Myoelectric activity in the intestines of healthy dairy cows during the recovery period after implantation of permanent electrodes

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Objective—To describe myoelectric patterns in the intestines of cows after electrode implantation.

Animals—7 lactating Simmental-Red Holstein cows.

Procedure—Cows were implanted with 7 pairs of bipolar silver electrodes (1 each in the ileum, cecum, and proximal loop of the ascending colon (PLAC) and 4 in the spiral colon). Myoelectric activity was monitored during 10 periods within the first 3 weeks after surgery. Recordings from the first 2 weeks were compared with recordings from the third week, which was considered a steady-state condition.

Results—Significant changes over time were detected for 18 of 57 variables, including 3 variables describing myoelectric activity of the ileum, 6 variables of the cecum, 6 variables of the PLAC, and 3 variables of the spiral colon. Compared with values for the steady-state condition, 16 variables differed significantly for the 14-day period after surgery (7 variables until day 11, 2 variables until day 8, 4 variables until day 5, 1 variable until day 3, and 2 variables until day 2 after electrode implantation). None of the variables had significant changes that lasted only 1 day after surgery.

Conclusions and Clinical Relevance—Significant changes were observed for several variables of myoelectric activity in all intestinal segments until as late as 11 days after electrode implantation, whereas a steady-state condition was reached 14 days after surgery. Effects of drugs, manipulations, or nutrition regimens on myoelectric activity of the bovine digestive tract should be evaluated no sooner than 2 weeks after electrode implantation. (*Am J Vet Res* 2004;65:797–805)

Motility patterns in the intestines of cattle are similar to those in other species, with a basic rhythm of slow waves and superimposed bursts of spiking activity organized in recurring cycles of activity (ie, **migrating myoelectric complexes [MMCs]**).[1-4] Spiking activity has been correlated with smooth muscle contractions, which allows for the use of myoelectric activity as an indicator of mechanical activity.[5-7]

During myoelectric studies in dogs, electrodes have been implanted in the wall of the intestinal segment of interest, and recording of myoelectric patterns has been initiated 5[6] to 10[8,9] days later (ie, after recovery from surgery). In cattle, recovery periods of 6,[2] 7,[1,10] 10,[3] or up to 14 days[4,11] have been allowed between electrode implantation and myoelectric recordings for physiologic evaluation of gastrointestinal tract motility. **Postoperative ileus (POI)**, a temporary impairment of propulsive motility of the gastrointestinal tract, is a life-threatening complication after abdominal and extra-abdominal surgery in humans and other animals that is characterized clinically by abdominal discomfort, bloating, and delayed defecation. Thus, POI has been studied, and it has been established that inhibition of myoelectric activity after surgery usually lasts only for periods of a few hours up to 3 days, depending on the segment of the digestive tract and the extent of the surgical procedure. However, return of myoelectric activity in the various intestinal segments does not always correlate well with the clinical endpoint of POI, defined as the first passage of feces or flatus.[12-21]

For myoelectric studies, implantation of electrodes in the intestinal wall would be expected to cause a local reaction that can influence motility patterns in the intestine and electric signals obtained and transmitted by the implanted devices. Many reports[15-19,22-28] can be found on the effects of various manipulations (eg, surgical procedures, general anesthesia, drugs, and diet) on myoelectric activity of the gastrointestinal tract. Those studies were conducted in animals with chronically implanted electrodes that were allowed to recover from surgery for electrode placement before the myoelectric recordings were started. The effects of manipulations were then evaluated with regard to baseline physiologic activity. Other studies[14,21] have evaluated myoelectric activity of the digestive tract during the immediate postoperative period, predominantly by use of retrievable electrodes in human patients undergoing surgical intervention. The purpose of those studies was to monitor the return of MMC patterns in relation to resolution of clinical POI, but results were not compared with baseline physiologic patterns. To the best of our knowledge, studies describing patterns of myoelectric activity in the bovine gastrointestinal tract after the implantation of permanent electrodes have not been published.

The objective of the study reported here was to describe myoelectric activity in the ileum, cecum, **proximal loop of the ascending colon (PLAC)**, and spiral colon of healthy dairy cows after implantation of permanent electrodes to determine the minimal recovery period necessary to reach a steady-state condition that will allow unbiased physiologic measurements.

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Thus, myoelectric recordings were performed during the immediate postoperative period until the third week after surgery to establish the interval needed for variables of myoelectric activity to reach a reliably stable state before evaluation of the effects of external factors (eg, medications or diet).

Materials and Methods

Animals—Seven nonpregnant lactating Simmental-Red Holstein crossbred cows were included in the study. Cows ranged from 3.5 to 5 years old (mean ± SD, 4.0 ± 0.6 years), and body weight ranged from 510 to 635 kg (mean, 568 ± 47.9 kg). Daily milk yield was 6.2 to 16.7 kg (mean, 11.1 ± 2.7 kg).

Cows were housed in tie stalls on straw bedding. They were examined daily, and feed intake and milk production were monitored. During recording sessions, cows were restrained in a chute in which they had access to water and hay. The project was approved by the Swiss Committee for Animal Care and Protection.

Implantation of electrodes—Materials and techniques for electrode implantation have been described in detail.[4] Briefly, cows were anesthetized in accordance with established methods and positioned in left lateral recumbency. Bipolar silver electrodes[a] (22 gauge) melted in a polyacrylamide head and connected to a specially insulated wire[b] were implanted at 7 locations of the gastrointestinal tract (ileum 40 cm orad to the ileocecal valve, cecal body midway between the ileocecal valve and apex of the cecum, PLAC 40 cm aborad from the ileocecal valve, and 4 sites on the spiral colon [the second outermost centripetal loop, immediately orad to the central flexure in the fourth outermost centripetal loop, the third outermost centrifugal loop, and the outermost centrifugal loop]). Care was taken to ensure that tips of the electrodes were located in the muscular layer of the intestinal wall. The electrodes were retained in place in the seromuscular layer by use of simple interrupted sutures of 4-0 polyglyconate.[c] To ensure recording of signals from each implantation site throughout the study despite possible failure of a particular electrode, a second bipolar electrode was implanted 10 cm aborad to the first electrode at each location.

