Smart Technology Improves Patient-Controlled Analgesia: A Preliminary Report

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A new adaptive system has been designed to improve patient-controlled analgesia through the use of a variable bolus dose and a variable background infusion of analgesic. A novel hand set allows patients to rate their own pain on a linear scale of 1 to 10. Data derived from the hand set signals are used by an expert algorithm to repeatedly adapt the drug dosage of the bolus and of the background infusion according to both current pain intensity and the patient's response to previous dosage. To test the system, we performed a small pilot clinical study, using a randomized, double-blinded, cross-over design. The new system was alternated with a conventional system every 12 h. Use of the new system was associated with significantly lower pain scores and fewer bolus requests but more analgesic administration, though without increased adverse effects. It was very well accepted by both patients and clinical staff. **Implications:** Pain relief after surgery is often best provided by patient-controlled analgesia, which uses an IV infusion pump and a patient-activated switch. We have developed a new computer-controlled or "smart" patient-controlled analgesia that rapidly learns a patient's individual needs and provides continuously tailored pain relief.

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Patient-controlled analgesia (PCA) has become accepted as a valuable method of managing acute postoperative pain. The advantages of PCA over regularly scheduled and as-required administration of analgesics have been shown in a number of studies (1,2). However, conventional PCA has a number of limitations. First, there is often uncertainty concerning the optimum bolus size (3–8). Second, the use of a background infusion is the subject of some disagreement, though it is not generally used (9–11). Third, the general underprescription of analgesia can be translated into conservative PCA prescriptions (12). Finally, the technology of PCA devices does not easily make allowance for higher analgesic requirements in the immediate postoperative period, although this period is important in managing the subsequent course of analgesic therapy (1,13–15). Manual adjustment of the PCA prescription is currently the only method by which higher initial analgesic requirements can be accommodated.

Bolus sizes are generally tailored for the patient population most sensitive to analgesics, yet patient requirements for adequate analgesia can vary up to 10-fold, especially among, but also within, patients over time (6,9,16,17). Conventional PCA devices allow patients to request only a single size bolus, and the frequency of button pressing is then the sole method by which patients can regulate the total dosage administered.

We report the development of a new adaptive PCA system which adjusts both the bolus dose and the background infusion rate of analgesic depending on the button-pressing profile of the patient.

Methods

The study was approved by the Royal Melbourne Hospital's Board of Medical Research/Scientific Subcommittee and by its Ethics Committee on Research. Written, informed consent was obtained from all patients.

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Technical Description

The basic elements of the adaptive PCA system are shown in Figure 1. A special hand set was designed that allows the patient to indicate the intensity as well as the presence of pain. Patient button pressing activates both a bolus delivery at the time of demand and, depending on the bolus amount selected, also a continuous background infusion rate. Expert knowledge based on the clinical experience of the medical staff was encoded in the system to determine both the bolus size and the background infusion rate in response to the pain rating recorded on the hand set. In the absence of any new demands from the patient, the background infusion level (if present) is progressively reduced in increments according to a predetermined program. Morphine was used.

Expert knowledge derived from the medical team has been encoded in the control algorithms of the adaptive PCA and is used to supervise and continuously monitor the system. The infusion algorithm and bolus dosages are intended to emulate as closely as possible best clinical practice provided by a bedside clinical team.

The adaptive PCA system was controlled by an IBM-compatible personal computer (80386 processor), with four serial RS232 ports, 4 MB of extended memory, and a 105 MB hard disk drive. All bolus doses and infusions were administered via a volumetric computer-controlled infusion pump (model 929, Imed, San Diego, CA). The hand set was custom designed using an MC68HC11-E2 micro-controller (Motorola, Huntsville, AL). The programming language used was Borland C^{++}.

"Traffic lights" displayed both system status and any alarms, so that major variables could be easily identified by clinical staff from a distance. The screen was positioned so as not to be visible to the patient in order to avoid the possibility of either confusing or influencing the patient. The top green light was on when the infusion was running, off when the infusion was not running, and flashing when the infusion was decreasing. The middle yellow light was on when a bolus request was permitted, off during bolus lockout, and flashing when a bolus was being delivered. The bottom red light was on when either a bolus or infusion limit had been reached, off when the system was otherwise functional, and flashing when the system was on pause (e.g., to change an infusion bag).

Patient Hand Set

The hand set displays a pain scale that resembles the traditional Visual Analog Pain Scale used clinically (18) (Figure 2). From the lowest to the highest pain intensity, the scale is colored from blue to yellow to red. The patient is asked to make a selection on the hand set by pressing the button corresponding to the level which best indicates the intensity of the pain being experienced. Visual confirmation of the choice being made is provided by a row of light-emitting diodes (LEDs) above the buttons, with all LEDs up to the level selected being lit. A separate "GO" button also becomes lit at this time. Until the GO button is pressed to indicate acceptance of the selection, a different pain level button can be selected. Pressing the GO button produces an audible tone and causes all lit LEDs to be extinguished. Failure to press the GO button within 8 s causes the hand set to time out and reset itself, so that a new selection has to be made.

This two-step process was designed to provide a margin of safety against accidental triggering. After the GO button is pressed, one of ten integer values is sent to the computer corresponding to the pain level button selected. The bolus amount of morphine administered is derived from the pain score recorded and ranges from 0.5 mg to 5.0 mg. For patients older than 60 yr, all doses are halved. The initial bolus dose delivered on start up is 2.5 mg and is independent of the first pain score recorded.

