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Contamination of Retail Meat Samples with Multidrug-Resistant Organisms in Relation to Organic and Conventional Production and Processing: A Cross-Sectional Analysis of Data from the United States National Antimicrobial Resistance Monitoring System, 2012–2017

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Background: During food animal production, animals are exposed to, colonized by, and sometimes infected with bacteria that may contaminate animal products with susceptible and multidrug-resistant organisms (MDRO). The United States' Organic Foods Production Act resulted in decreased antibiotic use in some animal production operations. Some studies have reported that decreased antibiotic use is associated with reduced MDRO on meat.

Objectives: The aim of this study was to investigate associations of meat production and processing methods with MDRO and overall bacterial contamination of retail meats.

Methods: Bacterial contamination data from 2012 to 2017 for chicken breast, ground beef, ground turkey, and pork chops were downloaded from the National Antimicrobial Resistance Monitoring System. Poisson regression models with robust variance were used to estimate associations with MDRO contamination and any contamination (adjusted for year and meat type) overall, and according to bacteria genus (*Salmonella*, *Campylobacter*, *Enterococcus*, *Escherichia coli*) and meat type.

Results: A total of 39,349 retail meat samples were linked to 216 conventional, 123 split (conventional and organic), and three organic processing facilities. MDRO contamination was similar in conventionally produced meats processed at split vs. conventional facilities but was significantly lower in organically produced meats processed at split facilities [adjusted prevalance ratio (aPR) = 0.43; 95% CI: 0.30, 0.63]. Meat processed by split vs. conventional processors had higher or similar MDRO contamination for all tested bacterial genera except *Campylobacter* (aPR = 0.29; 95% CI: 0.13, 0.64). The prevalence of any contamination was lower in samples processed at split vs. conventional facilities for aggregated samples (aPR = 0.70; 95% CI: 0.68, 0.73) and all meat types and bacterial genera.

Discussion: Organically produced and processed retail meat samples had a significantly lower prevalence of MDRO than conventionally produced and processed samples had, whereas meat from split processors had a lower prevalence of any contamination than samples from conventional processors had. Additional studies are needed to confirm findings and clarify specific production and processing practices that might explain them. https://doi.org/10.1289/EHP7327

Introduction

Antibiotic-resistant foodborne infections are increasing in the United States (CDC 2017; Geissler et al. 2017; Nair et al. 2018). Every year, more than 660,900 Americans become ill with antibiotic-resistant *Salmonella* and *Campylobacter* infections (CDC 2019); a portion of these illnesses are traced back to the animal agriculture sector (Hoffmann et al. 2017; Innes et al. 2020). Antibiotics are necessary to treat bacterial infections and maintain animals' well-being; however antibiotic use (and misuse) selects for antimicrobial-resistant bacteria (AMR) and multidrug-resistant organisms (MDRO), defined as organisms resistant to three or more antimicrobial classes (Aslam et al. 2018). During rearing, animals are exposed to, colonized by, and sometimes infected with pathogenic bacteria (Arnold 2013; Tomley and Shirley 2009). After animals grow to a desired weight, they are shipped to a processor facility for slaughter and harvest. Throughout this process, they can act as carriers for bacterial populations, including bacteria that are susceptible to antimicrobials and bacteria that are resistant to one or numerous antimicrobials (Bailey et al. 2019; De Filippis et al. 2013; Hald et al. 2003; Keelara et al. 2013; Saide-Albornoz et al. 1995). Animals may become contaminated with infectious bacteria, including *Salmonella* and *Campylobacter,* and less clinically significant bacteria like *Escherichia coli* and *Enterococcus* spp., all of which can act as reservoirs for resistance genes (Lambrecht et al. 2019; Leavis et al. 2007; Palmer et al. 2010; Poirel et al. 2018). Specific steps in the processing chain, including defeathering, evisceration, polishing, and scalding, have been shown to increase the likelihood of contamination of meat products with bacteria (Pacholewicz et al. 2016; Rouger et al. 2017; Saide-Albornoz et al. 1995; Tadesse et al. 2011; Wheatley et al. 2014), which may expose consumers to pathogens and increase the risk of foodborne illness.

Reduced antimicrobial use in livestock populations has been promoted by several U.S. initiatives, including Guidance for

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Industry policies #209 and #213, the Veterinary Feed Directive Amendment, and the Organic Foods Production Act (OFPA) (FDA/CVM 2000; FDA 2012, 2015). The U.S. Department of Agriculture (USDA) Agriculture Marketing Service established regulations for on-farm production and postproduction processing of USDA-Certified Organic (henceforth, organic) products that are more stringent than requirements for nonorganic (henceforth, conventional) products. For example, if offspring are to be labeled USDA-Certified Organic, producers cannot administer antibiotics to the dam after the third trimester for mammals or the second day of life for poultry. In addition, organic meat must be processed separately from and conventional meat (AMS 2006). Although individual processing facilities (henceforth, processors) can handle conventional and organic meat in the same facility and with the same equipment (known as "split processing") (Coleman 2012), equipment must be disinfected between organic and conventional meat batches (Ricke 2012).

Several smaller studies have investigated associations between retail meat contamination and organic and conventional producer practices (Davis et al. 2018; Yin et al. 2019), however, to our knowledge, no large-scale, multistate U.S. study has investigated contamination in association with both production and processing practices. Therefore, we used recently released data on U.S. retail meat contamination from the U.S. National Antimicrobial Resistance Monitoring System (NARMS) to study organic and conventional meat production and postproduction processing in relation to MDRO contamination of beef, chicken, pork, and turkey retail meat samples.

Methods

Study Design

The present study used the U.S. Food and Drug Administration (FDA) data from the retail meat arm of NARMS, an established surveillance network that has collected and tested specific minimally processed retail meat samples from the most popular food animal species—chicken breast, ground beef, ground turkey, pork chops—for bacterial contamination and antibiotic susceptibility (FDA 2009).

