Predictive Model of Mastitis Occurrence in the Dairy Cow

ABSTRACT

Mastitis occurrence within a lactation and times of mastitis onset were studied for about 1000 cows. The number of mastitis cases within a lactation was modeled through overdispersed Poisson regression with individual and herd covariants. The results emphasized the role of the herd variable. Increased production potential increased the number of cases per lactation at a rate of 1.4/10 kg. Calving month also played an important role. The incidence of mastitis was greater when calving took place in early autumn or winter, which led to an expanded housing period. The interval from calving to the first case of mastitis and the intervals between successive cases were modeled for cases occurring during lactation through random selections from fitted gamma distributions, these distributions being truncated to consider the lactation length. The results of both steps can be used to simulate mastitis occurrence in different conditions.

(Key words: dairy cow, mastitis, occurrence, predictive model)

Abbreviation key: MAR = Marcenat, ORC = Orcival, THX = Theix.

INTRODUCTION

Mastitis remains the most frequent disease of dairy cows throughout industrial countries (8). Its effects on performance have great economic consequences (4, 30, 35, 62). Dynamic simulation models that simultaneously consider the occurrence of mastitis, milk production, and their interrelationships under the influence of input variables, such as cow characteristics and feeding practices, may be a helpful tool for knowledge, prediction, and management purposes.

We developed such a model to investigate the effect of mastitis on milk production of the dairy cow (38). Because recurrent mastitis is relatively common (21, 49), successive cases of mastitis during a lactation may result in severe cumulative milk losses. Moreover, the period of occurrence is also important because the impact of mastitis is different in early lactation than in mid to late lactation (38, 41, 46, 50). Finally, in our earlier study (38), the week of mastitis onset was crucial in predicting both response pattern and milk loss in either early or mid to late lactation. Thus, predictive models that simulate both number of cases per lactation period and times of mastitis onset are required for simulating the effect of mastitis on cow performance.

Most studies (15, 20, 28) of mastitis occurrence in cows focus on the presence or absence of mastitis within a lactation without considering the number of episodes, except that of Morse et al. (49). Also, available models for incidence of mastitis cases consider mastitis at the herd level (60, 61). Although some researchers (6, 9) describe the occurrence of mastitis according to the stage of lactation, to our knowledge, very few studies attempt to model times of mastitis onset, except the study of Thysen (67), which was restricted to the interval from calving to first case of mastitis.

In this study, we built a predictive model of the number of mastitis cases per lactation period, using data from experimental farms. Such data allowed precise knowledge of cow characteristics and changes in herd management, the latter being probably more homogeneous than in observational studies conducted on private farms, a favorable condition under which to elicit the role of individual factors. We considered a set of variables related to either the cow (e.g., breed and parity) or the herd (e.g., level of risk induced by management practices). Then, we studied the...
intervals from calving to first case of mastitis and the intervals between successive cases. Results of both steps were used for prediction through a stochastic model by allowing, through random selections from probability distributions with modeled parameters, the assignment of a number of cases of mastitis and of times of mastitis onset to any cow-lactation when individual and herd covariants were known.

**MATERIALS AND METHODS**

**Available Data**

The data originated from a relational database (39) of 3851 lactations in 1179 cows managed at three experimental farms [Institut National de la Recherche Agronomique; Theix (THI), Orcival (ORC), and Marcenat (MAR)] over the last 10 to 20 yr.

Mastitis data considered here were clinical mastitis cases detected at milking by the presence of clots in the milk or detected at milking or during the dry period by inflammation of the udder. Mastitis cases were systematically treated with antibiotics that were administered topically to the udder or by systemic administration for cows with the most severe cases. Relapses caused by the same infection, which may have a great part in disease reoccurrence (52) were removed from the data, we considered only cases separated by at least 30 d within a lactation. This rule was not applied when one of two consecutive cases was a teat loss (noted in our study as mastitis). Moreover, we took into account cases observed <30 d after postpartum mastitis (d 7 of lactation), the latter having a peculiar epidemiological pattern (23).

