Human colonic smooth muscle electrical activity during and after recovery from postoperative ileus

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Condon, Robert E., Verne E. Cowles, Alvaro A. B. Ferraz, Senol Carilli, Mark E. Carlson, Kirk Ludwig, Ercument Tekin, Kenan Ulualp, Fikret Ezberci, Yutaka Shoji, Philip Isherwood, Constantine T. Frantzides, and William J. Schulte. Human colonic smooth muscle electrical activity during and after recovery from postoperative ileus. *Am. J. Physiol.* 269 (*Gastrointest. Liver Physiol.* 32): G408–G417, 1995.—Colon smooth muscle electrical control (ECA) and response activities (ERA) were recorded for up to 4 wk postoperatively for 48 patients after major abdominal operations. Bipolar electrodes were implanted into right and left colon circular muscle and exteriorized through the flanks, and signals were tape recorded for 2–24 h daily beginning on the 1st postoperative day. A computer program was used for data reduction and analysis. Recorded signals were digitized and filtered. The ECA frequency components were identified by fast Fourier transformation, and their relative tenancy in low, mid, and high frequency ranges was determined. Short and long ERA burst duration and frequency and number and velocity of propagating long ERA bursts were determined. ECA was omnipresent and exhibited a downshift of the dominant frequency from the mid to the low range as recovery from postoperative ileus progressed. Concurrently, first in the right and then in the left colon, the frequency of long ERA bursts increased, followed by the appearance of propagating long ERA. After the 6th postoperative day, no further significant changes in parameters of colon electrical activity occurred with time.

colon; myoelectrical activity; electrical control activity; electrical response activity; slow wave; spike burst; computer analysis

ILEUS, A STATE OF ABNORMAL motility characterized clinically by failure of coordinated bowel propulsion, regularly follows abdominal operations in animals and humans. This state of abnormal motility clears spontaneously over time and normal bowel functions return. In a series of investigations in animals, we have established that the colon is the last portion of the bowel to recover normal myoelectrical activity after laparotomy (11, 31).

Electrical control activity (ECA; slow wave, basic electrical rhythm, pace-setter potential) is a cyclic depolarization-repolarization of intestinal smooth muscle that controls the occurrence and spatial relationship of contractions (17, 18). Electrical response activity (ERA; spike burst, action potential) is a relatively high-frequency potential superimposed on ECA and is the electrical correlate of intestinal smooth muscle contraction. We (3, 8) and others (17, 18), using combined electrode-strain gauge force tranducers placed on the same site in the colon, have previously established that there is a 1:1 correlation between electrical events in colon smooth muscle and contractions of the colon.

In humans, utilizing recordings from bipolar electrodes implanted during an abdominal operation, we have identified and previously reported some characteristics of colon electrical activity that correlate with clinical recovery from postoperative ileus (4). These characteristics are a downshift in ECA frequency in the right colon, an increase in the number of long-duration ERA bursts, and the appearance of aborally migrating ERA in both the right and the left colon.

Does the appearance of colon electrical activity with these characteristics define the normal state? To gain insight into this issue, we have examined records of colon electrical activity made in patient volunteers for up to 4 wk postoperatively using a computerized analysis program and step-wise retrograde analysis of variance. We have identified additional features of colon electrical activity that permit us to define normal human colon electrical activity and to determine the time in postoperative recovery from ileus that normal activity has returned.

METHODS

These studies were carried out from 1984 to 1994 in 48 patients (26 men and 22 women) between 17 and 89 years old, none of whom had diabetes mellitus and all of whom had undergone an elective major abdominal operation (Table 1). The experimental protocols were reviewed and approved by the Human Research Review Committee of the Medical College of Wisconsin. All patients gave informed consent to participate in these studies.

Observations were begun on the 1st postoperative day, recording continuously for 1–24 h daily (mean 1.8 ± 0.3 h, median 1.5 h). Patients were fasting and had not received morphine or other opiates for analgesia for at least 2 h before recordings were made to avoid induced increased phasic electrical activity (3, 9, 23). Forty-eight patients were recorded between 0900 and 1600 once daily for periods of 1 to 6 h (mean 1.6 ± 0.1 h, median 1.7 h) during 1–7 days postoperatively. Patients had recordings made daily until they requested removal of the electrodes or they were about to be discharged from the hospital.

A group of 14 patients volunteered to keep their electrodes in place for varying periods after discharge from the hospital. They returned at intervals as dictated by their requirements for clinical postoperative care and were studied as ambulatory

Table 1. *Operations performed and clinical duration ileus*

Operation	No. of Patients	Postop Day Ileus Resolved	
		Median	Range
Fundoplication	15	4	3–6
Esophagectomy	6	4	3 6
Repair diaphragm hernia	3	3	3–4
Gastric resection or hypass	4	2	2–6
Colostomy formation or closure	5	2	2 6
Left colon resection or rectopexy	5	3	2–5
Right colon resection	3	4	3–4
Pancreas resection or anastomosis	2		3–4
Exploration, biopsy	2		3–4
Hepatectomy	1		4
Cholecystectomy	1		4
Renal artery angioplasty	1		3

outpatients in our Clinical Research Center. At the time of recording on and after the 8th postoperative day, all of these patients had been at home, were reasonably active, and had been consuming a general diet without limitation. No postoperative complications were present in these patients. Before these recordings, patients had been fasting and had taken no opioids or other medications for 10–14 h. Recordings of 2- to 24-h duration were made on single days between 11 and 29 days postoperatively.

Electrodes. Electrodes were placed on the right (ascending) colon alone ($n = 5$), on the left (descending) colon alone ($n = 21$), or on both the right and left colon ($n = 22$). Electrodes were inserted through the anterior tenia into the circular muscle (20, 21). Two single-wire electrodes, spaced 2–4 mm apart, were placed at each recording site to form a bipolar pair. Three of these electrode pairs were placed 5–10 cm apart on either side of the colon; the distance between electrode pairs was recorded to permit determination of velocity. The electrodes initially were fashioned from 0.3-mm Teflon-coated stainless steel wire (PN 316SS1DT, Medwire, Mt. Vernon, NY) as previously described (4, 20, 21; $n = 34$). More recently, electrodes designed for implantation into the myocardium during open-heart operations (MyoWire M-25B, A & E Medical, Farmingdale, NJ) have been used as colon electrodes ($n = 14$). Both types of electrodes were exteriorized by needle puncture through the abdominal flank and away from the incision used to provide access for the operation. At the completion of the study, electrodes were removed by direct traction. There were no complications related to electrode placement or removal.

