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ORIGINAL ARTICLE

Quantitative risk assessment of human salmonellosis in the smallholder pig value chains in urban of Vietnam

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Abstract

Objectives To quantify salmonellosis risk in humans through consumption of boiled pork in urban Hung Yen Province, Vietnam, using a quantitative microbial risk assessment.

Methods We collected 302 samples along the pork value chain in Hung Yen between April 2014 and February 2015. We developed a model in @Risk, based on microbiological, market, and household surveys on cooking, cross-contamination and consumption, and conducted sensitivity analysis.

Results Salmonella prevalence of pen floor swabs, slaughterhouse carcasses and cut pork were 33.3, 41.7 and 44.4%, respectively. The annual incidence rate of salmonellosis in humans was estimated to be 17.7% (90% CI 0.89–45.96). Parameters with the greatest influence risk were household pork handling practice followed by prevalence in pork sold in the central market. Wide confidence interval in the incidence estimate was mainly due to the variability in the degree of reduction in bacteria concentration by cooking, and pork consumption pattern.

Conclusions The risk of salmonellosis in humans due to boiled pork consumption appears to be high. Control measures may include improving the safety of retailed pork and improving household hygiene.

Keywords *Salmonella* · Pig value chains · Boiled pork · Quantitative microbial risk assessment · Vietnam

Introduction

Food safety is a major public health anxiety worldwide, particularly in developing countries where demand for safe and nutritious food supplies is increasing rapidly (Grace and McDermott 2015). In Vietnam, food safety and especially pork safety are of major matter to both consumers and policy makers; it is frequently reported in the media and is the subject of high-level policy discussions (Hung 2015; WB-Vietnam 2016). Pork safety is important because Vietnam's per capita pork consumption of 29.1 kg/year is among the highest in the world, and pork is the most popular consumed meat in Vietnam accounts for the 56% of total meat intake (OECD 2016). In Vietnam, up to 80% of pork is produced by smallholder farmers, and most pork is sold in wet markets (Lapar and Tiongco 2011).

Nontyphoidal *Salmonella* spp. are one of the most important causes of foodborne disease (Havelaar et al. 2015). Previous studies in Vietnam have found prevalences of *Salmonella* in cut pork at market ranging from 37 up to 69% (Phan et al. 2005; Van et al. 2007; Hien 2009; Thai

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et al. 2012). However, the extent to which this hazard translates into human health risk depends on consumer behaviors especially those relating to cooking and consumption. Quantitative microbial risk assessment (QMRA) consists of hazard identification, hazard characterization, exposure assessment and risk characterization [CAC/GL 30 (1999)] and provides an estimation of the probability and severity of illness in a given population from eating contaminated food. As such it supports information that is more useful to policy makers and risk managers than results of prevalence surveys (Grace et al. 2010).

Risk assessments have been used very successfully in developed countries to help address issues of food safety. In recent years, this approach has also been used to assess microbial pathogens in informal markets (Makita et al. 2012). Nonetheless, this has not been widely applied to food safety in Vietnam, although a small number of studies have assessed health risk related to *Salmonella* and dioxin contaminated foods (Toan et al. 2013; Tuyet-Hanh et al. 2015). The aim of this paper is to present a QMRA model for the smallholder pork value chains in Vietnam and an estimate of salmonellosis risk in humans. Development and implementation of this model will help scientists and policy makers involved in food safety by providing insight into the risks present in the value chain and help identify potential areas for successful mitigation of the risk.

Methods

Study sites

This study was carried out in three out of ten districts, Tien Lu, Khoai Chau and Van Giang, in Hung Yen Province. Hung Yen is located in the Red River delta and is a neighbor province to Hanoi, the capital city of Vietnam. In 2014, the population of Hung Yen was 1.2 million. The province has a hot and cold season with average temperatures of 29.0 °C in the summer (May–October) and 20.1 °C in the winter (November–April) (GSO 2014). The three selected districts represent three different pork production–consumption pathways: from peri-urban to urban (Tien Lu), rural to rural (Khoai Chau) and rural to urban (Van Giang). In each districts, we randomly selected three communes for sampling.

Study design

We applied a cross-sectional design for sample collection along the smallholder pork value chain between April 2014 and February 2015. In this study, household-based pig producers were scales of small (keeping 10 or fewer fattening pigs), medium (from 11 to 50 pigs) and large (more than 50 fattening pigs). For slaughterhouses, they were categorized as small and medium scales if they slaughtered 1–10 pigs/day and from 11 to 50 pigs/days, respectively. At retail level, we distinguished between roadside vendors as 1–2 stalls, commune markets as 3–20 stalls and central markets as over 20 stalls. In addition, selected study sites were traditional slaughterhouses (i.e., not modern slaughterhouse with hanging system), and retailers did not have a supermarket in the area. At consumer level, households in Hung Yen were defined as urban, peri-urban and rural areas.