NARMS reports the type of meat collected, USDA-Certified Organic labeling status, and the establishment number (e-number) of the facility in which the meat product was processed. Because e-numbers were recorded only in the data set from 2012 onward, the present study spans 2012–2017 (the most recent publicly available data at the time of analyses). With these NARMS data, multiyear, cross-sectional, secondary data analyses were performed.

NARMS protocols: retail meat collection. Between 2012 and 2017, NARMS continuously collected retail chicken breast, ground beef, ground turkey, and pork chops from 19 states across the United States. Participating laboratories randomly sampled retail meat from a randomly selected grocer within a 50-mile radius of their location. States are instructed to collect 40 samples of retail meat—10 from each meat type—every month (FDA 2009).

NARMS protocols: bacterial isolation and antimicrobial susceptibility testing. NARMS-funded laboratory personnel isolate bacteria from retail meat according to FDA protocols. Meat samples are placed into stomacher bags, where buffered peptone water is added, and subsequent homogenized fluid is plated and incubated to test for *Campylobacter*, *E. coli*, *Enterococcus*, and/or *Salmonella* contamination (FDA 2016). NARMS performs antimicrobial susceptibility testing and reports test data for individual antimicrobial drugs as well as multidrug-resistant (MDR) classifications as defined by NARMS. In general, a bacterial population is classified as resistant to an individual antimicrobial when the minimum inhibitory concentration (MIC) of the agent required to inhibit bacterial growth exceeds an established breakpoint value, and the population is classified as MDR or non-MDR, based on the number of antimicrobial agents or classes of agents it is resistant to, with resistance to a class of agents conferred by resistance to any agent within the class. For the present analysis we classified resistance to individual antimicrobial agents using minimum inhibitory concentration (MIC) breakpoints from the Clinical & Laboratory Standards Institute (CLSI) guidelines (Clinical and Laboratory Standards Institute 2019), whereas NARMS uses MIC breakpoints based on CLSI, European Committee on Antimicrobial Susceptibility Testing (EUCAST), and NARMS-established guidelines. Consistent with NARMS, we classified bacterial populations in retail meat samples as MDR if they were resistant to three or more antimicrobial classes. However, whereas NARMS treats beta-lactam subgroups as separate classes when determining MDR, we combined five subgroups of beta-lactam antimicrobials (-cillins, potentiated -cillins, monobactams, cephalosporins, and -penems) into a single class due to their similar mode of action (Pandey and Cascella 2021) and because resistance in one class was often indicative of resistance in the other classes. Therefore, our MDR classification is more conservative than the classification used by NARMS.

Classification of producers and processors. We initially classified each processing facility (identified by their unique e-numbers) based on NARMS data indicating whether each meat sample originated from an organic or conventional producer. Processing facilities where animals are slaughtered, butchered, and packaged were then categorized as "organic" if all meat samples processed by the facility were from organic producers, "conventional" if all meat samples processed by the facility were from conventional producers, and "split" if the facility processed samples from both organic and conventional producers.

Processor classification was further refined through linkage with the USDA Organic Integrity Database (OID), which documents and assigns unique identifiers to USDA-certified Organic processors. To link the data, we cross-referenced e-numbers from the NARMS database with historical data for 2012–2017 provided by the USDA's Food Safety and Inspection Service's (FSIS) Meat, Poultry, and Egg product inspection directory (MPI) to determine the physical address of each processor. We used Google Maps (Google LLC) to determine the physical address of each organic certified processor in the OID, and we used the physical addresses to link each certified organic producer in the OID to a producer in NARMS. Processors that were identified in NARMS as only processing conventional meat, but who were also listed as an certified organic processor in OID, were reclassified as split processors; otherwise they were left labeled as conventional processors. Processors that were identified as processing only organic meat in NARMS but were not matched to a certified organic processor in OID were left as organic or split, according to the original NARMS-based classification.

Statistical Analyses

MDRO contamination (primary analysis). Unadjusted and adjusted Poisson regression models with robust variance were used to estimate associations [prevalence ratios (PRs)] between producer and processor practices and MDRO contamination in retail meat, where each sample was classified as MDR if it were contaminated with bacteria resistant to three or more classes of antimicrobials, or as non-MDR otherwise. Non-MDR samples therefore included samples without any contamination, and samples with contamination, as long as the bacteria were resistant to fewer than three classes of antimicrobial agents. We used separate models to estimate associations with three different sets of categorical predictors: organic vs. conventional production (as the reference group), regardless of type of processor; split processing and

organic processing vs. conventional processing (as the reference group), regardless of organic or conventional production for split processors; and joint classification by production and processing as conventional samples processed by split facilities, organic samples processed by split facilities, organic samples processed by organic facilities, and (as the reference group) conventional samples processed by conventional facilities. In addition to unadjusted analyses, we repeated models with adjustment for meat type (i.e., chicken breast, ground beef, ground turkey, and pork chops as a categorical variable) and for meat type and year sampled (also as a categorical variable). In secondary analyses we estimated adjusted associations within strata of bacterial genus (i.e., *Campylobacter*, *E. coli*, *Enterococcus*, and *Salmonella*) and meat type.