Recordings. The electrical signals from the colon electrodes were recorded with either a polygraph (model 7, Grass Instruments, Quincy, MA) or with a multichannel telemetry system manufactured to our specifications by Koningsburg Instruments (Pasadena, CA). The output from the polygraph or telemetry system also was recorded simultaneously on magnetic tape (model 3968A, Hewlett-Packard, San Diego, CA; model MR-40, TEAC, Montebello, CA) for computer analysis.

Sampling and filtering data. Data analysis was conducted using a computer program written by V. E. Cowles. Data obtained from 438 and 511 h of recordings from the right and left colon, respectively, have been analyzed day by day postoperatively. Some data from the earlier years of our observations, which had been analyzed visually and previously reported (4), have been reanalyzed by the computer program and are included in this report.

The tape-recorded signals were digitized at 40 samples/s into a computer file (CODAS; Data Q Instruments, Akron, OH). To demonstrate that the sampling rate of 40 Hz was adequate for ERA analysis, the power spectra of long (> 6.7 s, see below; $n = 20$) and short ($n = 20$) duration ERA bursts were determined using fast Fourier transformation (FFT) sampled at 200 Hz. The power spectra of typical long and short ERA bursts are shown in Fig. 1. Figure 2 shows a short-duration ERA burst sampled at 200 and 40 Hz.

The original file created by CODAS was divided into individual files for each electrode, which were then digitally band-pass filtered between 1 and 10 Hz for ERA and 0.02 and 0.75 Hz for ECA (Fig. 3). The filter program used 4,096 points (~1.7 min of data) of time-domain data to create frequency-domain data by FFT. For ERA, all frequency components outside of the 1- to 10-Hz band were set to zero, and inverse FFT converted the data back to the time domain and stored it in another computer file. The same processing was used for ECA, except that frequencies outside 0.02–0.75 Hz were removed. This procedure was repeated until all raw data had been filtered (Fig. 4).

Frequencies below 24 counts/min (cpm) are attenuated to varying degrees by the Grass Instruments P122 amplifier. A sine-wave test signal was used to determine the frequency response of the P122 amplifier and to permit compensation for attenuation. The frequency of the sine wave plotted against attenuation as a percentage of the actual signal was nonlinear

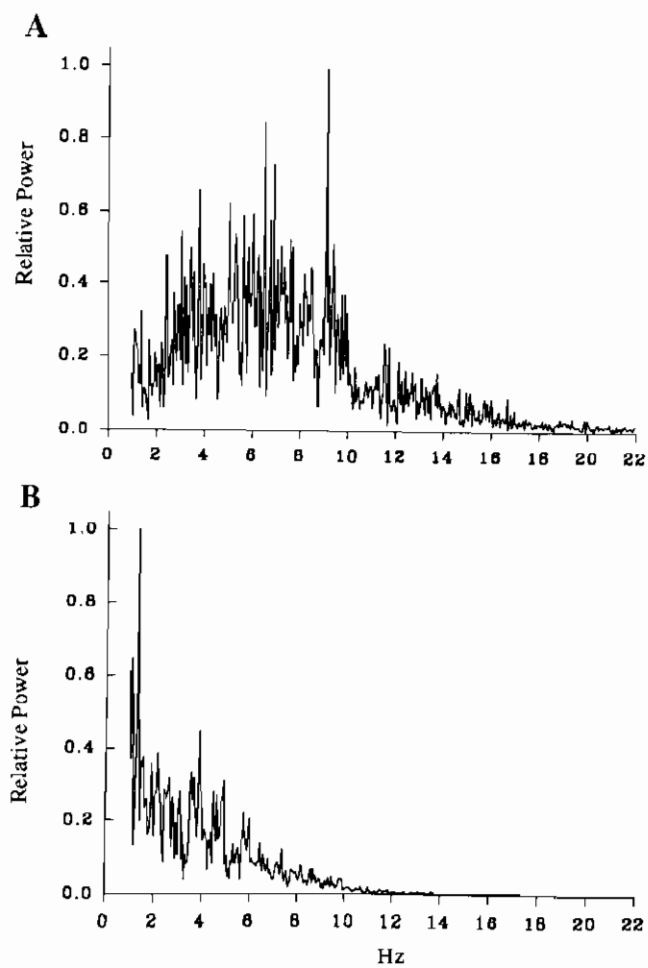

Fig. 1. Average power spectrum of 20 short (*A*) and long (*B*) electrical response activity (ERA) bursts in an unfiltered record sampled at 200 Hz. Short ERA bursts had significant peaks between 1 and 13 Hz, with the strongest peak at 9.08 Hz. Long ERA bursts had significant peaks between 1 and 6 Hz, with the strongest peak at 1.32 Hz.

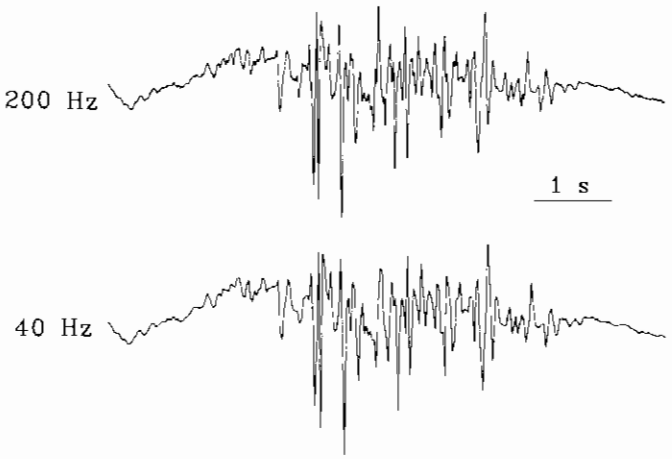

Fig. 2. Plot of a short ERA burst sampled at 200 and 40 Hz. Note that there is no difference between the amplitude and slope of the spikes, confirming that a sampling rate of 40 Hz is appropriate for fast Fourier transformation to determine power spectra.

(Fig. 5*A*). Plotting the log of cpm converted the nonlinear response to a line (Fig. 5*B*). Linear regression was then used to derive a compensation equation (20, 27). Attenuation was compensated in the filter program by dividing the frequency spectrum from the FFT by the percentage of attenuation before the inverse FFT was run, resulting in the ECA file containing the actual myoelectric signal generated by colonic smooth muscle. Compensation was not necessary with data recorded by the telemetry system, as its filters were specifically designed to accommodate the low myoelectric frequencies seen in colonic smooth muscle.

ECA analysis. The ECA frequency components in each minute of data were determined by FFT. The 2,400 samples contained in a minute of data were reduced to 120 samples by averaging every 20 samples (0.5 s). Each 60-s block of data (120 averaged samples) was then padded with zeroes to give 512 points for the FFT, yielding a resolution of 0.23 cpm. The power spectrum for each minute was determined by adding the magnitude squared of the real and imaginary parts of the FFT at each frequency component and then normalizing so that the strongest frequency has a magnitude of 10.