Sample collection

In four sampling stages, a total of 36 pig farms were randomly selected by sampling one farm in each of nine recruited communes. A 100-cm^2 surface of pen floor sample represented by four different sites (25 cm^2 per site) have been swabbed using a pre-moistened cotton swab. At slaughterhouse, 1–5 pigs, which depends on the number of slaughtered pigs of the slaughterhouse, have been randomly selected from 25 slaughterhouses to collect carcass swab ($n = 72$) and rectal content ($n = 72$) samples. This sample size was calculated based on recent *Salmonella* prevalence on pig carcass (25%) reported in a study in 2014 from Hung Yen (Yokozawa et al. 2016), with an absolute precision at 10% and confidence interval of 95%. To sample carcasses, done at final washing steps at slaughterhouses, a 400-cm^2 surface of carcass from four different sites (hind limb-medial, abdomen-medial, mid-back and lower part of neck) was swabbed (following ISO17604:2003) and pooled to one sample, while feces samples were taken from rectal content using sterilized forceps and sticks right after evisceration. At market, three pork shops in each of the selected communes were randomly selected for sampling. After four sampling visits at markets, a total of 108 cut pork samples had been collected by purchasing 400–500 g of lean meat from three to four parts of a carcass (ICMSF 1986). Swab samples were stored in 20 ml buffered peptone water (BPW; Merck, Darmstadt, Germany) medium and pork was placed in a sterilized bag. All samples were kept in a cool box and transported to laboratory for analysis within 8–10 h of sampling.

Salmonella analysis

Salmonella qualitative and quantitative tests were done following ISO 6579:2002 and 3-tube MPN method, respectively. In brief, 25 g pork and 10 g feces or swab samples were added up by 225 ml and 100 ml BPW (Merck, Darmstadt, Germany), respectively, for homogenization. All homogenates were incubated at 37 °C for

16–20 h. After incubation, *Salmonella* was cultured consecutively in the first selective media (Muller-Kauffmann Tetrathionate-Novobiocin broth and semisolid modification Rappaport–Vassiliadis agar) and in the second selective media (xylose-lysine-tergitol 4 agar and Rambach agar) (Merck, Darmstadt Germany). After culturing of suspected colonies in nutrition agar (Merck, Darmstadt Germany), biochemical tests were conducted to confirm typical profiles of *Salmonella* in triple sugar iron agar, urea broth and motility-indole-lysine agar (Merck, Darmstadt, Germany). Each *Salmonella* isolate was further serotyped using *Salmonella* polyvalent O antiserum (Bio-Rad, London, UK) according to Kauffmann–White scheme. *Salmonella* enumeration was performed for retail pork using the 3-tube MPN method (de Man 1983; ISO:21528-1 2004). All samples were processed and analyzed at the laboratory of the National Institute of Veterinary Research, Hanoi, Vietnam.

Consumer survey

A structured questionnaire was used for face-to-face interviews with 30 urban consumer households. This household survey was a subsample of a larger consumer survey carried out in Hung Yen Province. In addition, eight participants representing consumer households in Hung Yen urban were gathered in a focus group discussion (FGD) to explore pork cooking practices and consumption behavior. The questionnaire was developed in English, translated into Vietnamese and pre-tested with five consumers in Hung Yen prior to actual field survey. The FGD was led by one facilitator and one note-taker using audio recording and lasted about 1.5 h. Written consent was obtained before conducting the interview and discussion group. The interview and FGD were conducted by the first author and four trained and experienced research assistants.

Quantitative microbial risk assessments

Codex Alimentarius Commission quantitative microbial risk assessment (CAC/GL 30 1999) consisting of hazard identification, hazard characterization, exposure assessment and risk characterization was applied. Hazard identification was described in the Introduction. For hazard characterization, bacteria growth and dose–response relationship, models were obtained from the literature (Teunis et al. 2010; Velugoti et al. 2011).

Exposure assessment was done using surveys data described above. Reduction and cross-contamination of *Salmonella* in term of probability and concentration during cooking was modeled based on an experiment which was published in detail elsewhere (Sinh et al. 2014). In this study, four different scenarios for cooking procedures were considered with different possibilities of cross-contamination by equipment and hand from raw to boiled pork slices. Briefly, Scenario 1 presented a practice of after cutting raw pork, the knife, cutting board and hands used for it were washed once with soap and clean water. That same knife and cutting board were used to slice boiled pork without disinfection of hands. The probability of cross-contamination of scenario 1 was 72.7% and *Salmonella* concentration reduced from 10 to 0.34 CFU/g). Scenario 2 presented after cutting raw pork, the hands were washed once with soap and clean water. A new knife and a new cutting board were used for cutting boiled pork, but without hand disinfection. The probability of cross-contamination of this scenario was 9.1% and *Salmonella* concentration reduced from 10 to 0.047 CFU/g). Scenario 3 implied after cutting raw pork, the knife used for it was washed once with soap and clean water. Hands were washed and disinfected. Boiled pork was sliced using the same knife used for raw pork, but on a new cutting board. The probability of cross-contamination of scenario 3 was 27.3% and *Salmonella* concentration reduced from 10 to 0.047 CFU/g). Scenarios 4 indicated after cutting raw pork, the knife used was washed once with soap and clean water. Hands were washed and disinfected. Boiled pork was sliced using the same cutting board used for raw pork, but with a new knife. The probability of cross-contamination of scenario 4 was 63.6% and *Salmonella* concentration reduced from 10 to 1.0 CFU/g).

Risk characterization was carried out by combining the dose–response and exposure assessment by developing a risk model. The developed risk model comprised four parts: (i) prevalence and concentration of *Salmonella* on pork from different types of markets (central, commune markets and roadside vendors); (ii) *Salmonella* growth model between purchasing and cooking; (iii) cross-contamination of *Salmonella* in after boiling pork, and (iv) boiled pork consumption patterns (frequency and quantity) in different gender and age groups (less than 5 years old, male and female adults, and elders over 60 years old) (Fig. 1).