Electrode wires penetrated the peritoneum and abdominal muscles in the craniodorsal part of the right paralumbar fossa. Wires were tunneled through the subcutaneous tissues and exited through the skin via a stab incision at the most craniodorsal part of the right flank.

Cows were administered procaine penicillin G (30,000 U/kg, IM, q 24 h for 5 days) beginning 2 hours before surgery. Each cow also was administered 3 L of fresh ruminal fluid and 20 L of saline (0.9% NaCl) solution via orogastric tube on the first day after surgery.

Recording of myoelectric activity—Myoelectric activity was recorded for evaluation of the MMC in the various parts of the intestine (ie, ileum, cecum, PLAC, and spiral colon) during the postoperative period. Recordings were obtained 10 times within the first 3 weeks after surgery, starting on the first day after electrode implantation. Activity was recorded for 8 h/d or until 2 complete **bovine colonic MMCs (bcMMCs)** were obtained from the spiral colon. Myoelectric activity was recorded in all cows on days 1, 2, and 3 after electrode implantation. Because of practical constraints, myoelectric activity was recorded on day 4 after surgery in 2 cows and on day 5 in 5 cows. Similarly, recordings were obtained from some cows on day 7 (1 cow), 8 (4 cows), or 9 (2 cows) and on day 11 (5 cows) or 12 (2 cows) after surgery. During the third week after electrode implantation, myoelectric activity was recorded on 4 days between postoperative days 14 to 18 to establish reference values during a stable period (ie, steady-state condition).

Data for each cow were classified into 10 recording periods for statistical analysis. Periods 1, 2, and 3 represented recordings obtained on days 1, 2, and 3 after surgery, respectively. Period 4 comprised data recorded on days 4 and 5 after surgery, period 5 comprised data recorded on days 7 to 9 after surgery, and period 6 comprised data recorded on days 11 and 12. Thus, data from periods 1 to 6 were recorded during the first 14 days after surgery. Periods 7 to 10 represented recordings on the 4 days during the third week after surgery (ie, during the steady-state condition on days 14 to 18).

For recording of myoelectric activity of the intestines, electrodes were connected to a signal filtering and amplification system with a 1,000-fold gain. The low-pass filter was set at 39 Hz for small intestinal signals and 33 Hz for large intestinal signals, respectively; the high-pass filter was set at 10 Hz for the ileum and 12 Hz for the large intestine. Before digitization, filtered signals were amplified 8 times. Myoelectric signals were recorded at a rate of 150 samples/s/channel. Digitized data were collected and stored on a personal computer by use of a commercial software package.[d]

Analysis of myoelectric data—Signals were analyzed visually on a computer screen at compression rates of 30, 100, 1,000, and 8,000, corresponding to the display of 3, 10, 100, and 800 minutes of the recordings, respectively. Detailed physiologic patterns of myoelectric activity of the ileocecocolic area[3] and spiral colon[4] have been reported for cattle. In the study reported here, duration of an MMC, duration of specific activity phases (phase I, quiescence; phase II, irregular spiking activity; and phase III, regular spiking activity), number of spikes per minute, spike duration, and duration of myoelectric activity (as a percentage of total recording time) for each phase were used for description of myoelectric activity in the ileum, cecum, and PLAC. Duration of each bcMMC and duration of each phase (phases I to IV; the aforementioned phases I to III and phase IV, intermittent irregular activity following phase III) of the bcMMCs were used to describe myoelectric activity of the spiral colon. For phases I and II, spike frequency, spike duration, and duration of spiking activity (as a percentage of total recording time) were determined. Spiking activity during phase III in the spiral colon is characterized by a high degree of organization, with continuous spike bursts repetitively increasing and decreasing in amplitude. Spindle is a term used to describe each complex formed by spike burst activity of increasing and decreasing amplitude. Phase III always includes several regular spindles and 1 final spindle of longer duration.[4] Number, form, and duration of spindles; propagation velocity of phase III; number of hyperactivity complexes; and duration of quiescence and hyperactivity periods of phase IV were used to describe the 2 final phases of the bcMMCs. A computerized spike-counting program[e] was used for determination of spike frequency, spike duration, and duration of myoelectric activity as a percentage of total recording time. The limit for minimal duration of spikes was set at 0.5 seconds, and maximal duration of spikes was set at 20 seconds. A spike was considered to be separate when it started at least 0.2 seconds after the preceding spike.[4] Visual analysis was used to determine all other variables. Four MMCs were analyzed for each of the 10 periods for the ileum, cecum, and PLAC, whereas only 2 bcMMCs were available for each recording period because of their longer duration.[4]

Pairs of electrodes had been implanted in each location (separated by a distance of 10 cm) to ensure recording of signals from each site throughout the study. When both electrodes remained functional until the end of the study, the mean of both values was used for that location. When 1 electrode failed during the recording period, only values from the remaining electrode were considered for the entire study for that location. Propagation velocity of a bcMMC through the spiral colon was defined as the propagation velocity of phase III because its onset can be determined most reliably among the various myoelectric components of a bcMMC.

