Benefit-cost analysis of vaccination and preemptive slaughter as a means of eradicating foot-and-mouth disease

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Objective—To assess relative costs and benefits of vaccination and preemptive herd slaughter to control transmission of foot-and-mouth disease (FMD) virus (FMDV).

Sample Population—2,238 herds and 5 sale yards located in Fresno, Kings, and Tulare counties of California.

Procedure—Direct costs associated with indemnity, slaughter, cleaning and disinfecting livestock premises, and vaccination were compared for various eradication strategies. Additional cost, total program cost, net benefit, and benefit-cost value (B/C) for each supplemental strategy were estimated, based in part on results of published model simulations for FMD. Sensitivity analyses were conducted.

Results—Mean herd indemnity payments were estimated to be $2.6 million and $110,359 for dairy and nondairy herds, respectively. Cost to clean and disinfect livestock premises ranged from $18,062 to $60,205. Mean vaccination cost was $2,960/herd. Total eradication cost ranged from $61 million to $551 million. All supplemental strategies involving use of vaccination were economically efficient (B/C range, 5.0 to 10.1) and feasible, whereas supplemental strategies involving use of slaughter programs were not economically efficient (B-C, 0.05 to 0.8) or feasible.

Conclusions and Clinical Relevance—Vaccination with a highly efficacious vaccine may be a cost-effective strategy for control of FMD if vaccinated animals are not subsequently slaughtered and there is no future adverse economic impact, such as trade restrictions. Although less preferable than the baseline eradication program, selective slaughter of highest-risk herds was preferable to other preemptive slaughter strategies. However, indirect costs can be expected to contribute substantially more than direct costs to the total cost of eradication programs. (*Am J Vet Res* 2003;64:805–812)

Foot-and-mouth disease (FMD) is 1 of the most economically important diseases affecting livestock, because it can spread rapidly, impose serious losses to livestock productivity, and, most importantly, lead to severe international restrictions on trade.[1,2] When there is an outbreak of FMD in a region previously free of the disease, 2 general eradication strategies are considered: vaccination against FMD and slaughter of infected herds. Slaughter strategies can include preemptive slaughter of herds that are not infected but that have a high probability of exposure to **FMD virus (FMDV)**. Results of decision analyses for regions in which FMD is not endemic have suggested that prophylactic vaccination against FMD would not be a cost-effective strategy.[3-6] Similarly, emergency use of vaccination in cattle in the area surrounding a new outbreak of FMD has not been considered to be a cost-effective strategy, because vaccinated herds may have to be slaughtered after the epidemic is controlled. However, with recent technologic advances for development of vaccines, such as development of high-potency vaccines that can elicit host immune responses within 4 days after administration,[7-9] and improved diagnostic tests that may permit clinicians to discriminate between vaccinated and naturally infected groups of animals,[10] reassessment of the potential benefit for emergency use of vaccination against FMD in the United States can be justified.

Vaccines can be used in the face of an FMD epidemic to create a buffer zone between infected and noninfected herds to reduce the probability of FMDV transmission outside the region of the infected herds. In accordance with current guidelines, use of FMD vaccine in the United States would only be considered if an FMD epidemic persisted for 6 months, 1 million susceptible animals were slaughtered, wildlife in multiple states became endemically infected, or the **benefit-cost value (B-C)** favored vaccination.[11] In another study[12] conducted by use of an epidemic simulation model, vaccination of all herds within a defined radius of infected herds (ie, ring vaccination) was estimated to considerably reduce the number of herds that became infected when animals were vaccinated with a homologous strain of FMDV soon after FMD was first diagnosed.

A second common eradication strategy is preemptive slaughter of herds with a high probability of being subclinically infected or recently exposed to FMDV (ie, high-risk herds). This strategy, often called a stamp-out eradication strategy, was used to control transmission of FMDV in some regions of the United Kingdom during the epidemic in 2001, and it was also found to be effective in reducing the size and duration of hypothetical epidemics, as determined by the use of simulation modeling.[13] Experiences in the United Kingdom, in which there was widespread public disagreement about the implementation of a preemptive slaughter eradication

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strategy, suggest that it is necessary to reevaluate preemptive slaughter as a potential strategy for eradication of an outbreak of FMD in the United States. The decision on whether to vaccinate or pursue a stamp-out eradication strategy will likely be based on economic factors, with preference given to the strategy with the highest B/C, net benefits, or both. Cost of an FMD epidemic in southern California could range from $4.3 billion to $13.5 billion.[14] In that study, investigators considered expenses related to direct and indirect costs, such as losses in wages, future production output, and trade opportunities, which would represent the majority of the total cost. The purpose of the study reported here was to compare projected direct costs for indemnity, slaughter, cleaning and disinfection, and vaccination with estimated benefits for preemptive herd slaughter and ring vaccination strategies for eradication of FMDV.