Salmonella growth was modeled using below formula (Velugoti et al. 2011).

$$y(t) = y_0 + \mu_{\max} F(t) - \ln\left(1 + \frac{e^{\mu_{\max} F(t)} - 1}{e^{(y_{\max} - y_0)}}\right) \quad (1)$$

$$F(t) = t + \frac{1}{\mu_{\max}} \ln\left(e^{-\mu_{\max} t} + e^{-h_0} - e^{(-\mu_{\max} t - h_0)}\right), \quad (2)$$

where y_0 is initial cell concentration in $\log_e$CFU/g; $y(t)$ is cell concentration in $\log_e$CFU/g at time t, $y_{\max}$ is maximum cell concentration in $\log_e$CFU/g, $\mu_{\max}$ is maximum specific growth rate in $\log_e$CFU/g. The maximum CFU/g $10^{9.1}$ to calculate $y_{\max}$ was taken from Thayer et al. (1987). To

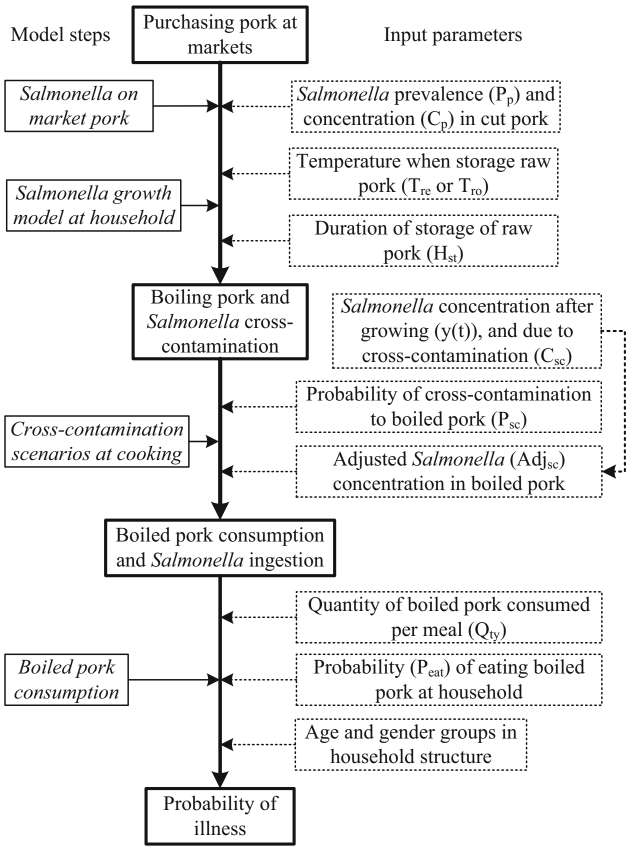

Fig. 1 Steps and input parameters of the developed salmonellosis risk assessment model from retail pork to consumption in urban Hung Yen, Vietnam, 2015 (*thin solid arrow* model steps, *dotted arrow* input parameters, *thick solid arrow* model flow)

model y_0, *Salmonella* concentration on sold pork was quantified and adjusted by the reduction rate in the experiments. To describe the effect of temperature on the maximum specific growth rates of the organism, the modified Ratkowsky equation was used as in Formula 3 (Ratkowsky et al. 1983).

$$\mu_{\max} = a(T - T_{\min})^2(1 - \exp(b(T - T_{\max}))), \qquad (3)$$

where $T_{\min}$ and $T_{\max}$ represent theoretical minimum and maximum temperatures beyond which organism's growth is impossible and T represents the range of actual temperature, while a (0.00245) and b (0.2038) are regression coefficients obtained from the author group of Velugoti et al. (2011) by personal communication. According to this, they used these coefficients for their modeling, but did not present them in their paper. For *Salmonella*, $T_{\min}$ is 6.97 and $T_{\max}$ is 47.44 (Velugoti et al. 2011).

Ambience temperature was measured as mean of 25 °C with a standard deviation of 4.25 °C (based on temperature data in the study region in 2015) (GSO 2014). Temperature in the refrigerator was assumed to be 4 °C. Data on *Salmonella* multiplication by time (h) was adapted from fitted data in the Baranyi model; h_0 mean was 2.14 and standard deviation was 0.71 (Baranyi and Roberts 1994). The temperature was also included to determine the growth model which followed the modified Ratkowsky Eq. 3 (Ratkowsky et al. 1983).

Salmonella prevalence and number was obtained from the conducted biological sampling and analysis as mentioned above. *Salmonella* number was analyzed as MPN/g which was assumed equal to CFU/g for fitting the growth model. At household level, pork handling and consumption information was used from the consumer survey (see above). To model pork consumption patterns according to gender and age groups, actual data were sampled using non-parametric bootstrapping. In the risk model sheet, 100 individuals by four gender and age groups (children, adult males and females, and elders) were modeled, and the means were used for the simulation of mean salmonellosis incidence probability (P_{ill}) using the Beta-Poisson dose response model (Formula 4). Parameters, statistic, distribution and data sources used in the risk modeling are shown in Table 1.

$$P_{\text{ill}} = 1 - (1 + \text{dose}/\beta)^{-\alpha}, \qquad (4)$$

where P_{ill} is probability of illness (salmonellosis), dose is a number of *Salmonella* (CFU) ingested per meal, $\alpha = 0.0085$ and $\beta = 3.14$ as described by Teunis et al. (2010).