Data were not available for complete analysis in 3 cows. At the beginning of the recordings for 1 cow, the high- and low-pass filters were set at values that were subsequently found to be suboptimal. For this reason, visual analysis was performed, but the data were not analyzed by use of the spike-counting program. For the second cow, the data had numerous artifacts attributable to a disturbance in the amplifying device. The data could be visually analyzed but were not analyzed by use of the spike-counting software to avoid biased results attributable to disturbances during data acquisition. Therefore, values for number of spikes per minute, duration of spikes, and percentage of time with spiking activity were determined for the 5 remaining cows. Despite implantation of 2 electrodes at each site, quality of signals in the cecum and the most distal site in the spiral colon of a third cow was insufficient to ensure reliable results; thus, data from these electrodes were discarded. Therefore, results reported for that cow consisted of data obtained from the ileum, PLAC, and 3 sites in the spiral colon.

Necropsy—Cows were euthanatized 28 to 101 days after electrode implantation. Gross necropsy of the abdominal cavity was performed, and the distances between electrode sites in the spiral colon were measured.

Statistical analysis—For all measures of myoelectric activity, the median value of the measurements of each recording period was calculated for each cow. Statistical analysis was performed on the daily median value. Coefficients of variation were calculated for each variable and each recording period.

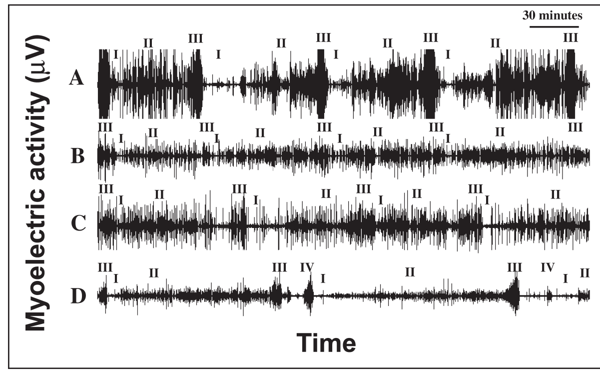


Figure 1—Representative sample of the original tracing of myoelectric activity in a cow recorded 1 day after electrode implantation revealing regular cycles of the migrating myoelectric complex (MMC) in the ileum (40 cm proximal to the ileocecal valve; A), cecal body (midway between the ileocecal valve and apex of the cecum; B), proximal loop of the ascending colon (PLAC; 40 cm aborad to the ileocecal valve; C), and spiral colon (second outermost centripetal loop; D). Amplitude of myoelectric signals (vertical axis) for each recording corresponds to 150 μV. Notice regular recurrence of phases I to III of the MMCs (phase I, quiescence; phase II, irregular spiking activity; and phase III, regular spiking activity) or I to IV of the bovine colonic MMCs (bcMMCs; phases I to III and phase IV, intermittent irregular activity following phase III).

Table 1—Results for variables of myoelectric activity in the ileum of 7 cows recorded for 10 periods during 3-weeks after surgical implantation of electrodes in the gastrointestinal tract

	< 14 days after surgery*						Steady state	
Variable	1	2	3	4	5	6	7 to 10	Pooled IQR
Duration of MMC (s)[a,b]	4,569	3,775	3,896	4,236	4,430	4,032	4,403	3,578–4,874
Phase I of MMC†								
Duration of phase I (s)[c]	599	396	1,017	606	1,212	977	742	424–1,173
Spike frequency (No. of spikes/min)	0.35	0.25	0.15	0.32	0.07	0.20	0.15	0.04–0.50
Spike duration (s)	0.81	0.75	0.96	0.81	0.92	1.12	0.81	0.40–1.11
Activity time (%)	0.58	0.45	0.23	0.60	0.13	0.46	0.28	0.08–0.95
Phase II of MMC†								
Duration of phase II (s)[d]	3,339	2,609	2,346	2,911	2,758	2,511	3,052	2,198–3,606
Spike frequency (No. of spikes/min)	5.00	3.80	3.40	3.50	3.92	4.90	5.60	2.62–6.66
Spike duration (s)	1.79	1.49	1.59	1.84	1.84	1.66	1.67	1.33–1.92
Activity time (%)	18.91	9.74	8.12	9.24	11.83	14.84	14.80	6.25–20.36
Phase III of MMC†								
Duration of phase III (s)	409	382	356	415	411	435	403	340–500
Spike frequency (No. of spikes/min)	10.02	10.27	9.40	10.10	9.42	9.00	9.85	8.70–10.70
Spike duration (s)	2.86	2.97	3.11	3.31	3.58	3.37	3.03	2.62–3.73
Activity time (%)	49.68	50.66	51.71	56.41	53.00	51.27	50.53	43.84–58.84

Results represent the median of each period within 14 days after surgery, (periods 1 to 6), the median for the 4 periods of the steady-state condition (periods 7 to 10), and the pooled interquartile range (IQR; 25th to 75th percentiles) for all periods (periods 1 to 10).

*Periods 1 to 10 represent recordings for days 1, 2, 3; 4 and 5 (2 cows on day 4 and 5 cows on day 5); 7 to 9 (1 cow on day 7, 4 cows on day 8, and 2 cows on day 9); 11 and 12 (5 cows on day 11 and 2 cows on day 12); and 4 days between days 14 and 18 after surgery, respectively. †Phases of the migrating myoelectric complexes (MMCs) are as follows: phase I, quiescence; phase II, irregular spiking activity; and phase III, regular spiking activity.

[a]Values differed significantly ($P < 0.05$) among the 4 periods of the steady-state condition. [b]Values for periods 5 and 6 each differed significantly ($P < 0.05$) from the value for the steady-state condition. [c]Values for periods 1 and 2 each differed significantly ($P < 0.05$) from the value for the steady-state condition. [d]Values for periods 1 through 6 each differed significantly ($P < 0.05$) from the value for the steady-state condition.