Materials and Methods

Study population—Animals in Fresno, Kings, and Tulare counties in the Central Valley of California were selected for use in the study. This region has diversity in types of animals and sizes of herds, which included approximately 2,238 beef, dairy, goat, sheep, and swine herds and 5 sale yards. Although there was a wide diversity of animal species, the area was considered to be predominantly a dairy region. In 1997, the region contained approximately 1.36 million domestic livestock, which included approximately 462,000 dairy cows, 67,000 beef cows, 614,000 calves and bulls, 124,000 pigs and hogs, and 94,000 sheep and lambs.[15]

Cost information—Assuming FMD were to affect US livestock herds, each herd in which FMD was diagnosed would be quickly slaughtered, and the livestock facility would be cleaned and disinfected in accordance with USDA guidelines.[11] The method of disposal of carcasses would depend on numerous factors, including animal species, herd location, availability of local rendering facilities, resources for burial or burning, and potential for groundwater contamination. Owners of herds slaughtered because of the FMD eradication policy would be entitled to reimbursement at fair market value for destroyed livestock, livestock products (eg, milk), and feedstuffs located on the farm. All feed commodities, silage, and hay potentially exposed to FMDV would be destroyed.

Results of 1 study[13] for the 3-county region indicated that dairy herds represented approximately 73% of the herds that would become infected in an outbreak of FMD; despite the fact that dairy herds represented only 23% of the herds in the region. Therefore, because dairy herds would be expected to be a major component of an FMD epidemic, cost information was based primarily on a typical drylot dairy with a mean herd size of 884 adult cows (calculated as 462,000 cows/547 dairy herds in the region). Adult cows typically represent 50% of a dairy herd, with the remainder of the herd represented by heifer calves and yearling heifers; therefore, we estimated that there were 924,000 dairy cattle in the region. Herds of other animals (ie, beef cattle, sheep, goats, and pigs) were aggregated into a single category of nondairy herds and assumed to contain, on average, 258 animals, which was calculated by determining the estimated number of nondairy animals in the region (1.36 million animals – 924,000 dairy cattle = 436,000 nondairy animals) and dividing that value by the number of nondairy herds (n = 1,691).[15] Costs for each dairy herd included indemnity costs for adult cows (50% of herd) and calves and yearling heifers (50% of herd), because the cattle would be under the same ownership, even though the calves and yearling heifers typically were housed at separate calf- and heifer-raising facilities, respectively.

Expenses for indemnification and herd slaughter—Market value of adult dairy cows in 2001 was estimated to be $2,000, which was equivalent to the compensation paid to dairy owners in Texas whose herds were purchased by the USDA during a campaign to eradicate *Mycobacterium tuberculosis* from the United States.[16] Values for yearling dairy heifers and heifer calves were estimated to be $1,200 and $700, respectively. Cost estimates for disposal and compensation of destroyed feedstuffs and contaminated milk were obtained by the California Department of Food and Agriculture as part of emergency-planning processes used to project resources and manpower needed to control an FMD outbreak. In the event of an FMD outbreak in the United States, actual indemnity payments to livestock producers would vary on the basis of animal species, weight, age, and purebred status. However, for the study reported here, costs for nondairy herds were based on a mean herd size of 258 animals/nondairy herd and a mean market value of $385/nondairy animal, which was estimated on the basis of values of $602 for each beef animal,[17] $120 for each pig,[a] and $231 for each sheep,[18] weighted on the basis of the distribution of the respective species in the region. We also varied the market value of a nondairy animal in a sensitivity analysis to assess its contribution to the total cost of FMD eradication.

Expenses for cleaning and disinfection—Number of person-hours and expenses for equipment rented to slaughter animals, destroy feedstuffs, and clean and disinfect buildings, pens, and equipment after FMD was diagnosed on a dairy were estimated as part of the same aforementioned emergency-planning process. Cost to clean and disinfect a facility for a nondairy herd was considered to be substantially less than that of a facility for a dairy herd, because there is less equipment and fewer buildings to clean and disinfect for nondairy herds. Mean herd size of a nondairy herd was 15% (ie, 258/1,768) that of a dairy herd; however, the fixed cost to clean and disinfect a facility for a nondairy herd was considered to be twice that percentage (ie, 30%) multiplied by the cost to clean and disinfect a dairy facility, because we expected that there would be fixed costs required to clean and disinfect a facility independent of herd size. For example, tilling or scraping the surface of 1 acre of land may be required to remove any FMDV remaining on the surface soil, regardless of whether 1 or 25 FMDV-infected animals grazed on that acre of land. Sensitivity analysis examined changes in overall costs associated with varying the costs for cleaning and disinfection.