For each case, time of mastitis onset (calendar date and week of lactation) was known, along with the cow characteristics that were chosen as covariants for modeling the number of cases of mastitis per lactation. The choice was based on a preliminary work (26) and on previous epidemiological studies devoted to mastitis occurrence (2, 6, 16, 25, 36). The characteristics were production potential [estimated from the initial production, i.e., the mean production of the 4th, 5th, and 6th d of lactation (11, 31)], calving month (6 mo from October to March; the remaining months were “other months” and were gathered to ensure sufficient numbers), breed (Montbéliarde, French-Friesian, Holstein, Montbéliarde × Holstein, and Holstein × French-Friesian), and parity (1, 2, and 3). For disease occurrence during wk 1 of lactation, initial production was estimated as by Lescourret and Coulon (38). For multiparous cows, estimation was the initial production of the previous lactation, corrected by the effect of parity from healthy consecutive lactations of our database and, for primiparous cows, that of the dam’s first lactation, when possible.

To model the number of cases of mastitis per lactation, lactations of >500 d or <180 d were excluded to reduce bias. With this last restriction, the majority of cases were taken into account because 81% of the cases recorded in the database had been completed <d 180 of lactation. Lactations were excluded when assessment of initial production was impossible. The original sample was composed of 3205 lactations achieved by 1046 cows. Of these 3205 lactations, 1046 were retained by randomly selecting one lactation per cow, according to methods of Bigras-Poulin et al. (7), to remove the clustering of lactations in cows, which was inconsistent with the independence assumption required by the statistical methods.

To model mastitis onset, only cases of mastitis before drying off were considered; the number of cases during the dry period were negligible (4% in the database). As was done previously, lactations of <180 d or >500 d were excluded. No covariant was considered here because we had no hypothesis on the effect of cow characteristics on the time of mastitis onset. As explained in later sections, several sets of intervals were studied separately. In every set, no herd effect was observed on the interval (one-way analysis of variance), so that intracluster correlation linked to herd was neglected. Several lactations per mastitic cow were retained. Among the sets previously evoked, the number of lactations per cow ranged from 1 to 1.5. Thus, we considered that the clustering of lactations in cows could be neglected. On the whole, 1056 lactations were considered.

**Construction of the Herd Variable**

Management practices, such as housing hygiene, milking practices, and drying off proce-
dures, are important risk factors for mastitis occurrence (3, 24, 34, 60). These practices were accurately known for the three experimental farms and were highly homogeneous within farms over long periods. A synthetic herd variable was constructed through a combination of herd number and period of time with homogeneity for those management practices within each combination. The variable was intended to reflect the general risk at the herd level. Two of the three farms made major changes in their facilities (ORC set up a milking parlor at the end of 1984) or teat disinfection practices (MAR added both premilking and postmilking teat disinfection at the end of 1975). Both changes by inspection were soon followed by dramatic changes in rates of mastitis (number of cases of mastitis per cow-day at risk). This inspection took into account possible confounding effects by verifying that those changes were not linked to evolution in time of individual risk factors, especially production potential. Therefore, the data were analyzed for five herd-periods: THX (Theix, 1968 to 1989), ORC 1 and ORC 2 (Orcival, 1980 to 1984 and 1985 to 1990, respectively), and MAR 1 and MAR 2 (Marceplat 1968 to 1975 and 1976 to 1989, respectively). A meaningful correspondence to these herd-periods is mean numbers of cases of mastitis per lactation. These numbers were computed after the model was fitted for the number of cases of mastitis per lactation. The predictive ability of the model allowed computation by running the model five times on a sample size of 1046 with the herd-period taking successively one of the five values for the whole sample; the other covariants were those of the original sample. Moreover, because the chosen model (a generalized linear model) performs for each factor adjustment for other factors, the computed numbers were not obscured by confounding effects.

Modeling the Number of Cases of Mastitis per Lactation

Poisson regression seemed to be a natural way to model the number of cases of mastitis per lactation. However, data did not follow a Poisson distribution, but rather were a negative binomial. In the absence of commercial software that could evaluate the likelihood of a negative binomial, Schukken et al. (59) and McDermott et al. (44), following methods of McCullagh and Nelder (43), recommended fitting such data as an overdispersed Poisson model. We adopted this strategy by including an overdispersion parameter, computed to be 1.21 using the Schukken et al. (59) procedure.