The program then determined whether the dominant ECA frequency, defined as that frequency with the greatest magnitude, was in a low (0–9 cpm), mid (9–15 cpm), or high (15–45 cpm) range for each minute of data, and also recorded the relative tenancy of the dominant frequency present in each range. Relative tenancy is the proportion of the total duration of record analyzed during which the dominant frequency was present in each range. The results of the ECA analysis of each minute of data are stored in a computer file for later minute-by-minute plotting of the power spectrum.

ERA analysis. The threshold for spike detection was determined by first measuring the amplitude and time of each peak in the ERA file by the method of Dumpala et al. (7) and storing these data in a temporary computer file. The program next calculated the means ± SD of the first 10 amplitude peaks in each 5-min segment of the file and used this value as a baseline. Then the program determined in each of these 5-min segments if the next peak amplitude was below the baseline threshold. If it was, then the new peak was added to the first ten and a new means ± SD for the baseline threshold in that 5-min segment was calculated. This process was then carried out repetitively for each 5-min period.

Next the program calculated the threshold for spike detection in each 5-min segment of each file. The value of the means ± 6 SD of the baseline was chosen empirically as the spike threshold, after trials of several ranges of amplitude variation, as the maximum value that could be utilized to eliminate noise without deleting true ERA bursts. The temporary peak file was then rescanned for amplitude peaks above the spike threshold. The time and amplitude of each peak above the spike threshold were recorded in another temporary computer file.

The duration of ERA bursts was then determined (Fig. 6). All spike peaks occurring within 0.7 s of each other were considered to be part of the same ERA burst. The time of 0.7 s was chosen empirically, after multiple trials of various time intervals in the range of 0.5–0.9 s, because it provided the best apparent fit to the data recorded. Further criteria were then applied to each detected ERA burst to eliminate noise. These criteria were that ERA bursts must have a duration of at least 0.6 s, an average of at least 4 spikes/s, and spikes within the ERA burst must have an average amplitude greater than the means ± 8 SD of the baseline threshold. The range of means ± 8 SD was chosen empirically after preliminary data analysis indicated that this was an appropriate value to eliminate noise. If all these criteria were met, the burst was regarded as a true ERA burst, and the start and stop time and duration of the ERA burst were determined. The program then divided the ERA bursts into two groups: those less than or equal to 6.7 s (short) or those greater than 6.7 s (long) in duration, and stored these data in another computer file.

To further reject artifact or noise, ERA bursts that started simultaneously and had the same duration in all electrodes

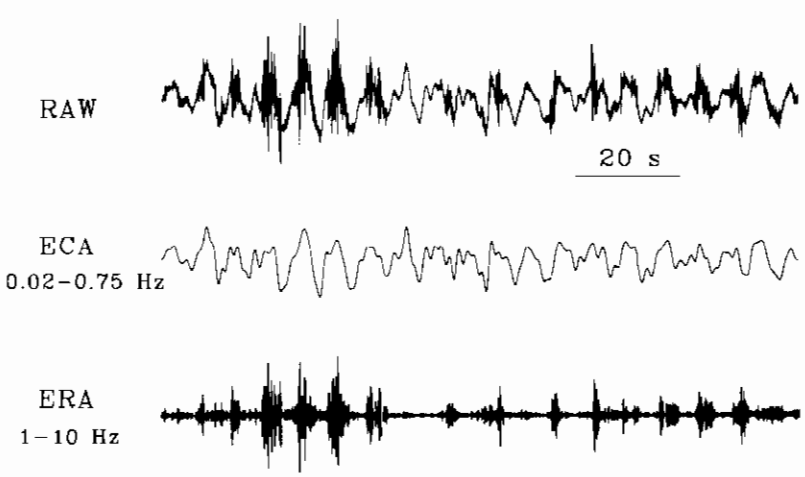

Fig. 3. Plot of raw signal sampled at 40 Hz, and same signal filtered between 0.02 and 0.75 Hz [1.2–45 counts/min (cpm)] for electrical control activities (ECA) and 1 and 10 Hz for ERA using the filter program described in text.

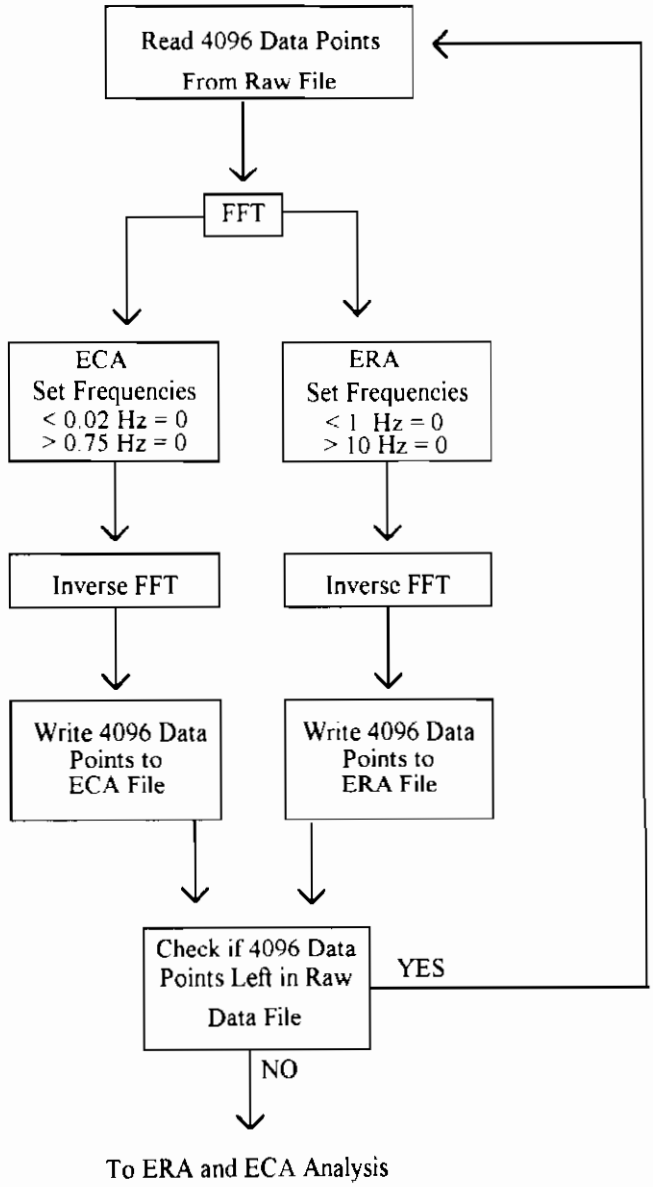

Fig. 4. Flow diagram of the filter program. FFT, fast Fourier transform.

implanted in the same segment of colon were rejected as noise. To be considered simultaneous, the start time of the ERA bursts must have been within 0.2 s and the duration within 0.5 s of each other. Although this process eliminates most artifacts, there are circumstances under which noise or artifact will not be detected (Fig. 7). To determine the extent to which this could be a problem, 1 h from each of 20 recordings analyzed by the computer program was independently analyzed visually by three experienced observers. They were asked to determine the start time and duration of each ERA burst. Each observer used their own judgment about the occurrence of an ERA burst. These data were then compared with the results of the computer analysis of the same record to determine agreement between the two methods.