Data management and analysis

Collected data were managed, processed and analyzed using MS Excel 2010 and RStudio version 3.2.2 (R Core Team). Descriptive statistical analysis was used to describe *Salmonella* prevalence. The risk model was developed and Monte Carlo simulation was performed using @Risk (Palisade, Corporation, US) for 10,000 iterations. Sensitivity analysis was conducted selecting all the uncertainty parameters and run for 1000 iterations at seven quantile values.

Results

Smallholder pig value chains to urban Hung Yen

In this study, the portions of fattening pigs raised in the small, medium and large-scale farms were 5.5, 29.2 and 65.3%, respectively. About two-thirds of finishing pigs were sent to slaughterhouses inside Hung Yen Province while the remainder was sent outside. There were no large-scale (over 50 pigs/day) slaughterhouses or supermarkets observed in the study site. Medium and

Table 1 Parameters, statistics, distribution and data sources using in the risk model in urban Hung Yen, Vietnam, 2015

Parameters	Statistics/distribution	Source
Market		
Salmonella prevalence of cut pork at central market (P_{pc})	Pork from small SH: Beta (13, 13) Pork from medium SH: Beta (10; 13)	Survey
Salmonella concentration in cut pork at central market (Cpc) (LogCFU/g)	LogNormal (0.24, 0.32)	Survey
Salmonella prevalence of cut pork at commune market (P_{pm})	Pork from small SH: Beta (16, 9) Pork from medium SH: Beta (1; 1)	Survey
Salmonella concentration in cut pork at commune market (Cpm) (LogCFU/g)	LogNormal (0.92, 0.32)	Survey
Status of *Salmonella* contamination in cut pork (Spo) from market types	Central market: binomial (1, P_{pc}) Commune market: binomial (1, P_{pm})	Survey
Growth model at household		
Temperature when store raw pork in refrigerator at household (Tre) (°C)	Fixed at 4 °C	Opinion
Temperature when store raw pork at ambience condition at household (Tro) (°C)	Normal (24.4, 4.9)	
Duration of storage raw pork at household before cooking (Hst) (Hour)	Actual data: mean = 2.1, min = 0, max = 5	Survey
Salmonella grow rate in food matrices (h_0) (LogCFU/g)	Normal (2.14, 0.71)	Baranyi and Roberts (1994)
Cooking and consumption at household		
Probability of *Salmonella* cross-contamination after boiling pork in cooking scenarios (P_{sc})	Scenario 1: P_{sc1} = Beta (8, 3) Scenario 2: P_{sc2} = Beta (1, 10) Scenario 3: P_{sc3} = Beta (3, 8) Scenario 4: P_{sc4} = Beta (7, 4)	Survey
Status of *Salmonella* cross-contamination after boiling pork in cooking scenarios (C_{sc})	Scenario 1: C_{sc1} = Binomial (1, P_{sc1}) Scenario 2: C_{sc2} = Binomial (1, P_{sc2}) Scenario 3: C_{sc3} = Binomial (1, P_{sc3}) Scenario 4: C_{sc4} = Binomial (1, P_{sc4})	Survey
Probability of eating boiled pork per meal by Hung Yen urban consumer (P_{eat}) ($0 < P_{eat} \leq 1$)	Non-parametric bootstrapping from household data (using DUniform)	Survey
Status of eating boiled pork in the meal by Hung Yen urban consumer (S_{eat})	Binomial(1, P_{eat})	Survey
Quantity of boiled pork consumed per meal by Hung Yen urban consumer (Qty) (g/meal)	Non-parametric bootstrapping from household data (using DUniform)	Survey
Illness probability from dose response model (I_{pro})	Beta-Poisson (α, β) equation, $\alpha = 0.00853$ and $\beta = 3.14$	Teunis et al. (2010)

SH slaughterhouse, *CFU* colony forming unit

large farms provided live pigs for both small and medium-scale slaughterhouses. Moreover, most pigs from small-scale farms were sent to the small-scale slaughterhouses. The proportion of pigs numbers from medium and large-scale farms slaughtered in small slaughterhouse were 76.2 and 40.4%, and for medium slaughterhouses 23.8 and 59.6%, respectively. At the market, 53.9, 25.6 and 20.5% of pork from small slaughterhouse were sold at central, commune markets and roadside vendor, respectively; whereas, almost all pork (93.9%) from medium slaughterhouse was sold at central market and a only small portion (6.1%) was sold at commune market. Among the interviewed households, three-fourth of them usually buy pork at central markets, and the remaining usually buy pork at commune markets (Fig. 2).

