made between the MI, enhanced MI with additional incisions in the heart, Ag-ELISA and an antibody detection against excretory/secretory (Ab-ELISA). The Ag-ELISA had the best performance of the four tests. When applying only the Ag-ELISA, an estimated 9% of carcasses would be diagnosed infected. Viable cysticerci still pass inspection due to a sensitivity of 36.37% of the Ag-ELISA, but unlike for MI, in which many carcasses that only contain degenerated or calcified cysticerci are found positive, there will not be (many) false positives and no or very few carcasses containing only non-viable cysticerci will be condemned due to BCC. This is a great advantage that will prevent unnecessary losses in value for the meat industry in the future. Condemnation of these carcasses might still occur due to other reasons such as the detection of a general infection of BCC, different lesions or organoleptic reasons. Implementing the Ag-ELISA as a detection technique would at first lead to a higher economic impact, but eventually these costs would diminish to a similar value compared to the current situation.

Furthermore, in this model, Belgium is seen as a closed country with no import and export from and to other countries. In reality, there is an important flow of people, cattle and meat coming from and going to other countries. Annually, on average (over the last ten years), 67,522 individual (adult) animals have been exported to and 23,311 imported from foreign countries and on average 130,177 ton of beef and veal was exported to and 53,103 ton was imported from foreign countries (production in Belgium: 250,000–300,000 ton/year) (Anon, 2018). Travelling and commuting people can also result in taeniosis cases acquired abroad but treated in Belgium. This will have an impact on the scenario (e.g. if Belgian beef prices increase, export will be affected and Belgian consumers will want to buy cheaper, foreign beef). Therefore, the scenarios with implementation of the Ag-ELISA are theoretical with Belgium as a closed system.

Although the use of the Ag-ELISA as a detection technique at slaughter would lead to a substantial decrease in the prevalence of BCC and taeniosis on the long term, implementation of this technique might be unwanted by several parties involved due to the high initial annual costs. Other options for controlling *T. saginata* should be investigated.

The new, risk-based inspection method that is being reviewed by the EU Commission is promising in certain situations and countries as farm management conditions differ between regions and countries, but might not be helpful for the Belgian BCC problem. Most Belgian cattle (except calves for white veal production) are allowed to graze during some time, so focussing on cattle that are generally considered to be at higher risk for exposure to *Taenia* eggs (older age, female), is not suitable. Many BCC cases will not be detected.

Human tapeworm carriers are essential for maintaining transmission and infection from man to cattle needs to be reduced. Preventing the distribution of tapeworm eggs in the environment is of paramount importance. Waste water management systems are not capable of eliminating taeniid eggs from waste water before being discharged into the surface water and cattle can get infected by access to risky surface water or after flooding during which eggs remain on pastures. Studies intended to improve waste water management are necessary, and would also prove beneficial for reducing transmission of other parasites. Improved knowledge on factors influencing survival of *Taenia* eggs in the environment and the maximum survival time can also lead to new methods to prevent infection in cattle. The medical sector and the general population bare an important responsibility in the control of *T. saginata*. The general public should be made aware of the risk they pose towards cattle, after developing a tapeworm. Information campaigns for physicians on how to treat patients and for patients on how to dispose of the expelled tapeworm are needed to reduce the infection risk for cattle.

Conflict of interest statement

None of the authors has a financial or personal relationship with other people or organisations that could inappropriately influence or bias this paper.

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