After preliminary examinations of links between numbers of cases of mastitis per lactation and potential covariants (scatplots of deciles of continuous covariants versus mean numbers of cases per lactation; chi-square tests for discrete covariants), production potential, calving month, breed, parity, and herd-period were introduced as fixed effects. The discrete covariants were coded by means of the reference group method (33); the reference group was that group with the lowest incidence risk of cases. The log-transformed lactation length was introduced as an offset variable. Selection of covariants was processed by a backward stepwise procedure using the reduction of the Akaike criterion and with the overdispersion parameter specified (10). Interactions were not included in the model because biological interpretation would have been meaningless. The global significance of the model was assessed by the likelihood ratio test (null model vs. model with covariants). The significance of the coefficients was assessed by Wald tests. Relative risks were estimated by the exponentials of parameter values (68). The goodness of fit of the model was assessed by examination of the graphed residuals (extreme points were identified through leverage values; influential points were identified through Cox distances) along with the deviance test, i.e., likelihood ratio test of the model with covariants versus the saturated model (1). Use of the deviance test has to be carefully considered because it is intended for grouped data (43) and may overestimate lack of fit in ungrouped data (68). Unfortunately, tests are lacking for this case. Predicted and observed values were compared for covariant patterns constructed by breaking down production potential, previously treated as a continuous covariant in the model, into ranges (≤17 kg, 17 to 25 kg, and >25 kg; a posteriori grouping). Because results of this work were to be used in simulation models on an individual basis (cow-lactation), numbers of cases per lactation were simulated for each lactation of the sample used here, and the obtained distribution was compared with the
observed distribution by chi-square tests at .05. The simulation was performed as follows: for each lactation, the number of cases predicted by the model (e.g., .12) was used as parameter of a probability distribution to simulate a realized number of cases (e.g., 0) through one random selection using a random number generator convenient for that distribution. One hundred such simulations (size, 1046) were performed, using as probability distributions the Poisson (parameter was the individual mean predicted by the model) or negative binomial (parameters were estimates deduced from the individual mean and variance provided by the model).

**Times of Mastitis Onset**

Times of mastitis onset were studied by considering the intervals from calving to the first case of mastitis and between successive cases. The process of mastitis occurrence was expected to be somewhat complicated. Examination of the graphed data did not allow the fitting of simple processes. To circumvent the problem, we used a simple modeling method, based upon examination of the graphed data through quantile-quantile plots with estimators based on the moments and plots of intervals by intervals of previous ranks (for example, interval between first and second case of mastitis by interval from calving to first case) and upon correlation tests. In a quantile-quantile plot, data are sorted and plotted against the corresponding quantiles of a chosen distribution, quantiles being numbers q associated to probabilities x such that P(X < q) = x. If the points in this plot are approximately straight, the assumption that the data conform the distribution is supported (5). This modeling method consisted of fitting these intervals to appropriate probability distributions separately according to the number of cases of mastitis per lactation and to the rank of the considered events. Each distribution was compared with three theoretical distributions that are currently used in studies of intervals between events—exponential, gamma, and Weibull. Maximum likelihood parameters were estimated from the data. Because results of this part of the work were intended to serve in simulation models on an individual basis (cow-lactation), some simulations were performed. The method of processing simulations can be explained for lactations with two cases of mastitis (n = 223).

We used the appropriate probability distributions fitted on the study sample for the intervals from calving to the first case (a) and between first and second cases (b). First, intervals from calving to the first case were simulated by randomly selecting 223 numbers from distribution (a). Second, intervals between first and second cases were simulated by randomly selecting 223 numbers from distribution (b). Random selections used random number generators that were convenient for distributions (a) and (b). Indeed, the distributions were truncated during the selection process to consider the lactation lengths that were those of the original sample. For each lactation, the interval from calving to first case of mastitis was truncated to lactation length. Then, the interval between first and second cases was truncated to the lactation length minus the interval from calving to first case previously simulated. Simulated and observed distributions were compared through empirical quantile-quantile plots (plots of two sorted data files interpreted as mentioned).

The statistical package used was S-PLUS®, especially the functions devoted to the generalized linear model (10).