Propagation of long ERA. Short ERA bursts did not propagate. To determine if a long ERA burst propagated to an adjacent electrode, a propagation window that allowed propagation velocities between 0.25 and 4.2 cm/s was used. In addition, recordings made after postoperative *day 10* were also analyzed using a window that allowed propagation velocities between 0.25 and 15 cm/s.

Propagation directed both distally (aboral) and proximally (adoral) was determined. At least three electrodes, at adjacent sites each located within 10 cm of each other, had to record signals for the program to analyze for propagation. Aboral propagation was calculated first. For each long-duration ERA burst recorded at the most proximal electrode site in either the right or left colon, the program looked at the next distal electrode for a long ERA burst that started within the propagation window. If one was detected, a propagation velocity was calculated. The program then looked for a long ERA burst with the same propagation velocity ± 10% (Fig. 8) occurring at the third electrode site. If such a burst was found, the long ERA burst at the first site was considered to propagate distally. Adoral propagation was determined in the same fashion as distal propagation, except that the analysis was begun at the most distal electrode in the colon segment. The program then calculated the total number of long ERA bursts per hour that propagated aborally and adorally and the mean velocity of their propagation.

A nonlinear method was used to estimate the day on which an electrical parameter reached a plateau or stability. The form of equation used to fit the data was a negative exponential, $y = 1B_0 \exp(-B_1x) + e$, in which y is the postoperative day, x is the parameter measured, B_0 and B_1 are coefficients,

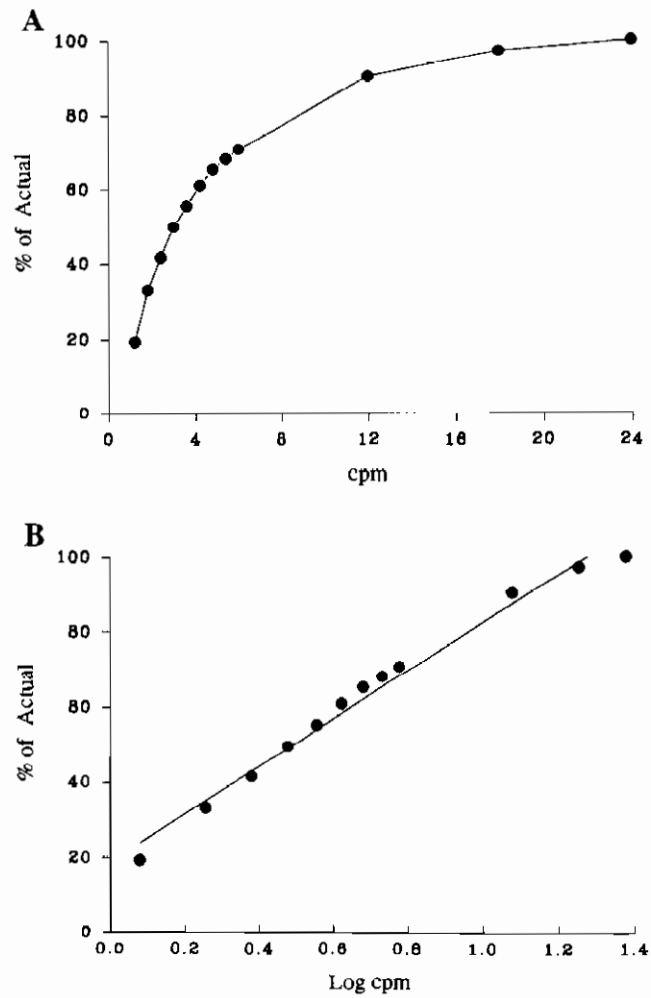

Fig. 5. Frequency response of the Grass P122 amplifier. *A*: frequencies below 24 cpm are attenuated in a nonlinear manner. *B*: log of cpm converts the nonlinear response to a line.

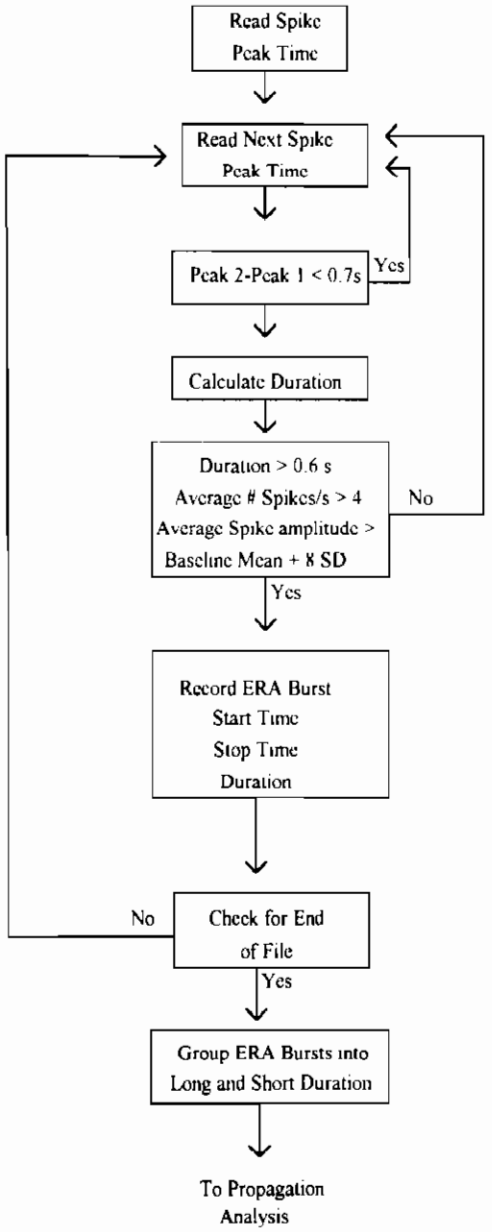

Fig. 6. Flow diagram for determining ERA duration.

and e is an error term. The day on which the electrical parameter measured returned to 90% of its plateau was estimated by the equation, $x_0 = \ln(1 - 0.9)/b_1$, in which x_0 is the day activity reached its plateau, b_1 is the estimate of B_1 from the nonlinear equation, and ln is the natural log. Stepwise retrograde analysis of variance was used to determine if there was a difference between mean ECA and ERA values from day to day. If a difference was found, the highest significant difference test was used to assess which means were different. Two statistical methods were used to estimate return of ECA, ERA, and propagating long ERA to normal. Analysis of variance on ranks was used to determine if there was a difference between postoperative days in the electrical parameters measured. If a difference was found, a Dunn's test was used to identify days that were different from the combined data of *days 11–29*. A P value of ≤ 0.05 was considered to indicate a significant difference.