The primary analyses evaluated meat samples from all state participants, which did not account for changes in participation over time. For example, in comparison with 2016, the 2017 NARMS public database included data for retail meat samples from five additional states—Iowa, Kansas, South Carolina, South Dakota, and Texas—whereas data from Connecticut were not included in 2017. State introductions and losses into the NARMS network could bias results if retail meat varied based on geographic locations where animals were raised and processed. Further, laboratories differed with regard to the bacterial genus evaluated in different meat samples. *Salmonella* and *Campylobacter* genera were tested in all retail meat samples across the NARMS network, whereas only four states—Georgia, Oregon, Maryland, and Tennessee—tested for all four genera (*Campylobacter*, *E. coli*, *Enterococcus*, *Salmonella*) throughout the study period. In addition, bacterial genera differ with regard to mechanisms for resistance and implications for colonization, infection, and disease. Therefore, we performed several sensitivity analyses. The first was limited to 36,039 samples from the 14 states that participated in NARMS before 2017 (excluding Iowa, Kansas, South Carolina, South Dakota, and Texas), including samples collected by these states in 2017 as well as in previous years. The second was limited to the 12,716 meat samples collected in 2017 from 18 states (excluding Connecticut, which did not contribute samples to NARMS after 2016). We performed an additional sensitivity analysis limited to samples collected in four states (Georgia, Maryland, Oregon, Tennessee) that tested for all four genera in all types of meat samples ($n = 10{,}714$). We also repeated the analysis of MDR *Campylobacter* contamination in 29,608 poultry samples, after excluding 6,589 ground beef and pork chop samples. In addition, we performed a sensitivity analysis using NARMS breakpoints to define antimicrobial resistance and with MDR defined with beta-lactam antimicrobial drugs treated as five separate classes to evaluate how our conservative methods for classifying MDROs may have influenced results in the primary analysis. All sensitivity analyses were adjusted for meat type and year, as appropriate.

As discussed above, we reclassified 49 of 265 processors that were initially classified as conventional based on NARMS data (indicating that all samples were from conventional producers) as split processors after they were identified as certified organic processors in the OID. Therefore, we performed an additional sensitivity analysis using the original processor classifications based only on NARMS data. In addition, we performed a probabilistic bias analysis using Monte Carlo simulations of Poisson regression models with robust variance (Phillips 2003; Scott and Maldonado 2015). Misclassification of 5%, 10%, 15%, and 20% of conventional processors was evaluated using 1,000 simulations. Measures of associations and standard errors were averaged, and 95% confidence intervals (CI) were calculated for crude and adjusted models.

Overall bacterial contamination (secondary analysis). In secondary analyses, we defined the outcome as the presence of any bacterial contamination (including both MDR and non-MDR bacteria) vs. no bacterial contamination. We used separate Poisson models with robust variance estimates to estimate associations with conventional vs. organic production; conventional, split, or organic processing; and the joint producer/processor categories, including unadjusted models, models adjusted for meat type, models adjusted for meat type and year, and separate adjusted models for each meat type. In addition, we used separate models to estimate associations between the predictors and any contamination with each bacterial genus.

Statistical significance was assessed at $\alpha = 0.05$ and Stata (version 16; StataCorp.) or R [version 3.6.0; RStudio (http://www.rstudio.com/)] was used for all statistical analyses.

Results

Processor and Retail Meat Sample Classification

Of the 55,779 retail meat samples collected between 2012 and 2017 and available in the NARMS publicly released data set with available meat-type information, 40,345 (72.3%) had an e-number. Of those, 39,349 (97.5%) had corresponding physical address information from MPI, resulting in 70.5% of all retail meat samples having valid e-numbers with affiliated physical processor addresses. A total of 15,434 (27.7%) retail meat samples lacked e-numbers, possibly due to secondary processing at the retail level. Retailers are exempted from supplying e-numbers on processed and repackaged meat performed in store (FSIS 1970, 1982). E-numbers without matches in MPI, amounting to 997 (1.8%) retail meat samples, likely reflect data entry errors into the NARMS database (Goldberg et al. 2008).

In total, we identified 342 unique processing facilities in the NARMS data, including 216 classified as conventional (conventionally produced meat samples only, and no linkage to the OID database) and 3 classified as organic (organically produce meat samples only) (Table 1). In addition, we classified 123 unique facilities classified as split processors, including 74 that were associated with both conventional and organic meat samples in NARMS, and 49 associated only with conventional meat samples but identified as certified organic in the OID.

Of the 39,348 samples included in our analysis, 3,235 (8.2%) were classified in NARMS as organically produced, including 5 samples processed by the 3 organic processing facilities, and 3,230 samples processed by 99 of the split processing facilities (Table 1). Of the 36,113 meat samples classified in NARMS as conventionally produced (91.8% of all samples), 9,490 (23.3%) were processed at the 216 conventional facilities, and 26,623 (73.7%) were processed at 111 of the split facilities.

Almost half of all samples were chicken breast (45.7%), followed by ground turkey (32.5%), ground beef (13.7%), and pork chops (7.9%) (Table S1). Ground beef samples included the largest proportion from organic producers (14.7%), followed by chicken (10.4%), ground turkey (4.4%), and pork (0.4%). The majority of turkey (86.1%), chicken (77.6%), and beef (64.9%) samples were processed by split facilities, whereas the majority of pork samples (57.4%) were processed by conventional facilities (Table S2). The numbers of samples increased during each year of the study period from 2,879 (7.3% of all samples) in 2012 to 12,716 (32.2%) in 2017.

MDRO Contamination (Primary Outcome)

In total, 1,422 of 39,348 samples (3.6%) were contaminated with at least one MDRO, including 1,393 of 36,114 conventionally produced meat samples (3.9%) and 29 of 3,235 organically produced meat samples (0.90%) (Table 2). When jointly classified by producer and processor characteristics, MDRO contamination was identified in 260 conventional producer/conventional

Table 1. Meat sample characteristics according to type of producer (organic or conventional) and type of processing facility (conventional, split, organic), NARMS, 2012–2017.