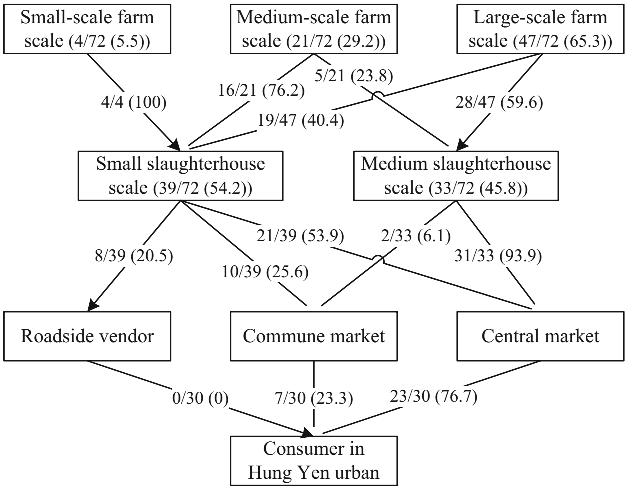

Fig. 2 Smallholder pig value chains flow provides pork to urban Hung Yen, Vietnam, 2015 (numbers in brackets are in percentage)

Salmonella prevalence in the smallholder pig value chains

Salmonella prevalence on pig pen floors and carcasses at slaughterhouse were 33.3 and 41.7%, respectively (Table 2). Overall *Salmonella* prevalence on cut pork at market was 44.4%. There was no significant difference on *Salmonella* prevalence among the three retail types ($\chi^2 = 0.77$, $df = 2$, $p = 0.68$). The *Salmonella* prevalence tended to be higher at the end of the pork value chain (feces 38.9%, carcass 41.7%, and cut pork 44.4%; $\chi^2 = 0.55$, $df = 2$, $p = 0.76$).

Exposure assessment

Data from focus group discussion (FGD) and non-parametric bootstrapping showed that each person consumed an average of 74 (minimum 20 to maximum 200) gram boiled pork/meal. Amount of boiled pork consumed varied by age and gender group: 37 g/meal (children), 100 g/meal (adult male), 87 g/meal (adult female) and 73 g/meal (elder). The frequency of eating boiled pork was 117 (minimum of 50 to maximum of 205) times/year.

Risk characterization

The overall mean estimated annual incidence rate of salmonellosis due to eating boiled pork for urban consumer in Hung Yen was estimated at 17.7% (90% CI 0.89–45.96, Table 3). The estimated annual incidence rate was lowest in children, followed by adult female; however, adult male and elder groups showed similar results (Table 3).

Sensitivity analysis

Sensitivity analysis results revealed the factors with the greatest influence on estimated salmonellosis incidence were cross-contamination rate in scenario 1 (using the same, both knife and cutting board, for raw and cooked pork), followed by the prevalence of *Salmonella* on pork in central market, where 76.7% of urban consumers purchase their pork and the *Salmonella* prevalence on pork at commune market. Two less important factors were cross-contamination rate in scenario 2 and scenario 3 (Table 4). By changing these seven uncertainty parameters into fixed mean values, the confidence interval of annual incidence rate (18.0%, 90% CI 1.16–45.51%) became only slightly narrower, which means the larger confidence interval was due to the variability such as amount of pork and reduction of *Salmonella* concentration at cross-contamination on a boiled pork.

Discussion

The domestic pork value chain is important for food and nutritional security in Vietnam. Our study confirmed the importance of small and medium farms and slaughterhouses in the pork value chain. Many agri-food systems in low and middle-income countries (LMIC) are characterized by a large number of small operators, operating mainly in the informal sector (Grace 2015). This can make promotion of good practices and monitoring of food safety difficult, and shifting to large-scale, modern food

Table 2 *Salmonella* prevalence on pen floor at farm, feces and carcass at slaughterhouse and cut pork at market in Hung Yen, Vietnam, 2015

Sample type	*Salmonella* prevalence [no. positive/*n* (%)]			
	Small	Medium	Large	Overall
Pig pen floor swab at farm	1/2 (50.0)	6/22 (27.3)	5/12 (41.7)	12/36 (33.3)
Fecal sample at slaughterhouse[a]	13/39 (33.3)	15/33 (45.5)	–	28/72 (38.9)
Pig carcass swab at slaughterhouse	14/39 (35.9)	16/33 (48.5)	–	30/72 (41.7)
Cut pork at wet market[b]	6/17 (35.3)	10/23 (43.5)	32/68 (47.1)	48/108 (44.4)

[a] Fecal sample was collected from rectum after evisceration

[b] At wet market, small scale was defined as roadside vendor (1–2 stalls), medium scale as commune market (3–20 stalls) and large scale as central market (over 20 stalls)

production and retail is often seen as a way to mitigate food safety risks (Wilhelm et al. 2012). However, there is limited empirical evidence showing the effect of this approach on food safety risk (Grace 2015).

Our study found significant levels of *Salmonella* along the pork value chain. Around 40% of carcass swabs were also positive. This is comparable to high-income countries, where a systematic review found an average of 55% of pork carcasses were *Salmonella* positive at the point of bleeding (O'Connor et al. 2012). Our study also found a tendency of increase in prevalence along value chain, and that around 40% of retailed pork was *Salmonella* positive: this is higher than findings from high-income countries (where typically 1–10%) of retailed pork is positive (Mataragas et al. 2008). However, it is lower than found in some other LMIC (Zaidi et al. 2006; Sanguankiat et al. 2010). In our study, degree of intensification in sellers was not associated with pork hygiene sold at central markets in terms of *Salmonella* prevalence compared to roadside vendor or commune markets.