RESULTS

Ileus cleared between 2 and 6 (mean 3.8 ± 0.2) days postoperatively as judged clinically by passage of flatus and initiation of defecation.

ECA. ECA always was present in recordings from both the right and left colon from the 1st postoperative day onward. Figure 9 illustrates a typical minute-by-minute plot of the ECA power spectrum for 60 min of data, whereas Table 2 records for these data the mean frequency and relative tenancy of ECA in the low-, mid-, and high-frequency ranges. Overall, in the right colon, the relative tenancy of low-frequency range ECA increased progressively each day (Table 3). On and after the 3rd postoperative day there was no further change in tenancy when compared with the late postoperative period (*days 11–29*), confirming our previous observation (4) that there is a significant downshift in the dominant ECA frequency in the right colon from the early (*days 1–2*) to later postoperative days.

A similar sequence of events occurs, although temporally somewhat later, in the left colon. During postoperative *days 1–5*, ECA frequencies in the mid-range have the greatest tenancy in the left colon. On and after the 7th postoperative day, the dominant ECA frequency in

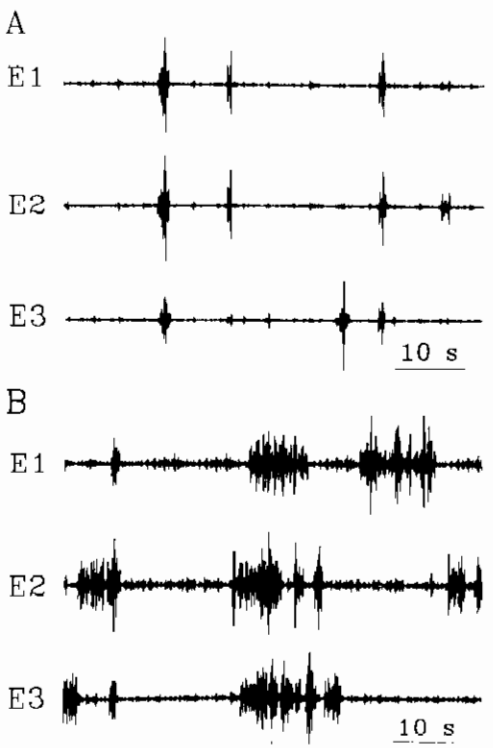

Fig. 7. Examples of circumstances under which noise or artifact will be detected as ERA bursts. *A*: the first ERA burst in *E1–E3* is rejected because of the same start time and duration. Second ERA burst in *E1* and *E2* is of great enough amplitude to be considered a true ERA burst, but ERA burst in third channel is not; program will count the 2 bursts in *E1–E2* as real ERA even though they are artifact. *B*: another situation in which artifact will be counted as a real ERA burst is if noise occurs during a true ERA burst in one of the channels, as is the case of the first ERA burst in *E2*, in which artifact occurs at the end of the burst and can be seen in *E1* and *E3*. This will result in the 3 events beginning at different times and having different durations so that the events will not meet the requirements for noise rejection.

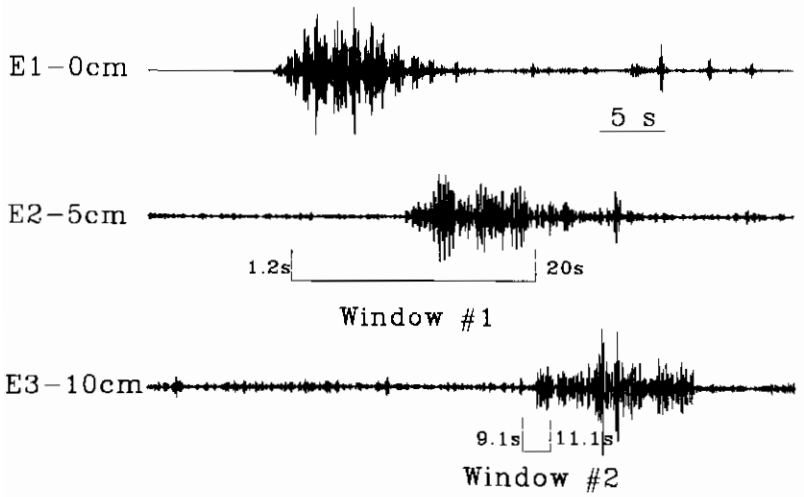

Fig. 8. Determination of long ERA burst propagation. In this example, electrodes are placed at 5-cm intervals along the colon. For ERA burst in *E2* to be recognized as propagated, it must start between 1.2 and 20 s (*window 1*) after start of ERA burst in *E1*. ERA burst in *E2* starts 10 s after ERA burst in *E1*, resulting in a propagation velocity of 0.5 cm/s. The program then calculates the propagation window for *E3*, which is ±10% of 0.5 cm/s. For a propagated burst to be accepted, ERA burst in *E3* must occur between 9.1 and 11.1 s (*window 2*) after start of ERA burst in *E2*. If this occurs, the ERA burst in *E1* is counted as a propagated ERA burst.

the left colon downshifts to the low-frequency range (Table 3). There is no difference in the tenancy of low-frequency ECA on and after the 7th postoperative day compared with the later postoperative period (*days 11–29*).

ERA. There is a bimodal distribution of ERA burst durations, with the majority of bursts being <6.5 s in duration (Fig. 10). In the comparison of visual and computer analyses, the three observers were in agreement with the computer in 84 ± 5% of cases for burst start time. For burst duration, with allowed variation of ±0.3 s, there was agreement in 69 ± 11% of cases; with variation of ±0.5 s, there was agreement in 81 ± 9%. The data for each observer are recorded in Table 4. Overall, only 0.9 ± 0.3% of all ERA bursts accepted as real by the computer program were found to be false on visual analysis, with the maximal disparity never being >5% for any 1 h of recording.

ERA in both short- and long-duration bursts was present on the 1st postoperative day. There was no difference in the number per hour of short-duration ERA bursts throughout the period of postoperative observations in the right and left colon. The mean duration of both long and short ERA bursts was not different from day to day during postoperative recovery (Table 5). There were significantly fewer long ERA bursts per hour on postoperative *days 1* and *2* in the right colon and postoperative *days 1–3* in the left colon compared with the late postoperative period (*days 11–29*). There was a significant increase in long-duration ERA frequency after postoperative *day 2* in the right colon and after postoperative *day 3* in the left colon.