**RESULTS**

**Number of Cases per Lactation**

Of the 1046 lactations, no mastitis occurred in 709; 1 case was observed in 231, 2 in 83, 3 in 15, and 4 in 8 lactations. Thus, 10% of lactations had ~2 cases. The reoccurrence rate (total number of cases per number of lactations with at least 1 case) was 1.41.

The stepwise procedure rejected the covariants breed and parity. The final model, which included production potential, calving month, and herd-period as covariants, was globally significant (P < .001). Each parameter value was significant except that of February for calving month (Table 1). Relative risks indicated a high role of herd-period in explaining the number of cases per lactation, in an increasing order from MAR 2 to THX relative to ORC 1 (see also Figure 1). Mean numbers of cases of mastitis per lactation corresponding to these levels, adjusted for the individual risk
factors, were predicted by the model to be .13 for ORC 1 (reference group), .38 for MAR 2, .45 for MAR 1, .48 for ORC 2, and .67 for THX. Hand computation of relative risks on

this basis gave results equal to those inferred from the model.

For calving month, the number of cases per lactation tended to decrease from October to March (Figure 1). Once adjusted for the other covariants, the maximum appeared in November, when the mean number of cases per lactation was 2.87 times that of the category “other months” (Table 1). For production potential, the number of cases per lactation increased at a rate of 1.4/10 kg (Figure 1 and Table 1).

The deviance test indicated good fit (P = .31 on 1034 residual df). Extreme points were noted, but their distribution among the number of cases was not skewed. Thirteen of 18 points that were considered as influential pertained to cows with 3 or 4 cases. However, no point was both extreme and influential.

We obtained 87 covariant patterns by combining three production potentials with the levels of the other covariants. The agreement between predicted and observed numbers among these covariants was considered to be sufficient (Figure 2; R² = .93; P < .001).

Finally, 100 random selections from Poisson distributions were performed on the samples (n = 1046), using the individual expected numbers provided by the model. For 63 of the cases, the comparison of observed and simulated distributions yielded no significant difference (P > .05). Such results were considered to be fairly convenient. Similar results were ob-

Figure 1. Mean numbers of mastitis cases within a lactation per covariant level: production potential deciles with indication of midpoints and smooth line, calving month, and herd-period. ORC = Orcival, MAR = Marce·nat, and THX = Theix. Numbers of lactations per calving month were 130 in October, 333 in November, 227 in December, 125 in January, 97 in February, 69 in March, and 65 in other months. Numbers of lactations per herd-period were 130 for ORC 1, 402 for MAR 2, 94 for MAR 1, 137 for ORC 2, and 283 for THX.

Figure 2. Comparison of observed and predicted numbers of mastitis cases among 87 covariant patterns defined by combining factor levels.
TABLE 1. Coefficients of the Poisson model for the number of cases of mastitis per lactation.

<table>
<thead>
<tr>
<th>Covariant</th>
<th>Value</th>
<th>SE</th>
<th>t Value</th>
<th>Relative risk</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production potential</td>
<td>.35</td>
<td>.09</td>
<td>3.69</td>
<td>1.42</td>
<td>1.18-1.71</td>
</tr>
<tr>
<td>Calving month</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>October</td>
<td>.78</td>
<td>.38</td>
<td>2.07</td>
<td>2.19</td>
<td>1.04-4.61</td>
</tr>
<tr>
<td>November</td>
<td>1.05</td>
<td>.36</td>
<td>2.94</td>
<td>2.87</td>
<td>1.42-5.80</td>
</tr>
<tr>
<td>December</td>
<td>.86</td>
<td>.37</td>
<td>2.35</td>
<td>2.36</td>
<td>1.15-4.83</td>
</tr>
<tr>
<td>January</td>
<td>.85</td>
<td>.38</td>
<td>2.25</td>
<td>2.35</td>
<td>1.12-4.95</td>
</tr>
<tr>
<td>February</td>
<td>.53</td>
<td>.40</td>
<td>1.34</td>
<td>1.71</td>
<td>.78-3.73</td>
</tr>
<tr>
<td>March</td>
<td>.85</td>
<td>.40</td>
<td>2.11</td>
<td>2.34</td>
<td>1.06-5.14</td>
</tr>
<tr>
<td>Herd-period</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAR 2</td>
<td>1.04</td>
<td>.27</td>
<td>3.86</td>
<td>2.84</td>
<td>1.67-4.82</td>
</tr>
<tr>
<td>MAR 1</td>
<td>1.21</td>
<td>.32</td>
<td>3.82</td>
<td>3.34</td>
<td>1.80-6.21</td>
</tr>
<tr>
<td>ORC 2</td>
<td>1.26</td>
<td>.28</td>
<td>4.43</td>
<td>3.52</td>
<td>2.02-6.14</td>
</tr>
<tr>
<td>THX</td>
<td>1.61</td>
<td>.27</td>
<td>6.00</td>
<td>4.99</td>
<td>2.96-8.44</td>
</tr>
</tbody>
</table>