Producer type	Processing facility type	No. processing facilities	No. samples	Bacterial isolation, [*n* (%)]	Multidrug resistant bacteria isolation, [*n* (%)]
Conventional	Conventional	216	9,490	3,243 (34.1)	260 (2.7)
Conventional	Split	111	26,623	6,428 (24.1)	1,133 (4.2)
Organic	Split	99	3,230	604 (18.7)	29 (0.9)
Organic	Organic	3	5	1 (20.0)	0 (0)

Note: Study samples were collected by NARMS and linked to processors (establishment numbers). There were 123 unique split processing facilities, including 74 unique facilities that were linked to both conventional and organic samples in NARMS, and 49 that were linked only to conventional samples but were identified as a certified organic facility via matching to the OID. Conventional processing facilities ($n = 216$) were linked only to samples from conventional producer in NARMS and were not matched to a certified organic facility. Organic processing facilities ($n = 3$) were linked only to samples from organic producers in NARMS. NARMS, National Antimicrobial Resistance Monitoring System; OID, Organic Integrity Database.

processor samples (2.7%), 1,133 conventional/split samples (4.2%), and 20 organic/split samples (0.9%). None of the five organically produced and organically processed samples were MDRO positive (including five tested for MDR *Salmonella*, one of which was also tested for MDR *Enterococcus* and *E. coli*); therefore associations with MDRO contamination were not estimated for organic vs. conventional processors, or for organic production/organic processing.

Producer practices. The prevalence of MDRO contamination was lower in organic meat in comparison with conventional meat samples across all models, with a PR of 0.23 (95% CI: 0.16, 0.34) before adjustment and an adjusted PR (aPR) of 0.44 (95% CI: 0.31, 0.64) after adjustment for meat type and year (Table 2). When stratified by type of meat, adjusted model estimates suggested a lower prevalence of MDRO contamination in organic vs. conventionally produced chicken breast (aPR = 0.55; 95% CI: 0.32, 0.96) and ground turkey (aPR = 0.50; 95% CI: 0.31, 0.82) (Table 3). We did not estimate corresponding PRs for pork chops or ground beef because none of those that were organically produced (out of 12 and 792 tested, respectively) were MDRO positive. However, a small proportion of conventionally produced pork chop (43 of 3,095) and ground beef (50 of 4,607) samples were positive for MDRO. When stratified by bacterial genus and adjusted for year and meat type, organic meat production was also associated with a lower prevalence of MDR *Salmonella* (aPR = 0.61; 95% CI: 0.31, 1.21) and MDR *E. coli* (aPR = 0.50; 95% CI: 0.32, 0.78) (Table 4). MDR *Enterococcus* contamination was not significantly different between organically vs. conventionally produced meat (aPR = 0.92; 95% CI: 0.21, 4.03), but only two of the 1,656 organic samples tested were MDR positive (compared with 49 of 18,452 conventional samples). Of the samples tested for MDR *Campylobacter*, none of the 3,015 organically produced samples and only 22 of the 33,182 conventionally produced samples were positive (Table 4).

Processor practices. Retail meat samples processed at split facilities had a higher prevalence of MDRO contamination than samples from conventional processors before adjustment for type of meat and year (PR = 1.42; 95% CI: 1.24, 1.62), but there was a nonsignificant inverse association after adjustment (aPR = 0.90; 95% CI: 0.79, 1.03) (Table 2).

When stratified by type of meat, adjusted estimates suggest a similar prevalence of MDRO contamination in chicken breast and ground turkey samples processed at split vs. conventional facilities and a lower prevalence of MDRO in ground beef (aPR = 0.74, 95% CI: 0.42-1.33) and pork chops (aPR = 0.45; 95% CI: 0.23, 0.90) (Table 3). When stratified by bacterial genus, adjusted estimates suggest a lower prevalence of MDR *Campylobacter* for samples processed at split vs. conventional facilities (aPR = 0.29; 95% CI: 0.13, 0.64), but a higher prevalence of MDR *E. coli* contamination (aPR = 1.20; 95% CI: 1.03, 1.40) and MDR *Enterococcus* contamination (aPR = 1.72; 95% CI: 0.80, 3.69) (Table 4).

Composite producer and processor practices. All but 5 of the 3,235 organically produced meat samples were processed at split facilities, including all 29 of the MDRO positive samples. Given this, it is not surprising that the association between MDRO organic production/split processing (vs. conventional production and processing, aPR = 0.43; 95% CI: 0.30, 0.63) was similar to the association between MDRO and organic vs. conventional production (Table 2). The crude prevalence of MDRO contamination was higher in conventional meat samples from split processors in comparison with conventional processors before adjustment (PR = 1.55; 95% CI: 1.36, 1.77), but there was no

Table 2. Prevalence of multidrug resistant organism contamination by production and processing practices.

Variable	Samples analyzed for all meat (*n*)	Samples with MDRO contamination (*n*)	Unadjusted PR (95% CI)	Adjusted PR (95% CI), Adjusted for meat type	Adjusted PR (95% CI), Adjusted for meat type and year sampled
Production type					
Conventional	36,114	1,393	Ref	Ref	Ref
Organic	3,235	29	0.23 (0.16, 0.34)	0.32 (0.22, 0.46)	0.44 (0.31, 0.64)
Processor type					
Conventional	9,491	260	Ref	Ref	Ref
Split	29,853	1,162	1.42 (1.24, 1.62)	0.98 (0.86, 1.11)	0.90 (0.79, 1.03)
Producer/Processor[a]					
Conventional/Conventional	9,491	260	Ref	Ref	Ref
Conventional/Split	26,623	1,133	1.55 (1.36, 1.77)	1.04 (0.91, 1.18)	0.94 (0.82, 1.07)
Organic/Split	3,230	29	0.33 (0.22, 0.48)	0.33 (0.23, 0.48)	0.43 (0.30, 0.63)

Note: Multidrug resistance is defined as bacteria which have resistance to three or more antimicrobial drug classes. Categories are separated into singular processor and production types, as well as a single variable which combines both covariates under the Producer/Processor covariate. All NE abbreviations are for "nonevaluable" due to low sample size. Meat type is defined as the four major retail meat products that the NARMS samples: chicken breast, ground beef, ground turkey, and pork chop. Year sampled is defined between as collections between 2012 and 2017, inclusive. None of the five organically produced samples were MDRO positive; therefore associations with MDRO contamination were not estimated for organic vs. conventional processors, or for organic production/organic processing. CI, confidence interval; MDRO, multidrug-resistant organisms; NARMS, National Antimicrobial Resistance Monitoring System; NE, nonevaluable; PR, prevalence ratio.