Most ERA bursts observed, of both short and long duration, were shorter than the corresponding ECA cycle. ERA bursts sometimes (8% right, 6% left colon) were noted to be longer in duration than the corresponding ECA cycle. When this occurred, the dominant ECA frequency was in the high range (15–45 cpm, mean 27 ± 3 cpm) or there was a secondary frequency present in this range.

Propagation of ERA. There were no propagating long ERA bursts present during the early postoperative period (*days 1–2*). Propagating long ERA first appeared in both the right and left colon on the 3rd postoperative day (Table 6). The velocity of propagating ERA did not change over time. Analysis of recordings from postoperative *days 11–29*, utilizing a propagation window that allowed propagation velocities of 0.25–15 cm/s, produced the same results as using a window allowing velocities of 0.25–4.2 cm/s. In all of our data, no propagation velocity above 2.5 cm/s was observed.

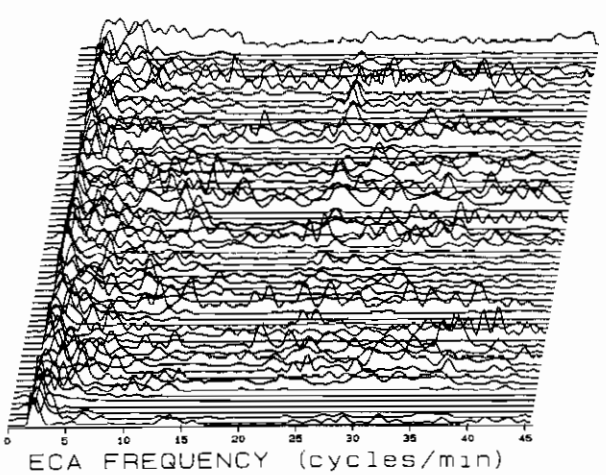

Fig. 9. Plot of 60 consecutive minutes of ECA power spectra. Each minute of data was normalized to the frequency with the greatest magnitude in that minute of data.

DISCUSSION

As patients recover from postoperative ileus, there are significant changes in the characteristics of both ECA and ERA with the passage of time. As previously reported (4), ECA is omnipresent from the 1st postoperative day in all subjects. We found the dominant ECA

Table 2. *Mean frequency and relative tenancy of dominant ECA for the power spectra plotted in Fig. 6*

Range, cpm	Mean, cpm	Tenancy, %
Low (0–9)	2.89	79
Mid (9–15)	12.46	11
High (15–45)	31.09	10

ECA, electrical control activity; cpm, counts/min.

Table 3. *Mean dominant frequency and relative tenancy of ECA*

Postop Day	n	Low		Mid		High	
		Frequency, cpm	Tenancy, %	Frequency, cpm	Tenancy, %	Frequency, cpm	Tenancy, %
		Right colon					
1	26	4.3±0.2	37±6*	11.5±0.1	61±6*	27.5±1.3	2±1
2	27	4.0±0.2	49±6*	11.2±0.2	47±6*	27.8±0.9	3±1
3	26	3.6±0.4	62±7	11.3±0.2	37±7	28.8±1.5	1±0
4	25	3.7±0.1	65±6	11.3±0.1	33±6	26.6±1.0	1±1
5	25	3.8±0.1	74±5	10.9±0.2	23±4	26.6±0.3	2±1
6	22	3.7±0.2	77±6	10.9±0.2	20±5	25.5±2.3	3±1
7	7	3.0±0.1	90±3	11.1±0.2	9±3	32.6±2.3	2±1
8	4	3.1±0.2	89±4	11.2±0.3	10±3	27.3±2.0	2±1
9	1	2.7±0.1	94±6	11.2±0.0	6±6	25.7±0.0	2±1
10	2	3.0±0.1	95±3	10.3±6.3	6±3		
11–29	10	3.5±0.2	80±4	11.1±0.2	20±4	26.6±1.3	2±1
		Left colon					
1	33	3.8±0.2	35±9*	11.1±0.2	64±9*	28.8±4.5	1±0
2	34	4.4±0.3	27±7*	11.2±0.2	66±7*	28.0±1.3	6±3
3	35	4.5±0.4	29±8*	10.9±0.3	69±8*	26.0±1.9	2±1
4	34	4.2±0.2	35±9*	11.3±0.2	63±9*	25.8±0.8	1±1
5	33	4.1±0.2	29±7*	11.2±0.2	70±8*	27.1±2.2	1±0
6	29	4.1±.2	51±9*	11.2±0.2	48±7*	27.4±3.3	1±0
7	9	3.1±0.1	63±6	11.0±0.2	34±7	28.3±4.8	3±1
8	5	3.3±0.2	67±7	11.0±0.3	30±8	27.6±2.5	2±2
9	2	3.7±0.1	63±14	10.3±0.3	36±14	25.1±4.0	1±1
10	1	3.4±0.1	88±8	10.0±0.4	14±10	22.9±0.0	1±1
11–29	12	3.3±0.2	77±4	10.9±0.2	20±4	27.1±1.2	2±1

n, no. of observations on each day. *$P \leq 0.05$ compared with *days 11–29*.

frequency in the human colon is present mainly in two ranges, 1–9 and 9–15 cpm. This observation is in agreement with previous reports (4, 20, 25, 28). Our observation that ECA cycle duration usually exceeds that of the associated ERA burst confirms that ECA controls ERA.

In both the right and left colon there was a significant shift in the relative tenancy of the dominant ECA frequency from the mid-range to the low range as postoperative recovery progressed. This could be an important permissive mechanism allowing an increase in the number of propagated long ERA bursts, since the increased time that ECA is in the 1–9 cpm range may increase the probability of ECA becoming phase locked. When ECA becomes phase locked in a segment of colon, ERA propagation can occur in the same segment (18).

There appears to be a relationship between clinical recovery from postoperative ileus and an increase in the absolute number as well as an increased propagation of long ERA bursts. Propagation of ERA was regularly present after the 3rd postoperative day in the right colon and after the 5th postoperative day in the left colon. This observation extends our observation in monkeys that the left colon is the last segment of the gastrointestinal tract to recover motility function postoperatively (11, 31).

Our data show that important changes in both ECA and ERA take place over the first 5 postoperative days in humans. The changes include a shift in the ECA frequency from the 9–15 cpm range to the 1–9 cpm range (Table 3) and an increase in the number and propagation of long ERA bursts (Tables 5 and 6). These changes coincide with clinical recovery from postoperative ileus as judged by passage of flatus, defecation, and the ability to consume a solid diet without nausea or vomiting. Once patients have recovered from postoperative ileus, there are no further significant changes in the characteristics of either ECA or ERA in the right or left colon. Therefore, recordings made on and after the 7th postoperative day represent normal human colon electrical activity.