Table 2—Results for variables of myoelectric activity in the cecum of 7 cows recorded for 10 periods during 3-weeks after surgical implantation of electrodes in the gastrointestinal tract

	< 14 days after surgery*						Steady state	
Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7 to 10**	**Pooled IQR**
Duration of MMC (s)	4,163	3,775	4,235	4,574	3,359	4,152	4,128	3,022–4,919
Phase I of MMC†								
Duration of phase I (s)[a]	220	189	113	103	176	260	288	149–365
Spike frequency (No. of spikes/min)[b]	0.27	1.00	1.29	0.90	0.62	0.57	0.10	0.05–1.00
Spike duration (s)	0.86	0.89	1.04	0.50	0.94	0.99	0.40	0.40–1.11
Activity time (%)[b]	0.46	1.35	3.13	1.67	1.25	0.84	0.16	0.06–1.56
Phase II of MMC†								
Duration of phase II (s)	3,480	3,182	3,704	3,992	2,411	3,511	3,510	2,315–4,316
Spike frequency (No. of spikes/min)[a]	4.02	6.75	7.82	7.75	6.27	4.70	4.32	4.05–6.95
Spike duration (s)	1.66	1.74	1.72	1.38	1.65	1.92	2.06	1.50–2.16
Activity time (%)	12.16	19.01	24.28	19.35	20.80	14.64	12.05	11.25–21.11
Phase III of MMC†								
Duration of phase III (s)	297	391	371	335	351	281	294	253–417
Spike frequency (No. of spikes/min)[a]	9.47	10.40	12.25	12.60	11.22	10.75	8.10	7.87–11.81
Spike duration (s)	2.25	2.17	2.19	1.88	2.28	2.52	2.71	1.87–2.92
Activity time (%)[b]	38.63	39.29	41.67	38.31	34.17	42.11	35.50	31.64–44.26

[a]Values for periods 1 through 4 each differed significantly ($P < 0.05$) from the value for the steady-state condition. [b]Values for period 6 differed significantly ($P < 0.05$) from the value for the steady-state condition.
See Table 1 for remainder of key.

Table 3—Results for variables of myoelectric activity in the proximal loop of the ascending colon of 7 cows recorded for 10 periods during 3 weeks after surgical implantation of electrodes in the gastrointestinal tract

	< 14 days after surgery*						Steady state	
Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7 to 10**	**Pooled IQR**
Duration of MMC (s)	4,790	5,840	6,258	5,511	4,635	5,762	6,747	4,112–8,460
Phase I of MMC†								
Duration of phase I (s)	270	292	381	301	235	360	286	189–449
Spike frequency (No. of spikes/min)[a]	0.60	0.50	0.25	0.35	0.60	0.37	0.00	0.00–0.60
Spike duration (s)[a]	0.71	0.83	0.73	0.51	1.01	0.88	0.00	0.00–1.01
Activity time (%)[a]	1.08	0.65	0.51	0.54	1.40	1.13	0.00	0.00–1.20
Phase II of MMC†								
Duration of phase II (s)	3,895	5,055	5,195	4,700	4,016	5,173	6,029	3,373–7,600
Spike frequency (No. of spikes/min)[a,b]	7.00	5.55	6.50	7.25	5.70	4.60	3.90	4.00–6.50
Spike duration (s)[c]	2.18	2.30	2.35	2.38	2.92	3.25	2.93	2.24–3.23
Activity time (%)[d]	24.88	21.01	25.89	29.78	29.22	25.10	22.25	20.41–28.19
Phase III of MMC†								
Duration of phase III (s)	376	454	453	432	368	568	388	295–555
Spike frequency (No. of spikes/min)	9.00	9.40	8.30	7.70	6.92	7.30	6.45	5.75–8.84
Spike duration (s)	2.55	2.34	2.42	2.72	2.75	2.67	3.21	2.44–3.56
Activity time (%)	37.75	36.68	33.28	34.91	33.18	33.96	33.96	29.25–39.99

[a]Values for periods 1 through 6 each differed significantly ($P < 0.05$) from the value for the steady-state condition. [b]Values differed significantly ($P < 0.05$) among the 4 periods of the steady-state condition. [c]Values for periods 1 and 2 each differed significantly ($P < 0.05$) from the value for the steady-state condition. [d]Values for periods 1 through 5 each differed significantly ($P < 0.05$) from the value for the steady-state condition.
See Table 1 for remainder of key.

Time-dependent patterns of the variables were reported as box-and-whisker plots. Time patterns were analyzed by use of a multivariate ANOVA for repeated measures as well as by use of a Friedman ANOVA. In a preliminary analysis, the interaction between time and location was tested in the multivariate ANOVA for measurements obtained from the spiral colon. Because we did not detect significant differences, data for the 4 locations in the spiral colon were pooled, and the median of the measurements from the 4 locations of each recording period was calculated and used for further analyses. To determine the period after surgery on which a steady-state condition was obtained, analyses were made in a stepwise manner. The time pattern for the period defined a priori as the steady state (ie, the period that encompassed the 4

Table 4—Results for variables of myoelectric activity in the spiral colon of 7 cows recorded for 10 periods during 3-weeks period after surgical implantation of electrodes in the gastrointestinal tract