1Confidence interval.
2Reference: "other months".
3MAR = Marcenat, ORC = Orcival, and THX = Theix; reference: ORC 1.

Times of Mastitis Onset

Of the 1056 lactations used in this part of the study, 752 had 1 case of mastitis; 223, 2 cases; 54, 3 cases; 25, 4 cases; and 2, 5 cases. Thirty percent of all cases occurred within 1 mo postcalving, and 44% occurred within 2 mo. For the 35% of lactations with 2 cases, the second case occurred within 2 mo after the first case. In the following, we considered only lactations with ≤3 cases; lactations with more cases were too few to yield meaningful results.

The six sets of intervals between events (interval from calving to first case and intervals between successive cases) are displayed in Figure 3. The shape and extent of distribution appeared to differ among the series, especially according to the rank of events (shape) and to the total number of cases (extent; here the truncation effect of production duration was obvious). Successive intervals between events were independent, either for samples with the same number of cases or for pooled samples (P > .05 in all cases but one). Thus, we studied the intervals separately. For each set of intervals, gamma distribution appeared to be the most appropriate.

Simulated data, obtained through random selections from truncated gamma distributions with maximum likelihood estimators, were in sufficient agreement with observed data (Figure 3). The general shape of distributions was adequately reproduced by the simulations, although some problems could occur, for example, at the tail for the interval between the first and second cases for lactations with two cases.

DISCUSSION

Methodology

Modeling of mastitis occurrence within a lactation for number of cases and times of mastitis onset is difficult because of the constraints of observational or experimental studies. As pointed out by Morse et al. (49), numerous data are required for studying uncommon events. The quantity of available data was very valuable for our purposes. Events should also be recorded similarly. However, procedures may vary over time. In our study, we suspected that the increasing number of cases of mastitis at ORC after 1984 were somewhat linked to improved diagnostic procedures. However, the procedures were consistent in the other situations. Definitions also varied among authors. In our study, for each mastitic cow, only cases separated by ≥30 d were considered, which lead to an esti-
mate of 1.41 for the rate of mastitis reoccurrence. Dohoo et al. (17), who found an estimate of 1.40 for mastitic cows requiring a topical treatment and 1.03 for cows requiring a general treatment, considered all cases separated by ≥7 d. McMillan et al. (45), who considered all cases, found 1.50, a rate close to those estimated Bigras-Poulin et al. (7), who considered cases separated by ≥10 d, or by Esslemont and Spincer (21).

Moreover, descriptions should be accurate. In our data, several types of mastitis were probably considered together in terms of severity, affected quarters, and infectious agents, leading to a possible intricated superposition of processes as described by Cox and

![Graphs and figures showing distributions of intervals from calving to first case or between successive cases for lactations affected by one to three episodes of mastitis.](image)

Figure 3. Observed and simulated (obtained through random selections from truncated gamma distributions) distributions of intervals from calving to first case or between successive cases for lactations affected by one to three episodes of mastitis. For horizontal axes, values are upper limits of the intervals.

Isham (12) and Cox and Lewis (13), which probably would make the study of mastitis onset difficult. However, all of these things were unknown. Such data are needed but are difficult to collect on farms. However, our study was enhanced by precise knowledge of cow characteristics, especially management practices and production potential, the latter being rarely considered in epidemiological studies.