Many studies of human colonic electrical activity have relied on visual analysis of motility recordings. Because of the complexity of colonic smooth muscle electrical activity, visual analysis may lead to observer bias in interpretation of the recorded signals (15, 17, 26, 27). In

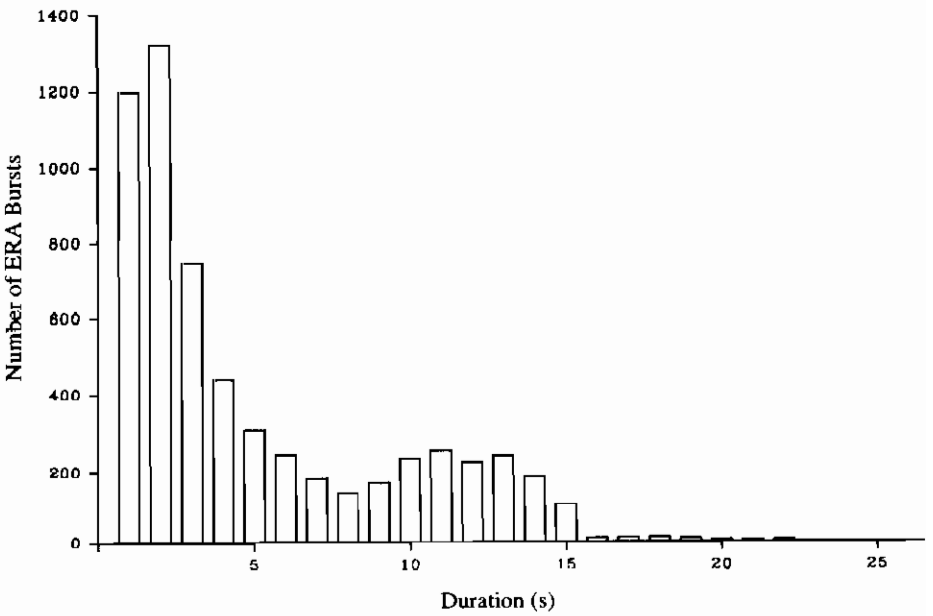

Fig. 10. Histogram of ERA burst durations from a recording made after postoperative *day 10*. There is a bimodal distribution of ERA burst durations with 1 peak around 2.5 s and a second peak between 10.5 and 13.5 s. Majority of ERA bursts are of short duration.

Table 4. *Agreement between computer and visual analyses (%)*

Observer	Start Time	Duration	
		Within ±0.3 s	Within ±0.5 s
1	91	71	83
2	74	48	64
3	87	87	95

addition, visual recognition of ECA is arduous because of the changing frequency and amplitude and the variable shape of the recorded signal over time. ERA is also difficult to quantitatively analyze visually because of the large number of bursts that may occur during the recording session. Additionally, the propagation velocity of ERA bursts may not be measured precisely; rather, if the ERA bursts appear to propagate, the observer may count them as propagated ERA. Another problem with visual analysis is the volume of data that must be analyzed. A typical recording may consist of six to eight data channels recorded for one or more control hours, followed by one or more test hours. Visual analysis of this amount of data may lead to tedium and observer fatigue error. Reducing the duration of each visual analysis session to avoid fatigue may introduce other errors because signal recognition can vary over time even with a constant observer (1).

Computer analysis of myoelectric recordings has the advantage that it is objective, and large quantities of data can be analyzed without the errors and bias that may result from visual analysis. Our first concern when developing the computer program was that we sampled the data at a high enough rate to avoid aliasing but not so fast that an inordinate amount of computer time would be used. According to the Nyquist sampling theorem, the sampling rate must be at least twice the frequency of the highest frequency in the waveform being sampled to avoid aliasing (16). Our data (Fig. 1) and that of Sarna et al. (21) showed that the major frequency peaks in an ERA burst were between 1 and 10 Hz, indicating that the 40-Hz sampling rate we used is adequate to avoid aliasing of the recorded signal. Filtering the recorded signal between 1 and 10 Hz for ERA analysis, which eliminates the lower frequency ECA components, as well as filtering between 0.02 and 0.75 Hz for ECA analysis, which eliminates ERA frequencies, are appropriate manipulations for ERA and ECA analysis (Figs. 1 and 3).

Table 5. *Number per hour and mean duration(s) of ERA bursts less and greater than 6.7 s*

Postop Day	*n*	No./h		Duration	
		Short	Long	Short	Long
		Right colon			
1	26	28 + 4	7.1 + 0.5*	2.4 + 0.2	9.2 + 0.7
2	27	37 ± 7	7.1 ± 2.3*	2.5 ± 0.2	9.8 ± 0.6
3	26	33 ± 8	16.9 ± 4.4	2.6 ± 0.2	10.3 ± 0.5
4	25	51 ± 9	16.2 ± 1.6	2.6 ± 0.2	10.6 ± 0.5
5	25	40 ± 7	15.9 ± 1.6	2.7 ± 0.2	10.5 ± 0.4
6	22	43 ± 3	18.3 ± 2.8	2.6 ± 0.2	12.2 ± 0.6
7	7	74 + 8	35.1 + 4.6	2.7 + 0.1	12.5 + 0.3
8	4	76 ± 6	24.8 ± 4.9	2.6 ± 0.1	12.1 ± 0.5
9	1	27 ± 5	21.1 ± 1.0	2.3 ± 0.1	12.0 ± 0.9
10	2	87 ± 7	39.1 ± 6.4	2.7 ± 0.1	11.8 ± 0.4
11–29	10	66 ± 13	25.2 ± 3.0	2.6 ± 0.1	11.7 ± 0.2
		Left colon			
1	33	42 ± 12	5.2 ± 1.6*	2.2 ± 0.2	10.9 ± 0.9
2	34	55 ± 10	4.5 ± 1.8*	2.1 ± 0.2	10.7 ± 0.9
3	35	49 ± 14	7.6 ± 2.6*	2.2 ± 0.2	10.2 ± 0.8
4	34	32 ± 7	13.2 ± 2.7	2.2 ± 0.2	12.3 ± 0.9
5	33	55 ± 11	16.8 ± 2.5	2.3 ± 0.2	10.6 ± 0.7
6	29	52 ± 11	15.2 ± 3.0	2.3 ± 0.2	9.9 ± 0.8
7	9	75 ± 7	26.3 ± 3.2	2.6 ± 0.1	12.1 ± 0.3
8	5	81 ± 11	20.3 ± 3.2	2.6 ± 0.1	13.1 ± 0.5
9	2	48 + 5	19.0 + 4.6	2.7 + 0.1	12.1 + 0.4
10	1	108 ± 20	40.1 ± 9.5	2.5 ± 0.1	12.4 ± 0.8
11–29	12	77 ± 8	18.6 ± 1.8	2.5 ± 0.1	12.0 ± 0.3

ERA, electrical response activity. *$P \leq 0.05$ compared with *days 11–29*.