	Periods < 14 days after surgery*						Steady state	
Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7 to 10**	**Pooled IQR**
Duration of bcMMC (s)	8,988	8,018	7,648	9,361	11,013	9,689	11,229	7,779–13,467
Phase I of bcMMC								
Duration of phase I (s)[a]	368	323	304	287	386	451	635	279–775
Spike frequency (No. of spikes/min)[b]	0.65	0.37	0.40	0.70	0.42	0.60	0.62	0.20–1.15
Spike duration (s)	1.08	1.04	1.21	1.15	1.19	1.21	1.23	0.80–1.46
Activity time (%)	1.37	0.80	0.90	1.67	0.90	1.37	1.32	0.35–2.65
Phase II of bcMMC								
Duration of phase II (s)	6,470	5,924	5,946	7,275	9,150	8,154	9,466	5,921–11,294
Spike frequency (No. of spikes/min)	8.02	8.30	8.22	8.25	8.45	9.00	8.67	7.50–9.50
Spike duration (s)	2.45	2.18	2.33	2.06	2.52	2.81	2.69	2.03–2.99
Activity time (%)[c]	33.20	30.25	36.45	31.47	32.78	39.80	39.36	28.33–45.32
Phase III of bcMMC								
Duration of phase III (s)	333	317	324	340	279	320	303	274–360
Number of regular spindles	4.5	5.0	5.0	5.0	4.0	5.0	5.0	4.0–6.0
Duration of regular spindles (s)	37.32	34.50	36.50	38.75	34.03	35.87	35.60	32.14–39.41
Duration of final spindle (s)	143.75	125.00	140.00	123.00	129.00	144.50	121.50	94.75–173.00
Phase IV of bcMMC								
Duration of phase IV (s)	1,210	1,336	1,026	984	1,057	732	872	659–1,522
Number of hyperactivity periods	2.0	2.0	2.5	2.0	2.0	1.5	2.0	1.0–3.0
Duration of quiescence periods (s)	287.50	314.50	233.41	219.33	266.41	210.00	231.20	164.00–404.00
Duration of hyperactivity periods (s)	233.00	224.62	199.30	201.00	218.27	194.00	188.20	152.00–274.83
Propagation velocity (mm/s)	0.610	0.678	0.674	0.708	0.719	0.816	0.724	0.590–0.830

bcMMC = Bovine colonic MMC. Phase IV = Intermittent irregular activity following phase III.
[a]Values for periods 1 through 3 each differed significantly ($P < 0.05$) from the value for the steady-state condition. [b]Values for periods 2 through 5 each differed significantly ($P < 0.05$) from the value for the steady-state condition. [c]Values for periods 1, 2, and 4 each differed significantly ($P < 0.05$) from the value for the steady-state condition.
See Table 1 for remainder of key.

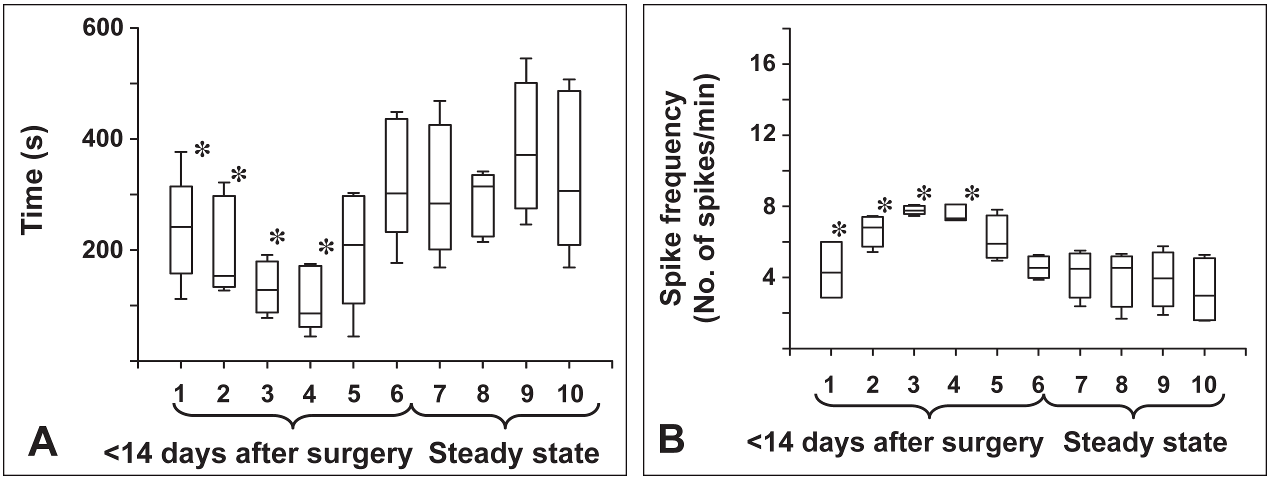
days on which recordings were obtained 14 to 18 days after surgery [periods 7 to 10]) was tested. Each consecutive step included adding data for the preceding recording period to the data pool. All statistical analyses were performed by use of a commercial software package.[f] Significance was set at $P \leq 0.05$.

Results

Surgery for electrode implantation was uneventful. All cows recovered within 1 day and passed normal feces on the day of surgery or the first day after surgery.

Tracings from all locations in the ileum and large intestine revealed regular recurrence of cyclic activity from the first day after electrode implantation in all cows (**Fig 1**). Typical features of a bcMMC in the spiral colon, such as phase IV and the organization of phase III in several regular spindles and an irregular final spindle,[4] were observed from the first recording day until the end of the study. Values for variables of myoelectric activity of the ileum, cecum, PLAC, and spiral colon were calculated (**Tables 1 to 4**). A consistent pattern of changes over time could not be identified for any variable of myoelectric activity or any location in the intestines (**Fig 2 and 3**). For example, duration of phase I in the cecum first decreased until period 4 before increasing to reach steady-state values, whereas spike frequency in phases II and III had an opposite pattern. Also, coefficients of variation did not change consistently over time for any variable of myoelectric activity and remained constant during the entire experiment, with overall median values of 0.343, 0.309, 0.302, 0.326, 0.340, and 0.307 for postoperative periods 1 to 6 and 0.318 for the steady-state condition (pooled for periods 7 to 10).