Vaccination—It was estimated that vaccine would cost $0.50/dose,[19] and 1 or more teams (consisting of 8 people/team) would work together to vaccinate as many herds as possible. It was assumed that vaccination teams would include 6 **general service level (GS)**-8 government employees earning $22/h (including benefits of 20%).[20] Those people would corral and restrain animals, place a metal vaccination identification tag in an ear of each animal, and complete appropriate paperwork, including recording the vaccine lot, animal identification tag, and vaccine ear-tag serial number. Each team also would include 2 GS-12 managers or veterinarians earning $35/h[20] who would supervise the vaccination operation, administer the vaccine, and assist as needed. A government per diem of $30/d[21] and $75/d for lodging were included for each team member, and each team was expected to require an additional $200/d for travel-related expenses and cleaning and disinfectant supplies. Assuming an average herd size of 608 animals (1.36 million animals/2,238 herds), it was expected that a team could vaccinate 1 herd/8-hour work day.[b,c] Results from the epidemic simulation model used for the study reported here were based on an assumption that the efficacy of the vaccine varied from 80 to 90%.[12] It also was assumed that vaccine stockpiles included the serotype of the outbreak strain and were available for use in herd vaccination within 4 days after the initial diagnosis.

Simulation results—Results of epidemic simulations from another study[13] of FMD eradication strategies were used to estimate the effectiveness of 3 supplemental eradication strategies, in addition to and compared with the USDA-mandated baseline strategy. The baseline strategy requires slaughter of herds for which FMD was diagnosed, closure of sale yards, and initiation of a 10-km infected area and a 20-km surveillance zone around each infected herd. Strategies of ring vaccination within 1 to 5 km of an infected herd, preemptive slaughter of herds within 1 to 5 km of an infected herd, or preemptive slaughter of the 1 to 10 herds with the highest risk for exposure were considered as supplemental eradication strategies in addition to the baseline strategy. Effectiveness of a supplemental eradication strategy was measured as the difference between the estimated median number of herds that would become infected by use of the baseline strategy and the estimated median number of herds that would become infected when a supplemental eradication strategy was considered (**Appendix**).

Benefit-cost analysis—The benefit-cost analysis was based on 2 variables: net benefit and B/C. Estimates of these variables were derived by comparing supplemental eradication strategies with the baseline strategy. Additional costs of a supplemental eradication strategy included those associated with vaccination or preemptive slaughter of noninfected herds. Benefits consisted of costs, such as those associated with indemnity payments, slaughter, and cleaning and disinfection, that were not incurred for a supplemental eradication strategy as a result of fewer herds becoming infected, compared with the baseline strategy. Net benefits of a supplemental eradication strategy were calculated as the sum of the benefits minus additional costs of the supplemental eradication strategy. Positive net benefits were interpreted to indicate the supplemental strategy would be economically feasible. The B/C was calculated as the benefits divided by the additional costs of the supplemental eradication strategy. A B/C > 1.0 was interpreted to indicate the supplemental strategy was economically efficient. If a net benefit were positive or negative, its B/C is > 1.0 or < 1.0, respectively.

Sensitivity analysis—Because some of the costs used in the model were based on estimates or assumptions, a sensitivity analysis was performed to evaluate responsiveness of the results to variations in program costs. Costs for 3 variables (vaccination, indemnity, and cleaning and disinfection of nondairy herds) were examined. Costs were varied by 30% to determine whether a program with a favorable economic return would remain so when costs of that program increased or whether a program with an unfavorable economic return would change and provide a favorable economic return when costs were decreased. Break-even values were calculated for these costs to determine the value at which it would be indifferent to selection of the alternative, compared with the baseline strategy.

Results

Cost—For a typical-sized dairy that maintained 884 adult dairy cows, mean indemnity cost for cattle was estimated to be $2,607,800 (**Table 1**). Mean total indemnity cost, including reimbursement for feedstuffs and destroyed milk, was $2,644,546/herd. Mean indemnity cost for animals in nondairy herds was $99,330/herd, and mean total cost for nondairy herds, including reimbursement for feedstuffs, was $110,359/ herd (data not shown).