[a]A categorical variable that incorporated producer and processor practices was evaluated for multidrug-resistant bacterial contamination. Each category represented a unique producer and processor type combination.

Table 3. Prevalence of multidrug resistant organism contamination by production and processing practices, stratified by meat type, adjusted for year.

Variable	Chicken breast			Ground beef			Ground turkey			Pork chops		
	Samples (*n*)	MDRO+(n)	aPR (95% CI)	Samples (*n*)	MDRO+(n)	aPR (95% CI)	Samples (*n*)	MDRO+(n)	aPR (95% CI)	Samples (*n*)	MDRO+(n)	aPR (95% CI)
Production type												
Conventional	16,160	319	Ref	4,607	50	Ref	12,252	981	Ref	3,095	43	Ref
Organic	1,872	13	0.55 (0.32, 0.96)	792	0	NE	559	16	0.50 (0.31, 0.82)	12	0	NE
Processor type												
Conventional	4,031	83	Ref	1,891	21	Ref	1,785	124	Ref	1,784	32	Ref
Split	14,001	249	0.98 (0.76, 1.25)	3,503	29	0.74 (0.42, 1.33)	11,026	873	0.99 (0.83, 1.19)	1,323	11	0.45 (0.23, 0.89)
Producer/Processor[a]												
Conventional/ Conventional	4,031	83	Ref	1,891	21	Ref	1,785	124	Ref	1,784	32	Ref
Conventional/Split	12,129	236	1.01 (0.79, 1.30)	2,716	29	0.94 (0.53, 1.65)	10,467	857	1.02 (0.85, 1.22)	1,311	11	0.45 (0.23, 0.90)
Organic/Split	1,872	13	0.56 (0.31, 1.00)	787	0	NE	559	16	0.51 (0.31, 0.85)	12	0	NE

Note: Multidrug resistance is defined as bacteria which have resistance to three or more antimicrobial drug classes. Categories are separated into singular processor and production types, as well as a single variable that combines both covariates under the Producer/Processor covariate. All NE abbreviations are for "nonevaluable" due to low sample size. Analyses are unadjusted with multidrug resistance presence as the outcome. None of the five organically produced samples were MDRO positive; therefore associations with MDRO contamination were not estimated for organic vs. conventional processors, or for organic Production/Organic processing. aPR, adjusted prevalence ratio; CI, confidence interval; NE, nonevaluable; Ref, reference.

[a]A categorical variable that incorporated producer and processor practices was evaluated for multidrug-resistant bacterial contamination. Each category represented a unique producer and processor type combination

clear difference when adjusted for meat type (aPR = 1.04; 95% CI: 0.91, 1.18) or meat type and year (aPR = 0.94; 95% CI: 0.82, 1.07) (Table 2).

Adjusted estimates suggest that MDRO prevalence was lower in samples from organic producers/split processors in comparison with conventional producers/conventional processors, with a nonsignificant inverse association for chicken breast samples (aPR = 0.56; 95% CI: 0.31, 1.00), and a significant inverse association for ground turkey (aPR = 0.51; 95% CI: 0.31, 0.85) (Table 3). Pork chop samples that were conventional/split had a lower prevalence of MDRO than conventional/conventional samples (aPR = 0.45; 95% CI: 0.23, 0.90), but corresponding associations were null for other types of meat. Our estimates suggest that MDR *Campylobacter* contamination was less prevalent in conventional/split than conventional/conventional samples (aPR = 0.31; 95% CI: 0.14, 0.70), whereas none of the 3,015 organic/split samples were positive for MDR *Campylobacter* (Table 4). The estimated prevalence of MDR *Salmonella* was also lower in organic/split samples than in conventional/conventional samples, though the difference was not significant, and the association was null for conventional/split samples. Associations with MDR *Enterococcus* were positive for both conventional/split and organic/split samples, but PRs were imprecise and not significant. Finally, the prevalence of MDR *E. coli* was significantly higher in conventional/split samples (aPR = 1.23; 95% CI: 1.06, 1.44) and significantly lower in organic/split samples (aPR = 0.59; 95% CI: 0.37, 0.94) in comparison with conventional/conventional samples.

MDRO Sensitivity Analyses

Sensitivity analyses indicated several notable results (Table S3). Consistent with the primary analyses, MDRO contamination of retail meat samples from Georgia, Maryland, Oregon, and Tennessee (states that tested for all bacterial genera) was inversely associated with organic vs. conventional production (aPR = 0.55; 95% CI: 0.35, 0.87), and with organic production/split processing compared with conventional production and processing (aPR = 0.64; 95% CI: 0.40, 1.00) (Table S3). However, in contrast with weak inverse or null estimates in the primary analysis, MDRO prevalence was positively associated with split vs. conventional processing (aPR = 1.17; 95% CI: 1.01, 1.36) and with conventional production/split processing (aPR = 1.20; 95% CI: 1.03, 1.39). Results were consistent with the primary analysis when limited to data collected before 2017 (Table S3). When limited to poultry samples, associations with MDR *Campylobacter* remained inverse for split vs. conventional processing and for conventional/split vs. conventional/conventional production/processing. We also performed two sensitivity analyses of the potential influence of misclassification of conventional processing facilities as split facilities. When classification of conventional vs. split processing facilities was based only on whether the facility processed only conventional meat samples, without considering organic certification, associations between split vs. conventional processing were consistent with the primary model estimates (Table S3). Results of Monte Carlo simulations performed to assess the impact of misclassifying 5%, 10%, 15%, or 20% of conventional processors as split processors were also consistent with the primary estimates (Table S4).