The time pattern was analyzed by use of a multivariate ANOVA and a Friedman ANOVA. Both tests yielded grossly the same conclusions; therefore, only results of the nonparametric analysis were reported. Results of statistical analyses for all steps for each location were included in Tables 1 to 4. Among the 57 variables analyzed, 18 had significant changes over time for the ileum (MMC duration, duration of phase I, and duration of phase II), cecum (phase duration, spike frequency, and activity as a percentage of time for phase I; spike frequency in phases II and III; and activity as a



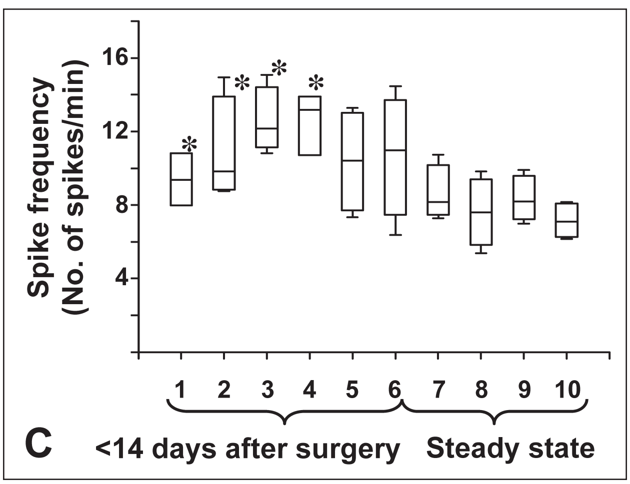


Figure 2—Box-and-whisker plots of myoelectric activity in the bovine cecum depicting fluctuations over time during the postoperative period for duration of phase I of the MMCs in the cecum (A), spike frequency during phase II of the MMCs in the cecum (B), and spike frequency during phase III of the MMCs in the cecum (C). The box-and-whisker plots represent the range of the central 50% of the values. The horizontal line within each box represents the median value. The whiskers show the range of values within a value of the upper or lower limit of the box ± (1.5 X [upper or lower limit of the box – median]). There were 10 recording periods after surgery, which corresponded to days 1, 2, 3; 4 and 5; 7 to 9; and 11 and 12; and to 4 days between days 14 and 18 after surgery, respectively. The 4 recordings during 14 to 18 days after surgery represented a steady-state condition. *Value differs significantly ($P \leq 0.05$) from values for the steady-state condition.

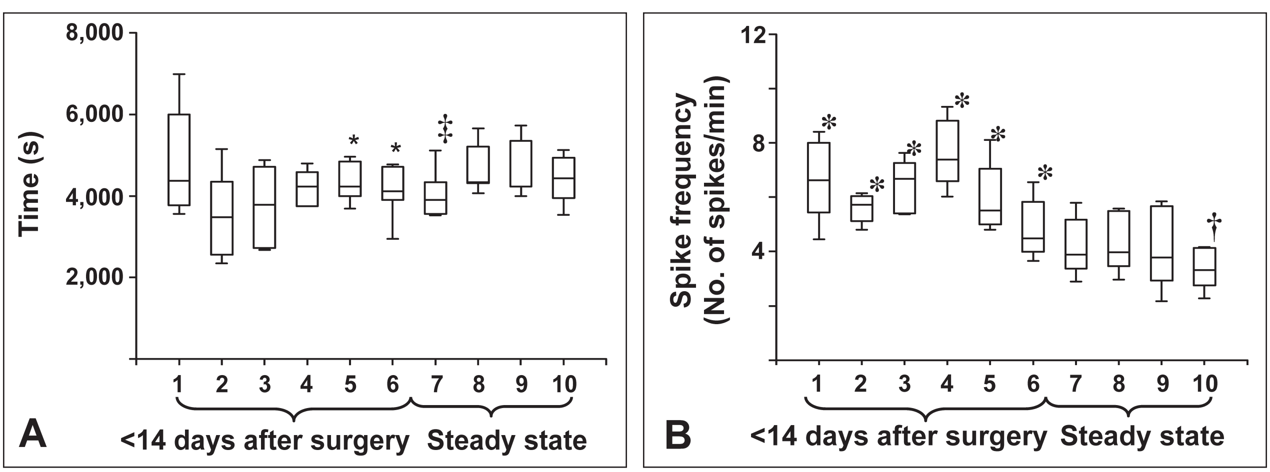


Figure 3—Box-and-whisker plots of variables of myoelectric activity in the bovine gastrointestinal tract depicting significant differences among the 4 periods within the steady-state condition (days 14 to 18 after surgery) for duration of the MMCs in the ileum (A) and spike frequency during phase 2 of the MMC 4 in the PLAC (B). For both variables, these differences were caused by especially low values for 1 of the 4 periods during the steady-state condition. ‡Especially low value on the first day of the steady-state condition (period 7). †Especially low value for the last day of the steady-state condition (period 10). *See* Figure 2 for remainder of key.

percentage of time during phase III), PLAC (spike frequency, spike duration, and activity as a percentage of time in phases I and II), and spiral colon (phase duration and spike frequency in phase I and activity as a percentage of time in phase II). Of these 18 variables with significant changes over time, 16 differed significantly from steady-state values: 7 still differed significantly until recording period 6 (ie, approx 11 days after electrode implantation), 2 differed significantly until recording period 5 (ie, approx 8 days after electrode implantation), 4 differed significantly until recording period 4 (ie, approx 5 days after electrode implantation), 1 differed significantly until recording period 3, and 2 differed significantly until recording period 2. None of the variables had significant changes limited to only 1 day after electrode implantation. For 2 variables (MMC duration in the ileum and spike frequency during phase II in the PLAC), analysis revealed significant differences within the steady-state condition. For the duration of the MMC in the ileum, the value for the first recording of the steady-state condition (period 7) was distinctly lower than for the other 3 periods (Fig 3), and Friedman analysis for periods 8 to 10 of the steady-state condition yielded a value of $P = 0.867$. Without the value for period 7, significant differences also disappeared for recording periods 6 and 5 ($P = 0.297$ and $P = 0.321$, respectively). For spike frequency during phase II of the MMC in the PLAC, a lower value was recorded the last day of the steady-state condition (period 10) than during the 3 preceding recording periods, and a nonsignificant ($P = 0.165$) test result was observed after exclusion of this value from the steady-state condition. Backward Friedman analysis for the first 3 periods of the steady-state condition (periods 7 to 9) and successive addition of postoperative recording periods revealed significant differences from the steady-state condition for recording periods 1 to 5 (P values of 0.013, 0.009, 0.007, 0.005, and 0.030, respectively) but not for recording period 6 ($P = 0.103$).