Total costs for slaughter of a dairy herd, animal disposal, and facility cleaning and disinfection were $60,205/herd (**Table 2**). Estimated total costs for animal slaughter and disposal and cleaning and disinfection of facilities for a nondairy herd were $18,062/herd. Mean cost of vaccination for dairy and nondairy herds (combined) was $2,960/herd.

Benefit-cost analysis—Total direct cost estimated for the mandated baseline eradication strategy for all herds with FMD identified in the simulation model was $92.4 million (**Table 3**). Total eradication cost when considering supplemental eradication strategies in addition to the baseline strategy varied from $60.7 million for a 50-km ring vaccination strategy to $551.0 million for a strategy involving preemptive slaughter of all herds within 5 km of each infected herd (**Table 4**).

On the basis of results of the benefit-cost analysis, all supplemental strategies that involved the use of vaccination would be recommended as economically feasible (net benefits > $0), whereas supplemental strategies that involved the use of preemptive slaughter would not, compared with the baseline eradication strategy. Net benefits of supplemental strategies that involved the use of vaccination ranged from $18.3 million (5-km ring vaccination) to $31.8 million (50-km ring vaccination). Net benefits of supplemental strategies involving the use of preemptive slaughter were all negative, ranging from –$4.8 million for slaughter of the herd with the highest risk of exposure for each infected herd to –$458.5 million for slaughter of all herds within 5 km of each infected herd. The B/C varied from 0.05 to 10.1. All supplemental strategies that involved the use of vaccination were considered to be economically efficient (B/C > 1.0), with B/C ranging from 5.0 to 10.1 for ring vaccination with a radius of 50 and 5 km, respectively. All supplemental strategies that involved the use of preemptive slaughter were economically inefficient. The B/C ranged from 0.05 for slaughter of all herds within 3 to 5 km of each infected herd to 0.8 for slaughter of the herd with the highest risk of exposure for each infected herd.

Table 1—Expected costs of indemnity for slaughtered animals and destroyed feedstuffs and milk for a typical drylot dairy (884 cows) infected with foot-and-mouth disease (FMD) virus (FMDV) in the region of Fresno, Kings, and Tulare counties in California

Description	Units	Estimated value per unit ($)	Total cost ($)
Livestock indemnity			
Lactating and nonlactating cows	884	2,000	1,768,000
Yearling heifers	442	1,200	530,400
Heifer calves	442	700	309,400
Subtotal	NA	NA	2,607,800
Feedstuffs and milk destroyed			
Hay (No. of tons)*	75	130	19,750
Silage (No. of tons)*	40	30	1,200
Commodities (No. of tons)*	80	100	8,000
Milk discarded (No. of cwt)†	576	14	8,064
Subtotal	NA	NA	36,764
Total	**NA**	**NA**	**2,644,546**

*To convert tons to kilograms, multiply value by 907.2. †To convert hundredweight (cwt) to kilograms, multiply value by 45.4.
NA = Not applicable.

Sensitivity analysis—Increasing the cost of herd vaccination by 30% increased additional costs for all supplemental strategies that involved the use of vaccination by the same percentage, but it decreased net benefits by 3 to 13% and mean B/C by 8 to 16% (**Table 5**). Despite the estimated increase in cost, supplemental strategies that involved the use of vaccination remained highly feasible (net benefits ranged from $15.9 to $29.8 million) and efficient (B/C ranged from 4.6 to 8.5), compared with the baseline strategy.

Decreasing the indemnity cost for all animals by 30% reduced additional costs by 31% and negative net benefits by 31 to 37% for all supplemental strategies that involved the use of preemptive slaughter (**Table 6**). However, in part because cost for the baseline eradication strategy also decreased, supplemental

Table 2—Expected costs for disposal, cleaning, and disinfection of a typical drylot dairy facility infected with FMDV in the region of Fresno, Kings, and Tulare counties in California