Table 3 Annual incidence rate of human salmonellosis due to boiled pork consumption by age and gender groups in urban Hung Yen, Vietnam, 2015

Age and gender groups	Estimated annual incidence rate [mean (90% CI)] (%)
Children (under 5 years old)	11.18 (0–45.05)
Adult female (6–60 years old)	16.41 (0.01–53.86)
Adult male (6–60 years old)	19.29 (0.04–59.06)
Elder (over 60 years old)	20.41 (0.09–60.76)
Overall	17.7 (0.89–45.96)

CI confidence interval

We estimated that the probability of acquiring salmonellosis from consumption of boiled pork was 17.7% in a given year. In high-income countries, several studies have suggested that consumption of pork is one of the major sources of human salmonellosis (Valkenburgh et al. 2004; Mullner et al. 2009). However, there is little good evidence on the incidence of salmonellosis in LMIC. The recent WHO report on the global assessment of foodborne disease, estimated that the annual incidence of foodborne salmonellosis in the Asian region including Vietnam was 1% (range 0.2–7%) (Havelaar et al. 2015). This is much lower than our estimate of 17.7%, but the methods are not comparable and the WHO report is acknowledged to give conservative estimates. Another study in Vietnam estimated that the annual risk of infection by *Salmonella* from pork in an urban areas of Hanoi was 9.5 (0.4–30)% due to lack of separation knife, hands and cutting board at a consumption level of 86 g/person/day and of a frequency of 219 times of eating pork/person/year (Toan et al. 2013). However, the risk scenarios of this study were not comparable with those from our study.

Our 90% confidence interval of annual incidence was wide. The variability parameters in our QMRA model such as quantity of pork consumption and *Salmonella* concentration (MPN/g) contaminated on boiled pork in cooking experiments had a wide variety, and the structure of model simulating salmonellosis in the sets of 100 individuals reflects these variations.

Table 4 Sensitivity analysis result of the influence factors on salmonellosis incidence in urban Hung Yen, Vietnam, 2015

Rank	Influence factors on salmonellosis incidence	Values at 50th (1st–99th) percentiles	Mean (90% CI) daily incidence of salmonellosis per 10,000 people
1	Probability of cross-contamination in scenario 1	0.74 (0.39–0.95)	6.47 (4.69–7.79)
2	Prevalence of *Salmonella* on pork (from medium slaughterhouse) at central market	0.43 (0.21–0.67)	6.36 (5.67–7.17)
3	Prevalence of *Salmonella* on pork (from small slaughterhouse) at commune market	0.64 (0.41–0.84)	6.32 (5.5–7.11)
4	Prevalence of *Salmonella* on pork (from small slaughterhouse) at central market	0.5 (0.28–0.72)	6.36 (6–6.79)
5	Probability of cross-contamination in scenario 4	0.64 (0.3–0.91)	6.31 (5.98–6.7)
6	Probability of cross-contamination in scenario 2	0.07 (0–0.37)	6.35 (6.33–6.42)
7	Probability of cross-contamination in scenario 3	0.26 (0.05–0.61)	6.36 (6.34–6.38)

CI confidence interval

Scenario 1 presented a practice of after cutting raw pork, the knife, cutting board and hands used for it were washed once with soap and clean water. That same knife and cutting board were used to slice boiled pork without disinfection of hands

Scenario 2 presented after cutting raw pork, the hands were washed once with soap and clean water. A new knife and a new cutting board were used for cutting boiled pork, but without hand disinfection

Scenario 3 implied after cutting raw pork, the knife used for it was washed once with soap and clean water. Hands were washed and disinfected. Boiled pork was sliced using the same knife used for raw pork, but on a new cutting board

Scenario 4 indicated after cutting raw pork, the knife used was washed once with soap and clean water. Hands were washed and disinfected. Boiled pork was sliced using the same cutting board used for raw pork, but with a new knife

In this study, much of the burden of salmonellosis was due to cross-contamination at the consumer level, when the same knife and cutting board was used for both raw and boiled pork. Other QMRA studies of pork have also identified this as a key process in amplifying risk (Swart et al. 2016). A previous study in Hanoi, found that pork consumption was not associated with self-reported diarrhea, but consumption of vegetables was strongly associated with diarrhea (Fahrion et al. 2013). This also supports the possible importance of pork as a source of bacteria which contaminate other foods which are eaten with minimal or no cooking.

Further, sensitivity analysis showed the importance of prevalence in marketed pork as the second most influential factor. This study did not identify the most critical stage for intervention; e.g., market, slaughterhouse or farm. The intervention targeted the value chains, e.g., farm, slaughterhouse, market or household will be incorporated in the intervention model which will be published elsewhere. However, the model developed in this study can be utilized in answering this question, and the risks will be studied under other settings in Vietnam further in future.

This study is the first published QMRA applied for food safety in Vietnam in international peer-reviewed literature. Risk-based approaches are now standard for food-safety issues in developed countries, as well as being the basis of rules governing international trade in food products. However, use of risk assessment, and especially quantitative risk assessment, has been limited in LMIC (Grace et al. 2010). This study shows that QMRA can be applied to informal value chains and give credible information as well as insights into managing risk as concentration and prevalence in pork at central market were sensitive. In addition, although the model developed in this paper is specific for *Salmonella*, other microbiological pathogens in pork also present a risk of disease to consumers. The information from this study could provide valuable insight into risk factors and behaviors for other microbiological pathogens in pork. In Vietnam, food safety is an important concern of the society and attracts great attention of all the stakeholders. Part of the problem is that hazards in food are often reported; however, there is little information on the magnitude of health risk caused by the hazards reported. Hence, the QMRA results here would offer a step forward by providing estimates of health impact.