In this study, cow effect was removed when the number of mastitis cases within a lactation were modeled, but such an effect may be important and needs to be modeled. Cow effect may refer to udder conformation (udder depth or teat length), an important risk factor of mastitis occurrence (42, 54), or of high SCC (48, 57). Morse et al. (49) computed repeatability coefficients of .13 for the total number of episodes within a lactation and .20 for the occurrence within a lactation. We performed such computations through random analysis of variance for THX (which corresponded to the highest rate) and found comparable values, .21 and .19, respectively. Although such computations are of limited value because they are not relevant to the distribution of data (Badia, 1994, personal communication), they show the value of introducing a random cow effect in the model. However, although theoretical works deal with the problem (27), to our knowledge, no commercial computer package does.

Difficulties arose in the study of times of mastitis onset because of the lack of standard convenient procedures (and of associated software) for such a complicated point process. First, the process is closely linked to milk production: calving initiates it, and drying off stops it (the peculiar cases of the dry period having been neglected here). Second, as already pointed out, the underlying process may be a multiple one. Third, methods have been developed for single events (e.g., death) that occurred for some study subjects (14) or for numerous multiple events observed in a single subject (12, 13), but studies devoted to multiple events (possibly in small numbers) occurring in a large number of study subjects are more rarely encountered [see, however, (37, 55)]. Although we considered our model to be sufficient for prediction that involved only rough estimates, further research is needed to elicit the pattern of times of mastitis onset.

### Biological Aspects

In our study, no significant effect was found for parity on the number of cases of mastitis per lactation, although mastitis incidence tended to increase, but not significantly, with parity. Results on this subject are conflicting; most authors (16, 49, 53, 65, 66) found a positive effect on occurrence of clinical mastitis, but others found either no effect (19, 56, 58) or an effect only after the second lactation (47). Such discrepancies may have resulted partly from differences in culling policies with regard to mastitis, which may bias the assessment of the age effect (58). Furthermore, the results may depend on whether or not other factors were considered, especially production, which is highly correlated with parity (22, 64).

Our results indicated a positive relationship between production potential and number of mastitis cases, in agreement with results of numerous studies (2, 18, 60, 63, 69). The introduction of this measure probably accounted for the rejection by the model of the age effect. Similarly, the effect of breed, which is highly correlated with production potential, was rejected by our model, although a breed effect had been proposed in some cases (19, 40). Further research is needed to eliminate the possible confusion between the effect of production potential and that of age or breed.

In our sample, 30% of mastitis cases occurred within 1 mo postcalving, which is within the range of literature results (9, 17, 23). Cows in early lactation are more susceptible because of metabolic and hormonal imbalance after calving and probably a pronounced sensitivity of teats to infectious agents at this same time (65).

The effect of calving period on mastitis occurrence is much debated in the literature. Although most authors (9, 53, 58, 66) do not observe any effect of calving month, a study conducted in a Californian herd (47) reported higher frequencies for winter or spring calvings from the increased flow of infectious agents favored by summer climatic conditions of high temperature and humidity (29). Our results, obtained in temperate conditions, indicated that mastitis occurrence increased the earlier in autumn or winter that calving took place, leading to an expanded housing period. Under conditions of our study (tied housing,
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CONCLUSIONS

This work is a transitional step toward answering questions that are only outwardly simple. Our results can be used for simulations through three steps. First is the estimation of individual expected numbers through covariants; the range of herd risk levels in our study was sufficient for simulations, but use of another submodel to link herd risk to management practices, as did Schukken et al. (60), would be useful. Second are random selections that use these estimates to assign a number of cases of mastitis to each individual. The third step is random selections from truncated gamma distributions relevant to the number of cases to simulate intervals from calving to first case of mastitis and intervals between subsequent cases. For example, a single simulation of two herds of 100 Holstein cows, using as input variables random selections from normal and multinomial distributions for production potential and calving month, respectively, illustrates the ability of the model to contrast situations differing in management practices.

Production potential of cows, and calving periods. The model of Lescourret and Coulon (38) can then be used to estimate milk losses induced by mastitis per year (Table 2). Our model of mastitis occurrence should be tried on data collected in other situations. Indeed, such trials performed under different climatic conditions and management practices (especially milking hygiene) will allow modifications of the model to increase its predictive power.

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