Item	Cleaning or disposal of materials (h)			
	Person	Equipment	Tractor or truck	Disinfection
Animal slaughter	217	0	160	0
Disposal of feedstuffs	125	0	125	0
Disposal of milk	7	0	6	0
Dairy barn	24	24	0	12
Alley ways	20	15	5	5
Feed bunks	16	12	4	6
Equipment (No. of vehicles)				
Tractors (3)	6	6	0	2
Feed trucks (2)	6	6	0	2
Other vehicles (5)	5	5	0	3
Front loader (2)	6	6	0	2
Miscellaneous*	10	10	0	4
Free-stall barn	80	60	20	20
Outside corrals				
Removal of manure	80	0	80	0
Clean under shades	48	48	0	12
Miscellaneous outside facilities				
Roads	40	5	5	7
Surrounding areas	50	20	10	10
Silage pit				
Disposal of silage	16	0	16	0
Silage area	10	5	5	10
Commodity barn				
Disposal of commodities	15	0	8	0
Commodity barn area	5	5	5	5
Hay barn				
Disposal of hay	24	10	14	0
Clean hay barn	4	4	0	4
Acidify manure lagoon	10	10	0	0
Dispose of manure	24	0	24	0
Contracted equipment used on dairy (No. of vehicles)				
Tractors (2)	4	4	0	2
Manure truck (2)	8	8	0	2
Front loader (2)	6	6	0	2
Subtotal	866	269	487	110
Cost for cleaning and disposal				
Rate ($/h)	20	15	50	50
Subtotal ($)	17,320	4,035	24,350	5,500
Management or supervision				
No. of hours	60	NA	NA	60
Rate ($/h)	75	NA	NA	75
Subtotal ($)	4,500	NA	NA	4,500
Total costs ($)	**21,820**	**4,035**	**24,350**	**10,000**

*Includes wagons used to feed calves, livestock trailers, and hay trailers.

Table 3—Total costs for slaughter, indemnity, cleaning, and disinfection for the baseline eradication strategy and supplemental strategies, assuming that 73% of infected herds were dairies and 27% were nondairy herds, as determined by use of simulation modeling[12]

Strategy	Indemnity and slaughter of infected herds ($)	Cleaning and disinfection of infected herds ($)	Total ($)
Baseline eradication	90,175,118	2,246,008	92,421,126
Radius for vaccination (km)*			
5	70,571,831	1,757,745	72,329,577
10	66,651,174	1,660,093	68,311,267
25	56,849,531	1,415,961	58,265,492
50	52,928,874	1,318,309	54,247,182
Radius for slaughter of all herds (km)*			
1	84,294,132	2,099,529	86,393,661
3	78,413,146	1,953,050	80,366,196
5	68,611,503	1,708,919	70,320,422
Slaughter of herds with highest risk for exposure (No. of herds)*†			
1	72,532,160	1,806,571	74,338,731
5	60,770,188	1,513,614	62,283,802
10	54,889,202	1,367,135	56,256,337

*Includes costs for the baseline eradication strategy and supplemental strategy. †Slaughter of herds with the first, fifth, or tenth highest risk for exposure to FMDV.

Table 4—Costs associated with a baseline eradication strategy and additional costs, net benefits and benefit- cost value (B/C) for supplemental strategies used to eradicate an outbreak of FMD within a 3-county study region in California

Strategy	Baseline cost ($)*	Additional cost ($)†	Total cost ($)	Net benefits‡ ($)	B/C§
Baseline eradication	92,421,126	NA	92,421,126	NA	NA
Radius for vaccination (km)||					
5	72,329,577	1,811,520	74,141,097	18,280,029	10.1
10	68,311,267	3,498,720	71,809,987	20,611,139	5.9
25	58,265,492	5,330,960	63,596,452	28,824,673	5.4
50	54,247,182	6,405,440	60,652,622	31,768,503	5.0
Radius for slaughter of all herds (km)||					
1	86,393,661	45,851,440	132,245,101	–39,823,975	0.10
3	80,366,196	264,041,050	344,407,246	–251,986,120	0.05
5	70,320,422	480,649,575	550,969,997	–458,548,871	0.05
Slaughter of herds with highest risk for exposure (No. of herds)||,¶					
1	74,338,731	22,925,720	97,264,451	–4,843,326	0.8
5	62,283,802	83,797,459	146,081,261	–53,660,135	0.4
10	56,256,337	140,716,487	196,972,825	–104,551,699	0.3

*Represents costs for slaughter, indemnity payments, cleaning, and disinfection. †Cost of vaccination or preemptive slaughter for the supplemental eradication strategy. ‡Net benefits were calculated by summing the costs avoided and then subtracting additional costs of a supplemental eradication strategy, compared with the baseline eradication strategy. §The B/C were calculated as the difference for costs associated with slaughter, indemnity payments, cleaning, and disinfection between the baseline strategy and each supplemental strategy (ie, costs avoided were equivalent to benefits) divided by additional costs for the supplemental strategy. ||Includes costs for the baseline eradication strategy. ¶Slaughter of herds with the first, fifth, or tenth highest risk for exposure to FMDV.

strategies that involved the use of preemptive slaughter remained inefficient, because B/C improved only 2% and remained between 0.05 and 0.8. Varying the cleaning and disinfection costs for nondairy herds by 30% had an extremely small (< 4%) effect on the economic feasibility and efficiency for the supplemental strategies that involved the use of preemptive slaughter.