There were several limitations in the study. First was the uncertainty of reduction in cooking that we do not know how accurate the reduction at household is. We based this only on the experiences that stimulated the cross-contamination. The study did not sample at households for *Salmonella* cross-contamination since it was challenging to conduct *Salmonella* sampling, e.g., costly and impossible for ethical consideration. Secondly, since the speculative nature of modeling, particularly as the model has not been validated, attribution studies based on field data would be more robust although much more expensive and challenging when implementing. There is also a huge gap between government reports and hospital cases as well as the limitation of cross-contamination of cooking at household base on the experiment due to the limited sample size used. Thirdly, the amount and frequency of pork eating also varied by individual and time. Therefore, the actual *Salmonella* cross-contamination and concentration might be lower which might lead to over-estimate and larger confidence interval of incidence in our findings. Moreover, this model has been applied for *Salmonella* in general using the Beta-Poisson dose–response and not specified for any *Salmonella* strains. In addition, our model was not able to simulate the differing susceptibility in different consumer groups (e.g., children or elder) as well as to the specific *Salmonella* strains. However, we propose the magnitude of salmonellosis was not much of our interest rather than for the future intervention along the pork value chains.

Conclusions and recommendations

This study shows high levels of *Salmonella* from farm to final product (pork at market) along the smallholder pig value chains. The risk of salmonellosis in humans due to boiled pork consumption appears to be high. Feasible mitigations to improve hygiene practices are required to reduce the risk for the consumer. Control at farm may benefit from good agricultural practices as well as technological innovations such as water acidification (Wilhelm et al. 2012). Similarly good practices and adequate infrastructure can improve hygiene at slaughter and retail. Given the important role of cross-contamination in the kitchen, public education should address household practices.

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Compliance with Ethical Standards

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Ethical approval Ethical approval for this study was obtained from Institutional Review Board of the Hanoi School of Public Health (No. 148/2012/YTCC-HD3). Informed consent was obtained from all individual participants included in the study.

References

Baranyi J, Roberts TA (1994) A dynamic approach to predicting bacterial growth in food. Int J Food Microbiol 23(3–4):277–294

CAC/GL 30 (1999) Principles and guidelines for the conduct of microbiological risk management. Codex Alimentarius-Joint FAO/WHO Food Standards Programme, Rome

de Man JC (1983) MPN tables, corrected. Eur J Appl Microbiol Biotechnol 17:301–305

Fahrion AS, Lapar ML, Nguyen-Ngoc T, Do-Ngoc T, Grace D (2013) Food-borne hazards in a transforming pork value chain in Ha Noi: basis for future risk assessments. Vietnamese J Prev Med 24:18–25

Grace D (2015) Food safety in low and middle income countries. Int J Environ Res Public Health 12(9):10490–10507

Grace D, McDermott J (2015) Food safety: reducing and managing food scares, 2014–2015 Global Food Policy Report. USA, International Food Policy Research Institute, Washington

Grace D, Makita K, Kang'ethe EK, Bonfoh B (2010) Safe food, fair food: participatory risk analysis for improving the safety of informally produced and marketed food in sub-Saharan Africa. Revue Africaine de Santé et de Productions Animales 8(S):3–11

GSO (2014) General Statistics Office of Vietnam: Administrative Unit and Climate in 2014. Retrieved 15 April, 2016, from https://www.gso.gov.vn/default.aspx?tabid=732

Havelaar AH, Kirk MD, Torgerson PR, Gibb HJ, Hald T, Lake RJ, Praet N, Bellinger DC, de Silva NR, Gargouri N, Speybroeck N, Cawthorne A, Mathers C, Stein C, Angulo FJ, Devleesschauwer B (2015) World Health Organization global estimates and regional comparisons of the burden of foodborne disease in 2010. PLoS Med 12(12):e1001923

Hien PTT (2009) Microbiological contamination of fresh minced pork from the retail market in Hanoi, Viet Nam. Mater thesis, Chiang Mai University and Freie University of Berlin

Hung NV (2015) Task force of risk assessment for food safety in Vietnam: operational research to assist policy and capacity building. Retrieved April 4, 2016, from https://cgspace.cgiar.org/handle/10568/69432

ICMSF (1986) Microorganisms in Foods 2. Sampling for microbiological analysis: principles and specific applications, 2nd edn. International Commission on Microbiological Specifications for Foods

ISO:21528-1 (2004) Microbiology of food and animal feeding stuffs-Horizontal methods for the detection and enumeration of Enterobacteriaceae—part 1: detection and enumeration by MPN technique with pre-enrichement. International Organization for Standardization. Geneva, Switzerland

Lapar M, Tiongco M (2011) Private standards in pork value chains: role, impact and potential for local innovation to improve food safety and enhance smallholder competitiveness. Farm Policy J 8(3):39–53

Makita K, Desissa F, Teklu A, Zewde G, Grace D (2012) Risk assessment of staphylococcal poisoning due to consumption of informally-marketed milk and home-made yoghurt in Debre Zeit, Ethiopia. Int J Food Microbiol 153(1–2):135–141