As a final sensitivity analyses, we used NARMS criteria to classify individual antimicrobial resistance and defined MDR bacteria after disaggregating beta-lactams into five separate subclasses (Table S5.) Results of this analysis were largely consistent with the main analysis, except that meat processed in split facilities had a significantly lower prevalence of MDRO contamination than meat processed at conventional facilities (aPR = 0.71; 95% CI: 0.66, 0.78), and conventional/split samples had a

Table 4. Prevalence of MDRO contamination by production and processing practices, stratified by bacteria genus, adjusted for year and meat type.

Variable	MDR *Campylobacter* contamination			MDR *Salmonella* contamination			MDR *Enterococcus* contamination			MDR *Escherichia coli* contamination		
	Samples (*n*)	MDRO+(n)	aPR (95% CI)	Samples (*n*)	MDRO+(n)	aPR (95% CI)	Samples (*n*)	MDRO+(n)	aPR (95% CI)	Samples (*n*)	MDRO+(n)	aPR (95% CI)
Production type												
Conventional	33,182	22	Ref	36,103	11	Ref	18,452	49	Ref	18,444	1,092	Ref
Organic	3,015	0	NE	3,232	11	0.61 (0.31, 1.21)	1,656	2	0.92 (0.21, 4.03)	1,655	18	0.50 (0.32, 0.78)
Processor type												
Conventional	8,431	11	Ref	9,488	263	Ref	5,747	8	Ref	5,746	188	Ref
Split	27,766	11	0.29 (0.13, 0.64)	29,842	9	0.98 (0.72, 1.33)	14,360	43	1.72 (0.80, 3.69)	14,352	922	1.20 (1.03, 1.40)
Producer/Processor[a]												
Conventional/Conventional	8,431	11	Ref	9,488	54	Ref	5,757	8	Ref	5,746	188	Ref
Conventional/Split	24,751	11	0.31 (0.14, 0.70)	26,615	209	1.01 (0.74, 1.37)	12,705	41	1.74 (0.81, 3.76)	12,698	904	1.23 (1.06, 1.44)
Organic/Split	3,015	0	NE	3,227	9	0.62 (0.30, 1.27)	1,655	2	1.41 (0.29, 6.87)	1,654	18	0.59 (0.37, 0.94)

Note: Multidrug resistance is defined as bacteria which have resistance to three or more antimicrobial drug classes. Categories are separated into singular processor and production types, as well as a single variable which combines both covariates under the Producer/Processor covariate. All NE abbreviations are for "nonevaluable" due to low sample size. Analyses are unadjusted with multidrug resistance presence as the outcome. None of the 5 organically produced samples were MDRO positive, therefore associations with MDRO contamination were not estimated for organic vs. conventional processors, or for organic production/organic processing. aPR, adjusted prevalence ratio; CI, confidence interval; MDR, multidrug-resistant; MDRO, multidrug-resistant organism; NE, nonevaluable; Ref, reference.

[a]A categorical variable that incorporated producer and processor practices was evaluated for multidrug-resistant bacterial contamination. Each category represented a unique producer and processor type combination.

significantly lower prevalence of MDRO than conventional/conventional samples (aPR = 0.75; 95% CI: 0.69, 0.81).

Any Bacterial Contamination (Secondary Outcome)

In total, 10,276 of 39,348 samples (26%) were classified as contaminated with any bacteria (regardless of antimicrobial resistance or susceptibility), including 9,675 conventionally produced meat samples (27%) and 605 organically produced meat samples (18.9%) (Table 5). When jointly classified by producer and processor characteristics, bacterial contamination was identified in 3,244 conventional producer/conventional processor samples (34%), 6,341 conventional/split samples (24%), and 604 organic/split samples (19%). Only one of the five organically produced samples processed as an organic facility was positive for bacterial contamination (a *Salmonella* isolate), therefore associations with any bacterial contamination are not reported for organic vs. conventional processors, or for organic production/organic processing.

Production practices. Model estimates suggest that the prevalence of any bacterial contamination (vs. none, regardless of antimicrobial resistance or susceptibility) was lower for samples from organic producers than for samples from conventional producers (aPR = 0.84; 95% CI: 0.78, 0.90) (Table 5). When stratified according to meat type, the association was also inverse for organic vs. conventionally produced ground beef (aPR = 0.46; 95% CI: 0.38, 0.55), but null for chicken and turkey samples (Table S6). We did not estimate associations between production practices and any contamination of pork chop samples because none of the 12 organic pork chop samples tested were positive. However, 31% of the conventionally produced pork chop samples (960 of 3,095) were positive for any contamination. We estimated weak positive associations between organic vs. conventional production and contamination with *Campylobacter* and *Salmonella* (e.g., *Campylobacter* aPR = 1.14; 95% CI: 1.00, 1.30) and inverse associations for contamination with the indicator organisms (*Enterococcus* aPR = 0.83; 95% CI: 0.76, 0.91; *E. coli* aPR = 0.91; 95% CI: 0.81, 1.02) (Table S7).

Processor practices. Retail meat from split processors was less likely to be contaminated with any bacteria than meat from conventional processors (aPR = 0.70; 95% CI: 0.68, 0.73) (Table 5). Bacterial contamination was also less common for conventionally produced meat processed at split facilities vs. conventional facilities for all meat types (Table S6) and bacterial genera tested (Table S7).

Producer and processor practices. Consistent with findings for split vs. conventional processing, adjusted estimates suggest that the prevalence of any contamination was lower in conventional meat samples processed at split facilities (aPR = 0.71; 95% CI: 0.68, 0.73) and in organically produced meat processed at split facilities (aPR = 0.66; 95% CI: 0.61, 0.71) than in conventionally produced and processed samples (Table 5). The estimated relative prevalence of any contamination was lower in conventional/split samples across all meat types, and for organic/split chicken, beef, and turkey samples (not significant for turkey; Table S6). Forty percent of the conventionally produced and processed pork chop samples were positive for any contamination, but none of the 12 organically produced/split processed pork chop samples were positive. Model estimates suggest that, in comparison with conventionally produced and processed samples, the prevalence of any contamination was significantly lower in conventionally produced samples processed at split facilities for all bacterial genera evaluated. Associations with any contamination were also inverse for organic/split vs. conventional/conventional samples for all bacteria tested, though associations with

Table 5. Prevalence ratio of overall bacterial contamination by production and processing practices.