Analysis to determine break-even costs revealed that costs associated with vaccination would have to increase substantially above the originally estimated cost of $2,960/herd before supplemental strategies that involved the use of vaccination would not be recommended over the baseline eradication strategy. Break-even cost for herd vaccination was $32,829 (11.1-fold increase), $20,398 (6.9-fold increase), $18,965 (6.4-fold increase), and $17,640 (6.0-fold increase) for ring vaccination programs with a radius of 5, 10, 25, and 50 km, respectively.

Table 5—Sensitivity analysis of the impacts on additional cost, net benefit, and B/C of supplemental eradication strategies that involved the use of vaccination to eradicate FMD within a 3-county study region in California

Supplemental strategy	Additional cost ($)*	Net benefits ($)†	B/C‡
Radius for vaccination (km)			
5	2,354,976	15,925,053	8.5
10	4,548,336	19,561,523	5.3
25	6,930,248	27,225,386	4.9
50	8,327,072	29,846,872	4.6

Analysis was conducted by use of a baseline vaccination cost of $2,960/herd, which was increased by 30%.
*Represents additional costs, compared with costs for baseline eradication program alone. †Net benefits were calculated by summing the costs avoided and then subtracting additional costs for a supplemental eradication strategy, compared with the baseline eradication strategy. ‡The B/Cs were calculated as the difference for costs associated with slaughter, indemnity payments, cleaning, and disinfection between the baseline strategy and each supplemental strategy (ie, costs avoided were equivalent to benefits) divided by additional costs for the supplemental strategy.

Discussion

Analysis of results of the study reported here indicates that, in conjunction with the baseline strategy, ring vaccination would be less expensive than any of the supplemental slaughter strategies for eradicating FMD. The B/C of 10.1 for ring vaccination with a 5-km radius and 5.0 for ring vaccination with a 50-km radius were considerably better than those for supplemental strategies considered here that did not involve the use of vaccination, partly because of the relatively low cost to vaccinate herds, compared with the overall cost of the eradication program (Table 4). For example, the expected cost to vaccinate all herds within a specified radius of an infected herd ranged from $1.8 million (5-km radius) to $6.4 million (50-km radius), which represented only 2.4% ($1,811,520/$74,253,577) to 10.6% ($6,405,440/$60,652,622) of the direct cost for eradication. Alternative supplemental strategies that involved the use of preemptive slaughter of the highest-risk herds, however, were considerably more expensive because of the high indemnity value for dairy herds. At a cost of $2.6 million/herd, the total cost of $5.2 million to slaughter all cattle at only 2 average-sized dairy herds was almost as much as the $6.6 million it would cost to vaccinate all of the herds in the study region ($2,960/herd × 2,238 herds; Table 1).

Numerous factors related to production, storage, use, and efficacy of FMD vaccines should be examined before considering vaccination as a possible eradication strategy. For each ring vaccination strategy evaluated here, at least a 7-day delay in administering vaccine was assumed because of time required to identify the specific FMDV serotype, prepare the vaccine, and deliver it to the region.[12] Herds were assumed to have been vaccinated on the same day they were identified as candidates for vaccination. Although it was assumed that there would be sufficient human and financial resources available to rapidly implement such a herd vaccination campaign, this may be overly optimistic.

Table 6—Sensitivity analysis of the impacts on additional cost, net benefit, and B/C of supplemental eradication strategies that involved the use of slaughter of all herds within a specified radius and preemptive slaughter of herds with the highest risk for exposure to FMDV risks to eradicate an outbreak of FMD within a 3-county study region in California

	30% Decrease in animal indemnity payments			30% Decrease in costs to clean and disinfect a nondairy facility		
Strategy	Additional costs($)*	Net benefits ($)†	B/C‡	Additional costs ($)*	Net benefits ($)†	B/C‡
Radius for slaughter of all herds (km)§						
1	31,600,015	–27,355,618	0.10	45,617,937	–39,594,861	0.10
3	181,972,500	–173,483,706	0.05	262,696,396	–250,650,245	0.05
5	331,255,329	–315,692,541	0.05	478,201,823	–456,117,212	0.05
Slaughter of herds with highest risk of exposure (No. of herds)§, ||						
1	15,800,007	–3,066,817	0.8	22,095,597	–4,106,821	0.8
5	57,751,751	–36,529,767	0.4	80,763,216	–50,781,924	0.4
10	96,979,356	–71,512,975	0.3	135,621,250	–99,643,699	0.3