Necropsy of the abdominal cavity revealed that electrode location and sequence were correct for all cows. Electrode heads and parts of the electric wires were embedded in a thick layer of fibrous tissue, but signs of active abdominal inflammation were lacking. Draining tracts had formed in the subcutaneous tissues around the silicone cannulas in all cows.

Discussion

Typically organized MMC patterns were evident in the ileum and large intestine of healthy dairy cows from the first day after implantation of permanent electrodes by use of general anesthesia. For the ileum, this is in agreement with a study[21] on POI in humans in which investigators described return of the MMC only hours after surgery and implantation of recording devices. However, only phase-III activity was recorded during a 24-hour period from permanently implanted electrodes in the small intestine of sheep after laparotomy for implantation of additional electrodes in the intestine, and typical MMC patterns were detected only 48 hours after the second implant surgery.[15] The authors of that study underlined the importance of differences among species in postoperative motility patterns. Others[12,17] have observed that return of phase-III activity after laparotomy in humans and other species often precedes restoration of complete MMC patterns. In the study reported here, all phases of the MMC were observed in all intestinal segments from the first day after surgery until the end of the study.

The observation of typically organized bcMMCs on the first day after surgery was not necessarily expected because prolonged disturbances of colonic motility have been described in several species after abdominal surgery. Even though intensity and amplitude of myoelectric activity were reduced after surgery, phase-III activity was recorded in the ileum of 6 of 8 horses as early as 2 hours after surgical procedures that included experimental induction of POI (through rubbing of the small intestines with dry gauze sponges and exposure to air) and electrode implantation, and phase-III activity was recorded in all horses the day after surgery. However, myoelectric activity was virtually nondetectable in the cecum on the day of surgery and reduced the day after surgery, whereas colonic MMC was only observed in 2 of these 8 horses immediately after surgery and during the first day after surgery.[20] Similar observations have been reported in humans[14,21,29] and monkeys[13,19]; in those studies, motility of the small intestine returned within hours after surgery, but motility of the colon did not return until several (2 to 5) days after surgery.

In the study reported here, significant differences for variables of myoelectric activity between the postoperative recovery period and steady-state condition were most numerous and distinct in the cecum and PLAC, whereas there were few in the ileum and spiral colon. The paucity of significant differences for the ileum is compatible with the rapid resolution of POI in the small intestine in other species. Myoelectric activity of the spiral colon has been described in detail, and it is typical that every phase III of more proximal segments of the intestine does not get propagated to the spiral colon, resulting in longer-lasting activity cycles in the spiral colon corresponding to a mean of 2.58 and 1.78 MMC in the ileum and PLAC, respectively.[4] Therefore, 4 MMCs/d were recorded and analyzed for the ileum, cecum, and PLAC, whereas only 2 bcMMCs/d could be recorded. The resulting reduction in the available data pool for the spiral colon, in comparison with more proximal locations, may have prevented us from detecting significant differences over time. Results from 4 locations in the spiral colon were pooled for analysis, which provided more stable data; however, it did not increase the data pool available for statistical comparisons. Furthermore, a large degree of variability is a physiologic characteristic for the myoelectric activity of the spiral colon in cattle,[4] which possibly prevented the emergence of significant differences for variables recorded from that intestinal segment.

In monkeys, the time of first defecation after abdominal surgery correlates with the return of colonic motility.[13] This is in accordance with the fact that defecation was observed in all our cows on the day of surgery or the next morning, and bcMMC patterns were evident from the onset of myoelectric recording on the first day after electrode implantation.

Surgery for electrode implantation was performed under general anesthesia to prevent movements of the cows that may have interfered with ideal placement and fixation of the electrodes to the intestinal wall. In dogs, sheep, and monkeys, general anesthesia does not affect myoelectric activity of the digestive tract.[13,15,25] In horses, 3 protocols for general anesthesia caused only transient reductions in myoelectric activity of the ileum and large intestine, and motility patterns had returned to normal 9 hours after recovery from anesthesia achieved by use of all protocols.[24] Because recording of myoelectric activity was initiated on the day after electrode implantation in the study reported here, possible effects of anesthesia of short duration (lasting only a few hours) may have already resolved at the time of first measurements that were obtained 15 to 20 hours after the end of anesthesia.

Many investigators have analyzed motility patterns in the digestive tract of several species, especially humans, immediately after surgery to elucidate mechanisms of POI.[12,14,21,29] The objective of our study was to determine the minimal recovery period necessary after electrode implantation prior to conducting physiologic studies of myoelectric activity in the intestines of cows. Therefore, recordings were not initiated immediately after surgery; instead, they were begun the morning after surgery and continued for 3 consecutive weeks to determine the time point at which a steady-state condition was reached.