Variable	Samples (*n*)	Any contamination (*n*)	Unadjusted PR (95% CI)	Adjusted PR (95% CI), Adjusted for meat type	Fully adjusted PR (95% CI), Adjusted for meat type and year sampled
Production type					
Conventional	36,114	9,675	Ref	Ref	Ref
Organic	3,235	605	0.70 (0.65, 0.75)	0.70 (0.65, 0.75)	0.84 (0.78, 0.90)
Processor type					
Conventional	9,491	3,492	Ref	Ref	Ref
Split	29,853	7,035	0.69 (0.66, 0.71)	0.69 (0.67, 0.72)	0.70 (0.68, 0.73)
Producer/Processor[a]					
Conventional/Conventional	9,491	3,244	Ref	Ref	Ref
Conventional/Split	26,623	6,341	0.71 (0.68, 0.73)	0.71 (0.69, 0.74)	0.71 (0.68, 0.73)
Organic/Split	3,230	604	0.55 (0.51, 0.59)	0.55 (0.51, 0.60)	0.66 (0.61, 0.71)

Note: Overall bacterial contamination is defined the contamination of retail meat by any bacteria, independent of susceptibility. Categories are separated into singular processor and production types. Meat type is defined as the four major retail meat products that the NARMS samples: chicken breast, ground beef, ground turkey, and pork chop. Year sampled is defined between as collections between 2012 and 2017, inclusive. Only one of the five organically produced samples was positive for any bacterial contamination, therefore associations with bacterial contamination are not reported for organic vs. conventional processors, or for organic production/organic processing. CI, confidence interval; NARMS, National Antimicrobial Resistance Monitoring System; PR, prevalence ratio; Ref, reference.

[a]A categorical variable that incorporated producer and processor practices was evaluated for multidrug-resistant bacterial contamination. Each category represented a unique producer and processor type combination.

Campylobacter and *Salmonella* contamination were not significant (Table S7).

Discussion

Findings from this multiyear (2012–2017), cross-sectional study of a nationally representative retail meat surveillance database in the United States suggest that samples from certified organic production facilities had a lower prevalence of MDRO contamination than retail meat samples from conventional production facilities. Organically produced poultry products also had a significantly lower prevalence of MDRO, and none of the organically produced ground beef and pork chop samples were contaminated with MDRO. Numbers of MDR positive samples were small when associations with organic vs. conventional production were stratified by bacteria genus, but associations were also inverse. When stratified by meat type, split vs. conventional processing was inversely associated with MDRO contamination of ground beef (nonsignificant) and pork chop (significant) samples, whereas associations were null for chicken breast and ground turkey samples. The lower prevalence of MDRO contamination among split processors was confirmed in a sensitivity analysis that used NARMS antimicrobial drug class definitions, a less conservative metric for MDR classification that treated subgroups of beta-lactam drugs as separate classes when counting the number of antimicrobial classes to which organisms were resistant. Results also suggested that retail meat handled by split processors had a lower prevalence of overall contamination than conventional processors across all analyzed strata. Similarly, retail meat that was produced with either organic or conventional standards had a lower prevalence of overall bacterial contamination if processed in a split facility than conventional meat processed in a conventional facility. The estimated prevalence of any contamination was also significantly lower for organic/split chicken breast and ground beef samples and for any contamination with indicator bacteria when compared with conventional/conventional samples. Out findings are consistent with studies that have found that, in comparison to conventional raised animals, organic-raised animals had lower proportions of antimicrobial resistance among retail meat (Halbert et al. 2006; Kilonzo-Nthenge et al. 2015; LeJeune and Christie 2004), carcasses (Luangtongkum et al. 2006), live animals (Halbert et al. 2006), and even in their living environment (Halbert et al. 2006; Holtcamp 2011; Van Wagenberg et al. 2017). However, although we could estimate associations with organic vs. conventional production, we could not estimate associations with organic processing, or organic production combined with organic processing, because data were available for only three organic processing facilities that processed only five samples.

Animal Production

Several smaller-scale studies have compared antibiotic-resistant bacteria in retail meat from conventional and organic-raised food-producing animals and found lower proportions of antibiotic-resistant bacteria among poultry (Davis et al. 2018; Johnson et al. 2007, 2017; Lestari et al. 2009; Mollenkopf et al. 2014; Pesciaroli et al. 2020; Yin et al. 2019), pork (Johnson et al. 2007; Yin et al. 2019), and beef (Johnson et al. 2007; Yin et al. 2019) products. LeJeune et al. evaluated "raised without antibiotics" retail meat—a label similar to organic in terms of antibiotic-use restrictions—and reported a lower prevalence of MDR isolates in the samples in comparison with isolates from meat samples that did not specify they were produced without antibiotics (LeJeune and Christie 2004). Similarly, studies that investigated antibiotic use in live cattle concluded that animals raised in an antibiotic-free environment vs. a conventional setting had lower rates of antibiotic-resistant bacterial carriage (Call et al. 2008; Halbert et al. 2006). Studies of swine operations that implemented antibiotic-use restrictions reported lower prevalence of antibiotic-resistant bacteria in comparison with conventionally produced swine in Denmark, France, Italy, and Sweden (Österberg et al. 2016), whereas studies in the United States have reported no significant difference (Susick et al. 2012) or higher prevalence (Tadesse et al. 2011).