*Additional costs are those associated with a supplemental eradication strategy, compared with costs for the baseline eradication program alone. †Net benefits were calculated by summing the costs avoided and then subtracting additional costs for a supplemental eradication strategy, compared with the baseline eradication strategy. ‡The B/C was calculated as the difference for costs associated with slaughter, indemnity payments, cleaning, and disinfection between the baseline strategy and each supplemental strategy (ie, costs avoided were equivalent to benefits) divided by additional costs for the supplemental strategy. §Includes costs for the baseline eradication strategy. ||Slaughter of herds with the first, fifth, or tenth highest risk for exposure to FMDV.

In addition to potential logistical constraints to rapid administration of FMD vaccine, there are other important concerns about the use of FMD vaccines. Included in those concerns are the fact that minimal cross-protection among FMDV serotypes necessitates that the vaccine contain a strain antigenically similar, if not identical, to the outbreak strain[22]; the vaccine should lack nonstructural viral proteins (eg, 3ABC) so that diagnostic tests are able to differentiate between vaccinated and naturally infected animals[10]; transmission of FMDV is reduced, but vaccination does not always prevent replication of FMDV in the esophageal-pharyngeal tissues, indicating that the potential for aerosol transmission still exists[2,23]; FMD vaccines can have a short shelf life and must be kept cold (2 to 6°C) to prevent loss of immunogenicity[24]; the vaccine may cause allergic reactions, which may temporarily decrease growth or productivity (eg, milk production)[25]; in rare instances, administration of vaccine has caused an outbreak of FMD[26]; and use of FMD vaccine will require development of a comprehensive plan for monitoring vaccinated animals, because international animal health organizations do not classify countries that vaccinate against FMD in the same trading status as countries that do not vaccinate against FMD. Some countries vaccinated animals to slow transmission of FMDV during an outbreak and then slaughtered the vaccinated animals to regain preferred FMD-free trading status (eg, The Netherlands in 2001).[27] For the analysis considered here, assuming that slaughter of vaccinated animals was required to obtain a favorable classification for international trade, any cost savings attributed to a supplemental vaccination strategy would probably be negated because of the large number of vaccinated animals that would subsequently have to be slaughtered.

Although it was not considered here, supplemental strategies, such as preemptive slaughter, may be used to reduce the duration and number of herds infected in an epidemic, thus reducing the probability of transmission outside the study area. In this case, preemptive slaughter of herds to control FMDV transmission may offer a reasonable alternative to ring vaccination if adequate supplies of FMD vaccine were not available, if it were not logistically possible to vaccinate herds soon after the index herd was diagnosed, or if there were no reliable diagnostic tests that could distinguish vaccine-induced antibodies from infection-induced antibodies. The supplemental strategy to slaughter the herd with the highest risk for FMDV exposure for each FMD-infected herd had a lower eradication cost than the other supplemental strategies that involved slaughter of all herds within a specified radius or slaughter of the herds with the highest risk for exposure to FMDV (Table 4). Although comparisons may not be possible between the recent FMD epidemic in the United Kingdom and a potential future epidemic in this region of California because of differing herd sizes, species, and contact dynamics, the ratio of noninfected herds slaughtered (7,288) to infected herds slaughtered (2,030) of 3.6:1 for the epidemic in the United Kingdom[28] was of a similar order of magnitude to the ratio of 5:1 for the preemptive slaughter strategy, which was economically less preferred than the ratio of 1:1 for the alternative supplemental slaughter strategy considered here.

Estimates were not obtained for costs to clean and disinfect livestock facilities that predominately raise beef, sheep, swine, or goats. Results of the sensitivity analysis, however, indicated that the cost to clean and disinfect a livestock facility for a nondairy herd did not contribute substantially to the estimated overall eradication costs. Varying the cost to clean and disinfect facilities for nondairy herds by 30% changed the additional costs, net benefits, and B/C by 0.5 to 2% for all supplemental preemptive slaughter strategies, compared with the baseline eradication strategy (Table 6). Consequently, results would not have changed substantially had a potentially more accurate estimate been obtained for the cost to clean and disinfect facilities for nondairy herds.

Results from the study reported here may not be applicable to other regions of California or the United States. The impact that the unique distribution of dairies in this region of California may have on projected costs and benefits is not known. However, compared to other herd types, dairy herds are believed to have more direct and indirect contacts with other dairy herds and may have a higher probability of becoming infected.[29] Therefore, it could be presumed that different results would be expected had the analysis been performed by use of data from another geographic location with another distribution of herd types.