Mataragas M, Skandamis PN, Drosinos EH (2008) Risk profiles of pork and poultry meat and risk ratings of various pathogen/product combinations. Int J Food Microbiol 126(1–2):1–12

Mullner P, Jones G, Noble A, Spencer SE, Hathaway S, French NP (2009) Source attribution of food-borne zoonoses in New Zealand: a modified Hald model. Risk Anal 29(7):970–984

O'Connor AM, Wang B, Denagamage T, McKean J (2012) Process mapping the prevalence of salmonella contamination on pork carcass from slaughter to chilling: a systematic review approach. Foodborne Pathog Dis 9(5):386–395

OECD (2016) Meat consumption (indicator). Retrieved March 1, 2016, from https://data.oecd.org/agroutput/meat-consumption.htm

Phan TT, Khai LTL, Ogasawara N, Tam NT, Okatani AT, Akiba M, Hayashidani H (2005) Contamination of Salmonella in retail meats and shrimps in the Mekong Delta, Vietnam. J Food Prot 68(5):1077–1080

Ratkowsky DA, Lowry RK, McMeekin TA, Stokes AN, Chandler RE (1983) Model for bacterial culture growth rate throughout the entire biokinetic temperature range. J Bacteriol 154(3):1222–1226

Sanguankiat A, Pinthong R, Padungtod P, Baumann MPO, Zessin KH, Srikitjakarn L, Fries R (2010) a cross-sectional study of *Salmonella* in pork products in Chiang Mai, Thailand. Foodborne Pathog Dis 7(8):873–878

Sinh DX, Phuc PD, Nam NH, Thanh NT, Hue VTK, Long NH, Hung NV (2014) Salmonella crosscontamination of pork for health risk assessment: simulation of cooking preparation at households. Vietnam J Pract Med 5(933–934):233–237

Swart AN, van Leusden F, Nauta MJ (2016) A QMRA model for *Salmonella* in pork products during preparation and consumption. Risk Anal 36(3):516–530

Teunis PF, Kasuga F, Fazil A, Ogden ID, Rotariu O, Strachan NJ (2010) Dose-response modeling of *Salmonella* using outbreak data. Int J Food Microbiol 144(2):243–249

Thai TH, Hirai T, Lan NT, Yamaguchi R (2012) Antibiotic resistance profiles of *Salmonella* serovars isolated from retail pork and chicken meat in North Vietnam. Int J Food Microbiol 156(2):147–151

Thayer DW, Muller WS, Buchanan RL, Phillips JG (1987) Effect of NaCl, pH, temperature, and atmosphere on growth of Salmonella typhimurium in glucose-mineral salts medium. Appl Environ Microbiol 53(6):1311–1315

Toan LQ, Nguyen-Viet H, Huong BM (2013) Risk assessment of *Salmonella* in pork in Hanoi, Vietnam. Vietnam J Prev Med 24:10–17

Tuyet-Hanh TT, Minh NH, Vu-Anh L, Dunne M, Toms LM, Tenkate T, Thi MH, Harden F (2015) Environmental health risk assessment of dioxin in foods at the two most severe dioxin hot spots in Vietnam. Int J Hyg Environ Health 218(5):471–478

Valkenburgh SM, VanOosterom RA, Stenvers OFJ, Steijn K, VanPelt W (2004) Report on trends and sources of zoonotic agents: The Netherlands 2003, The Dutch Food and Consumer Product Safety Authority and the Ministry of Agriculture, Nature and Food Quality

Van TT, Moutafis G, Istivan T, Tran LT, Coloe PJ (2007) Detection of *Salmonella* spp. in retail raw food samples from Vietnam and characterization of their antibiotic resistance. Appl Environ Microbiol 73(21):6885–6890

Velugoti PR, Bohra LK, Juneja VK, Huang L, Wesseling AL, Subbiah J, Thippareddi H (2011) Dynamic model for predicting growth of *Salmonella* spp. in ground sterile pork. Food Microbiol 28(4):796–803

WB-Vietnam (2016) Abstracts: World Bank Vietnam Food Safety management. Retrieved 4 April, 2016, from http://www.eurochamvn.org/sites/default/files/uploads/Sector%20Committees/FAASC/

News/Abstracts%20WB%20Vietnam%20Food%20Safety%20management%201.2016.pdf

Wilhelm B, Rajic A, Parker S, Waddell L, Sanchez J, Fazil A, Wilkins W, McEwen SA (2012) Assessment of the efficacy and quality of evidence for five on-farm interventions for *Salmonella* reduction in grow-finish swine: a systematic review and meta-analysis. Prev Vet Med 107(1–2):1–20

Yokozawa T, Sinh DX, Hung NV, Lapar L, Makita K (2016) Transition of Salmonella prevalence in pork value chain from pig slaughterhouses to markets in Hung Yen, Vietnam. J Jpn Soc Vet Epidemiol 20(1):51–58

Zaidi MB, McDermott PF, Fedorka-Cray P, Leon V, Canche C, Hubert SK, Abbott J, Leon M, Zhao S, Headrick M, Tollefson L (2006) Nontyphoidal *Salmonella* from human clinical cases, asymptomatic children, and raw retail meats in Yucatan, Mexico. Clin Infect Dis 42(1):21–28