Retail Meat Processing

Most studies that have evaluated organic and conventional practices considered the source (live animals at the farm level) or the end stage (retail meat). However, the role of processor facilities has been less scrutinized with regard to bacterial prevalence (Erickson et al. 2019). Only a few studies have evaluated processors for outcomes related to AMR (Bouhamed et al. 2018; Bridier et al. 2019; Cadena et al. 2019; Marault et al. 2014; Morach et al. 2019); and to our knowledge, no studies have compared MDRO prevalence in meat samples processed at conventional, split, and organic facilities. We classified processing facilities as conventional, split, or organic based on how the meats processed by each facility were produced (organically, conventionally, or both) and whether processors linked only to

conventionally produced meats were certified as organic processing facilities. However, because few processing facilities were classified as organic (as opposed to split), we could not evaluate them as a separate group. Reasons for low organic processor representation may be due to a small market share of organic processors, a failure of random sampling in NARMS to capture organic processors, or both.

Of note, relative to retail meat samples handled by conventional processors, samples handled by split processors had a significantly lower prevalence of overall contamination but a similar prevalence of MDRO contamination. Several plausible mechanisms may explain this, although future studies involving direct sampling of processor and production facilities would be needed to replicate and further examine this finding. One explanation may be differential sanitation protocols for split and conventional processors, where sanitation at conventional processor or production facilities may be insufficient, possibly resulting in a higher probability of cross-contamination among retail meat batches. This hypothesis was best supported by the models that were stratified by bacteria genus, where meat processed at split facilities had a significantly lower prevalence of being contaminated with bacteria regardless of MDR status than those processed at conventional facilities. Inadequate decontamination efforts may provide environments for bacteria populations to persist on processor equipment, especially among biofilm-forming bacteria (Cadena et al. 2019; Chen et al. 2020; Culotti and Packman 2015; De Filippis et al. 2013; Galié et al. 2018; Møretrø and Langsrud 2017; Morita et al. 2011; Piras et al. 2014; Umaraw et al. 2017; Visvalingam et al. 2019). Organic protocols specifically mandate that split processors must clean equipment between organic and conventional batches, and therefore more frequent and/or thorough cleaning may occur among split vs. conventional processors (Ricke 2012); however, organic protocols do not address sanitation standards in production facilities. Cleaning regimens among processor and production types are not captured in NARMS and therefore could not be assessed. Future studies that examine disinfection type, duration, or frequency of equipment cleaning among conventional, split, and organic processors are warranted.

To facilitate research on outcomes related to organic processing, NARMS could increase the number of organic processing facilities represented in their surveillance data by oversampling organic retail meat to achieve a higher probability that samples will have been handled by organic processors. Alternatively, NARMS could collect data to identify processors as conventional, organic, or split, and use the information to oversample retail meats processed by organic facilities, thus increasing power to study organic processors as a separate group. In addition, differences in associations between split processing and MDR contamination vs. any bacterial contamination, as well as inconsistent patterns of associations between MDR contamination according to the type of meat or bacterial genus (in contrast with consistent inverse associations for any contamination), may reflect random variation resulting from the relatively small numbers of MDR positive samples. Therefore, larger numbers of samples will be needed to investigate the potential influence of split processing on MDR contamination specifically.

Limitations

This study has several limitations and relies on assumptions that should be noted. First, although this study included most components of the farm-to-fork pathway, analyses did not account for integrator entities, i.e., larger companies that contract producers for their meat and that have specific protocols for their producers; thus, the integrator may confound the relationship between the explored explanatory variables and the overall contamination outcomes. Unfortunately, integrator data are not presently captured in available data sets. Other uncontrolled factors may have confounded the relationships performed in this study, including specific processor-level practices (e.g., cleaning protocols) and organic husbandry practices outside of antimicrobial use. Because misclassification of processor facilities may have also influenced results, processors were classified based on samples included in NARMS and enhanced with the OID. Nonetheless, Monte Carlo simulations that evaluated 5%, 10%, and 20% misclassification scenarios demonstrated effect estimates that differed only by 6%. Future efforts by FDA and USDA to harmonize and integrate data sets among the NARMS, MPI, and OID systems would enhance processor classification. The analyses also assumed that processor practices remained unchanged from 2012 to 2017. It is possible that individual processors converted from conventional to split practices or vice versa, and such changes were not captured during this study. Organic processors were vastly undersampled in the NARMS data set; this sample size may be proportional to an actual low representation in overall organic processors. Regardless, the small sample size was insufficient to evaluate associations in comparison with those of split and conventional processors. Similarly, the NARMS sampling strategy shifted over time, where more samples were collected with each year. This shift may be explained by increases in monetary investment into NARMS. However, this implicitly biases the data set, because the interpretations are more heavily weighted to the more recent years, when antibiotic use, general production, and processing practices may have changed; thus, the later years are more representative based on the larger power due to the increased sample size and the number of participatory states that contributed to NARMS. Additional bias may have occurred via selection bias, which may be inherent in the NARMS sampling strategy.

Conclusions

Our findings suggest that certified organic meat products in NARMS—a nationally representative retail meat data set, which covers years 2012–2017—exhibit a lower prevalence of both MDRO and overall contamination than conventionally raised and processed meat products exhibit, which has implications for consumer exposures. Heightened MDRO and overall bacterial exposures will inherently increase consumer risk for antimicrobial-susceptible and resistant foodborne illness and may enhance the community spread of antimicrobial resistance genes. Our analysis suggests that organic production practices are associated with lower prevalence of overall contamination, which may affect subsequent foodborne exposures. Additionally, our estimates suggest that the prevalence of MDRO contamination was slightly lower in retail meat processed at split vs. conventional facilities and significantly lower in organically produced meats processed at split facilities in comparison with conventionally produced and processed meats. In contrast, the prevalence of any contamination was significantly lower in retail meats processed at split vs. conventional facilities, regardless of whether the meat was conventionally or organically produced. To our knowledge, this is the first study that has attempted to differentiate animal producer practices from processor practices to evaluate prevalence along the U.S. food system chain related to MDR and overall bacterial contamination in retail meat. Our findings suggest that organically raised meat may have lower prevalence of MDRO contamination and that retail meat processed at split facilities has a lower prevalence of any bacterial contamination than meat processed at conventional facilities.

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