The study reported here considered only direct eradication costs that were expected to vary on the basis of the specific eradication strategy. The actual cost of an epidemic of FMD in California would be much higher, particularly if the epidemic spread to regions outside the study area, as would be expected for the 3-county region studied here. This is particularly evident when considering results from another study[29] for this region that indicated substantial direct and indirect contact among herds inside and outside the 3-county area. Additional direct costs would be expected to be associated with implementing an emergency response command center, initiating and enforcing infected areas and surveillance zones, routinely inspecting herds for FMD, and cleaning and disinfection of creameries, slaughter houses, and packing plants. These types of costs were not considered in the study reported here, because they would not vary substantially among eradication strategies.

Indirect costs, such as lost wages, diminished future production, and lost trade, which can vary greatly depending on the duration of an epidemic, also were not considered here. These costs could be expected to account for most of the total cost for an outbreak of FMD. For example, in addition to $4.4 billion in direct eradication costs, it was estimated[30] that there were losses of $9.2 billion to agricultural-, food-, and tourism-related industries as a result of the FMD epidemic in the United Kingdom in 2001. In another study,[14] it was estimated that the indirect cost to the United States for an outbreak of FMD in southern California would be $8.7 billion, but that estimate did not include lost revenue for the travel, tourism, and horse-racing industries, which were severely impacted during the FMD epidemic in the United Kingdom. It is unclear as to the degree of impact that an outbreak of FMD in California would have on the state's annual $75.4-billion travel and tourism industry[31] or $4-billion horse-racing industry.[32]

In the study reported here, the financial impact for 11 (baseline + 10 supplemental) eradication strategies was compared to assess the potential benefits of alternatives. A ring vaccination strategy with a radius of 5 km had the most favorable economic results, compared with the baseline slaughter eradication program, and may be an appropriate strategy to pursue, assuming an efficacious vaccine can be produced, delivered, and administered within 7 days of the first diagnosis of FMD in the region. Slaughtering 1 to 10 of the highest-risk herds for each infected herd, as opposed to slaughtering all herds located within 1 to 5 km of an infected herd, was the most effective supplemental preemptive slaughter strategy. Slaughtering the single highest-risk herd for each infected herd had a more favorable economic result, compared with slaughtering 5 or 10 of the highest-risk herds. However, none of the alternative preemptive slaughter strategies was recommended on the basis of their economic impact. Knowledge gained from this study may be useful to people faced with making decisions about implementation of a cost-effective approach to FMD eradication or to those formulating legislation or guidelines on how best to eradicate FMD should it return to the United States.

[a]Skip Lien, Panoche Livestock Co, Fresno, Calif: Personal communication, Jan 11, 2002.

[b]Dr. P. LaRussa, USDA: Animal Plant Health Inspection Service: Veterinary Services, Sacramento, Calif: Personal communication, Oct 26, 2001.

[c]Dr. D. York, California Department of Food and Agriculture, Animal Health Branch, Sacramento, Calif: Personal communication, Oct 26, 2001.

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Appendix on next page.

Appendix

Median size and duration of a modeled epidemic of foot-and-mouth disease (FMD) and number of noninfected herds affected by supplemental eradication strategies

	Median size of epidemic		Median No. of additional herds affected	Median duration of epidemic	
Strategy	**No. of herds infected**	**%***		**Days**	**%†**
Baseline eradication	46	NA	NA	71	NA
Radius for vaccination (km)					
5	36	22	612	56	21
10	34	26	1,182	51	28
25	29	37	1,801	48	32
50	27	41	2,164	47	34
Radius for slaughter of all herds (km)					
1	43	7	58	68	4
3	40	13	334	60	15
5	35	24	608	56	21
Slaughter of herds with highest risk (No. of herds)‡					
1	37	20	29	59	17
5	31	33	106	52	27
10	28	39	178	49	31

*Percentage reduction from the number of herds affected for the baseline eradication strategy. †Percentage reduction for the epidemic duration, compared with the duration for the baseline eradication strategy. ‡Slaughter of herds with the first, fifth, or tenth highest risk for exposure to FMD virus.

NA = Not applicable.

(Adapted from Bates TW, Thurmond MC, Carpenter TE. Results of epidemic simulation modeling to evaluate strategies to control an outbreak of foot-and-mouth disease. *Am J Vet Res* 2003;64:205–210.)