Because most physiologic evaluations of myoelectric activity have been performed 5 days to 2 weeks after electrode implantation,[1-4,6,8-11] we assumed that a steady-state condition would be reached after a recovery period of 2 weeks and arbitrarily considered the measurements made during the third week after surgery (periods 7 to 10) as the steady-state condition. The accuracy of this assumption was tested statistically and revealed that no significant differences were detected among variables for the 4 recordings of that period, except for 2 variables (duration of the MMC in the ileum and spike frequency during MMC phase II in the PLAC). For both of those variables, the value for 1 of the 4 recording periods was distinctly lower than values for the other 3 recording periods (Fig 3). In the case of duration of the MMC in the ileum, the value for the first recording day of the steady-state condition (period 7) was lower than values of the 3 subsequent recording periods, and significant differences were no longer evident for this variable after exclusion of the data for period 7. The fact that this lower value was observed on the first day of the steady-state condition may indicate that a stable amount of myoelectric activity had not yet been achieved 14 days after electrode implantation but was achieved on day 15. However, because a significant difference was observed only for the overall duration of the MMC but not for any of the single phases (I to III) of the complex, the statistical result may not necessarily reflect a biologically relevant difference. For spike frequency during phase II of the MMC in the PLAC, the value for the last recording period (period 10) of the steady-state condition was lower than values for periods 7 to 9. Similar to the situation for the duration of the MMC in the ileum, significant differences were not evident among the other 3 recording periods of the steady-state condition after exclusion of data for period 10. Because 3 recording periods during the steady-state condition preceded the period with a lower value, it is unlikely that the significant difference observed during the steady-state condition indicated that a stable degree of myoelectric activity had not been reached at that time.

Furthermore, we analyzed 57 variables by use of significance set at $P \leq 0.05$, meaning that 5% (ie, 1 of 20) of tests would have significant differences attributable to chance alone. Values of $P < 0.05$ for 2 of 57 variables is within the range of expected type-I statistical error. For spike frequency during phase II of the MMC in the PLAC, repetition of the backward analysis without values for period 10 did not markedly influence the results because differences over time remained significant until period 5 (whereas they were significant until period 6 when data for period 10 were included), thus indicating that a steady-state condition was not achieved for this variable for at least 8 days (instead of 11 days) after electrode implantation. Because we found significant differences for several other variables up to 11 days after surgery, this did not influence our overall conclusions for the study.

We could not identify an overall pattern (eg, decreased activity at first recording, followed by a phase of hyperactivity before establishment of a stable amount of activity) for variables of myoelectric activity in the intestines after electrode implantation. For most variables that had significant variations over time, these differences were evident from the beginning of the recordings and disappeared between days 2 and 11 after surgery, which is congruent with time-limited and waning effects of surgery and electrode implantation in the intestinal wall. In addition to a few significant differences in the duration of phases I and II of the MMCs in the ileum, cecum, and spiral colon, most significant differences over time were observed for variables describing the intensity of spiking activity (ie, spike frequency, spike duration, and percentage of time with spiking activity), such as for phase I of the MMCs in the PLAC, which had an extremely low amount of spiking activity during the steady-state condition. We did not detect differences over time for variables known to have little intra- and interindividual variations, such as the variables used to describe phase III of the bcMMCs.[4]

Following intra-abdominal surgery in humans, there is a reduction in propagation velocity of phase III in the small intestine for up to 6 days.[12] In sheep with permanently implanted electrodes, handling of the gastrointestinal tract and implantation of additional electrodes inhibits myoelectric activity of the jejunum and ileum for 48 hours, and propagation velocity of phase III is reduced for 3 days.[15] In the study reported here, we did not detect significant differences over time for the propagation velocity of phase III in the spiral colon. This may have been attributable to the large physiologic variability for variables of myoelectric activity in the bovine spiral colon[4] or to the limited number of bcMMCs recorded each day, as previously discussed. Alternatively, the bovine spiral colon may be less sensitive to manipulations than the small intestine in other species, and propagation velocity of phase III of the bcMMCs may have remained unaffected by the implantation of electrodes.

It has been established that serosal surfaces in cattle respond to irritations such as manipulations, contamination, or foreign material by generating large quantities of protein-rich fluid and forming fibrin to wall off lesions.[30] Necropsy of the cows from the study reported here (28 to 101 days after surgery) revealed that electrode heads were embedded in a thick layer of fibrous tissue, but there were no signs of active inflammation in the abdominal cavity. After resolution of the slight amount of local inflammation created by manipulation of the intestines during surgery and attributable to the implants (none of the cows had clinical signs of peritonitis), this fibrous tissue probably contributed to stabilization and protection of the electrodes during the remainder of the study.

Larger variability for the variables that describe myoelectric activity of the intestines during the first days after electrode implantation as a result of postoperative abdominal inflammation and reaction to the implants would not have been unexpected. However, this hypothesis could not be confirmed because coefficients of variation remained constant throughout the entire study period.

This study was conducted with a relatively small number of cattle. Therefore, we believe that the significant changes observed for several variables of myoelectric activity in all intestinal segments until 8 to 11 days after electrode implantation truly reflected the fact that a steady-state condition is achieved later than this time (ie, ≥ 14 days after surgery). Thus, we conclude that physiologic studies on the effects of drugs, manipulations, or nutrition regimens on myoelectric activity of the digestive tract in cattle should be performed no sooner than 2 weeks after electrode implantation to avoid bias attributable to long-lasting effects from insertion of recording devices.

[a]Round sterling-silver wire, TB Hagstotz and Sons Inc, Philadelphia, Pa.
[b]LITCT-Kabel, Firma Firag, Ebmatingen, Switzerland.
[c]Maxon, Tüscher AG, Berne, Switzerland.
[d]Windaq, Dataq Instruments Inc, Akron, Ohio.
[e]ESR, Oberli Engineering GmbH, Hasle-Rüegsau, Berne, Switzerland.
[f]SYSTAT 10.0 for Windows, SPSS Inc, Chicago, Ill.

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