Table 6. *Number per hour and velocity of propagation of long ERA bursts*

Postop Day	Right Colon		Left Colon	
	No.	Velocity, cm/s	No.	Velocity, cm/s
1	0*		0*	
2	0*		0*	
3	0.9 ± 0.3	0.58 ± 0.31	0.1 ± 0.0*	0.61 ± 0.51
4	1.4 ± 0.2	0.61 ± 0.40	0.3 ± 0.1	0.58 ± 0.37
5	1.6 ± 0.2	0.57 ± 0.22	0.8 ± 0.2	0.61 ± 0.22
6	1.6 ± 0.4	0.62 ± 0.21	1.3 ± 0.2	0.60 ± 0.18
7	2.5 ± 0.7	0.79 ± 0.09	2.3 ± 0.6	0.74 ± 0.07
8	1.2 ± 0.6	1.00 ± 0.27	1.7 ± 0.7	0.57 ± 0.10
9	2.6 ± 0.0	0.33 ± 0.10	1.1 ± 0.7	0.46 + 0.13
10	2.8 ± 1.7	0.61 ± 0.25	2.5 ± 1.5	0.91 ± 0.91
11–29	2.3 ± 1.0	0.93 ± 0.38	1.4 ± 0.3	0.71 ± 0.11

*$P \leq 0.05$ compared with *days 11–29*.

The low, mid, and high ECA ranges were chosen from a historical perspective as previous reports in the literature have divided ECA into similar ranges. Several investigators have reported that ECA is present in at least two ranges: 0–9 and 9–14 cpm (4, 20, 25, 28–30). Others have reported that ECA is also represented in a range from ~15 to 45 cpm (12, 13, 24, 29). This high range was also reported by Sarna et al. (21) but was referred to as the contractile electrical complex (CEC). They postulated that CEC controlled long-duration contractions in the colon. In vitro experiments have shown that when signals in the high ECA frequency range are present with superimposed ERA, contractions of the same frequency summate to form a long-duration contraction (12, 13).

As illustrated in Fig. 9, multiple ECA frequencies are present in each minute of data. To reduce the data to manageable proportions, only frequencies with the greatest relative power are used to determine the mean dominant frequency and relative tenancy. The origin of frequencies with lower power is not known but could represent a smaller population of smooth muscle cells cycling at a frequency different from the majority of cells (12, 13, 24). Smith et al. (24) reported that there are two pacemaker regions in the dog colon. One located near the submucosal border has a frequency of 4–6 cpm; the other in the boundary between circular and longitudinal

muscle has a frequency around 22 cpm. These two pacemaker activities are thought to summate and may be responsible for the variable ECA waveform recorded by extracellular electrodes in vivo.

The cutoff for short-duration ERA bursts was set at 6.7 s because this would be the maximum duration of an ERA burst if it were controlled by ECA cycling at 9 cpm or higher (60 s/9 cpm = 6.7 s/cycle) (18). Dapoigny et al. (6) and Latour et al. (14) found a bimodal distribution of ERA burst durations, with the dividing point being ~7 s. Both of these studies classified ERA bursts with a duration of < 7 s as short and those with a duration > 7 s as long. We also found a similar bimodal distribution of ERA burst durations, although the dividing point was not as clear. Frexinos et al. (10) and Bueno et al. (2) also classified ERA burst durations as short and long. They did not give a time range for their classification of ERA bursts, but the mean duration of short and long ERA bursts reported was 3.1 ± 0.4 and 10.3 ± 3.6 s, respectively, values similar to those of Dapoigny et al. (6), Latour et al. (14), and our classification of short and long ERA bursts.

The degree of agreement between the visual analysis and the computer analysis of ERA bursts varied with the individual observer as might be expected (Table 4). Benson et al. (1) also tried to correlate visual and computer analyses by having the same observer analyze the same recording twice. They found that between analyses of the same record by the same observer the percentage agreement varied between 41 and 90%. Their data and ours indicate that there can be disagreement between what expert visual observers consider to be true ERA bursts. In this respect, computer analysis has an advantage over visual analysis as the computer program does not change on a day-to-day basis the parameters by which it judges an event.

Propagation velocities of human long ERA burst have been reported to range from 0.25 to 16 cm/s (2, 4, 10, 21, 22). The studies reporting the lower velocities were done in humans who had electrodes implanted at the time of abdominal surgery (4, 21, present study). In contrast, the studies that found higher propagation velocities were done in subjects who had had either a saline or water enema administered 12–24 h before the study and a polyvinyl tube containing the electrodes placed in the bowel lumen by colonoscopy (2, 10, 22). Whether the differences in experimental methods are responsible for the difference in propagation velocities observed by us and some other investigators is not known. Sarna and Arndorfer (19) have recently reported that placing a recording tube in the dog colon lumen disrupted normal colonic motor activity.

Several other investigators have used a computer program to analyze either colonic ECA, (15, 20, 26, 27) or ERA (14). For the computer analysis of ECA, most studies (20, 26, 27) have used FFT to determine the frequencies present. However, Parker et al. (15) used a pattern recognition program to determine the duration of each individual ECA cycle and assign it to a frequency group. In addition, Latour et al. (14) analyzed ERA by digitizing the tape-recorded signal after it was passed through an electronic filter (active band pass) and contour follower (rectifier-integrator). Their program determined the duration of ERA bursts but did not analyze for propagation.

In summary, using a computer program for analysis of human colonic smooth muscle electrical activity recorded from a group of 48 patients for up to 29 days, we have determined that recovery from postoperative ileus occurs during the initial 6 postoperative days. Changes in electrical activity characterizing recovery from ileus are a downshift in the dominant ECA frequency to a range of 1–9 cpm first in the right and then in the left colon, followed by an increase in the number of long (≥6.7 s) ERA bursts, and propagation of long ERA bursts (0.33–1.0 cm/s). On and after the 7th postoperative day, no further significant changes in the parameters of colon electrical activity occur. Thus colon electrical activity is normal after the 1st postoperative week.

This study was supported in part by grants from the National Institute of Diabetes and Digestive and Kidney Diseases (DK-40966), Department of Veteran's Affairs Medical Research Funds, Parson Surgical Fund, and the Government of Brazil to A. A. B. Ferraz.

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Received 17 May 1994; accepted in final form 29 March 1995.

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