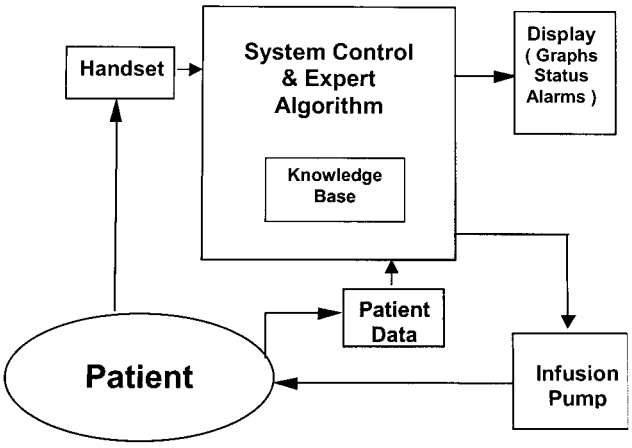

Figure 1. Block diagram of the adaptive patient-controlled analgesia system.

Background Infusion

The new adaptive PCA system also includes a self-adjusting background infusion of analgesic. The patient's button-pressing profile serves as the basis for varying the background infusion rate, with the controlling variables being the amount of analgesic administered in the latest bolus request and the time between successive bolus requests. The background infusion rate can range between 0 and 5.0 mg/h and can increase or decrease in set increments of 0.5 or 1.0 mg/h.

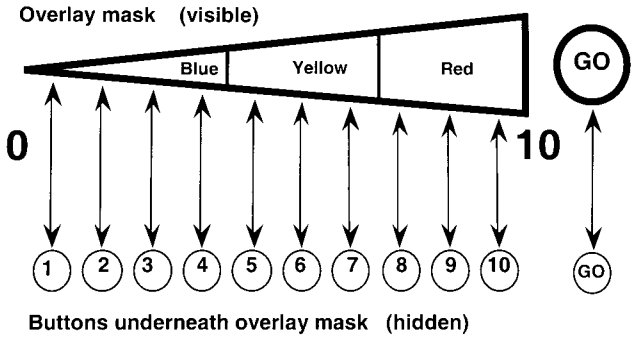

Figure 2. Top view of the patient hand set for the adaptive patient-controlled analgesia system.

The principles of the algorithm are as follows:

i. The initial infusion is commenced at 2.5 mg/h.
ii. The infusion is unchanged if the last bolus is less than the median dose (2.5 mg).
iii. The infusion increases by 0.5 mg/h if the last bolus is greater than the median dose but less than the maximum dose (5 mg).
iv. The infusion increases by 1 mg/h if the last bolus is maximum.
v. The infusion decreases by 0.5 mg/h if there have been no bolus requests for 1 h.
vi. The infusion decreases by 1 mg/h if there have been no bolus requests for 2 h.
vii. The infusion stops if there have been no bolus requests for 3 h.

As with the bolus doses, all background infusion rates are halved in patients older than 60 yr.

Patients

Patients having major abdominal or orthopaedic surgery and being considered for conventional PCA with morphine postoperatively were eligible for entry into the trial. There were no other criteria for inclusion. The criteria for exclusion were confusion, inability to speak English, or a history of drug abuse. A randomized, double-blinded, cross-over design was used, so that the patients were used as their own controls. Patients entering the trial received routine preoperative education in PCA, together with additional education in the use of the new adaptive PCA, in particular, in the use of its two-step hand set.

For conventional PCA (Lifecare 4200, Abbott, Chicago, IL), the bolus dose of IV morphine was prescribed in the usual way by the hospital's pain service. In accord with common local and international practice, no background infusion was prescribed. This control group thus represented current routine clinical practice.

For the new adaptive PCA system, the bolus doses and background infusion rates of IV morphine were automatically given in response to the pain intensity indicated by the patient on the specifically designed hand set, as described above.

Both PCA systems were treated as a conventional PCA system as far as lockout intervals, discontinuation of PCA, and replacement by oral analgesics were concerned.

Both PCA systems ran simultaneously, with each triggered by the new adaptive PCA hand set. However, at any time, only one system delivered the active analgesic solution while the other system delivered placebo (isotonic saline). The solutions were prepared independently by a research nurse who was not otherwise involved in the trial. A table of random numbers was used to determine which system was first assigned the active solution. Every 12 h, for the 48-h duration of the trial, the active and the inactive solutions were interchanged. The patient and the nursing staff were not aware which system was active at any time. The infusion sets from both systems were combined using a Y-connector and anti-reflux valves, so that the patient required only a single IV cannula as for conventional PCA.

Each trial was considered complete when the planned 48-h limit was reached, the patient made no bolus requests for 12 h, or the medical staff decided to discontinue the trial, whichever was sooner.

The main assessments of efficacy were the routine hourly verbal pain scores, 12 hourly pain questionnaires, and the score automatically recorded from the hand set each time a request was made. Analgesic consumption and successful and unsuccessful bolus requests for each system were recorded by the adaptive PCA computer. Nursing staff recorded respiratory rate (bpm) and sedation scores (on a scale from 0–6, with 6 being maximum) as well as the pain scores (on a scale from 0–10, with 10 being maximum) on an hourly basis as part of normal nursing protocol for PCA.

Continuous data were compared using the Mann-Whitney *U*-test and categorical data by the χ^2 or Fisher's exact tests. Multiple comparisons were made using analysis of variance after normalization of the data by transformation if necessary (StatView ver. 4.5; Abacus Concepts, Berkeley, CA). A conventional level of significance was used ($P < 0.05$), and this was not adjusted for multiple comparisons. There was insufficient pretrial information to permit a realistic estimate of the power of the study and, thus, any potential type II error.

Results

Of the 20 patients enrolled, 10 were randomly assigned to receive either PCA system first. Three patients were withdrawn, two for technical difficulties and one became too disorientated to use any type of PCA. The patients were aged 17–83 yr (mean, 58 yr),

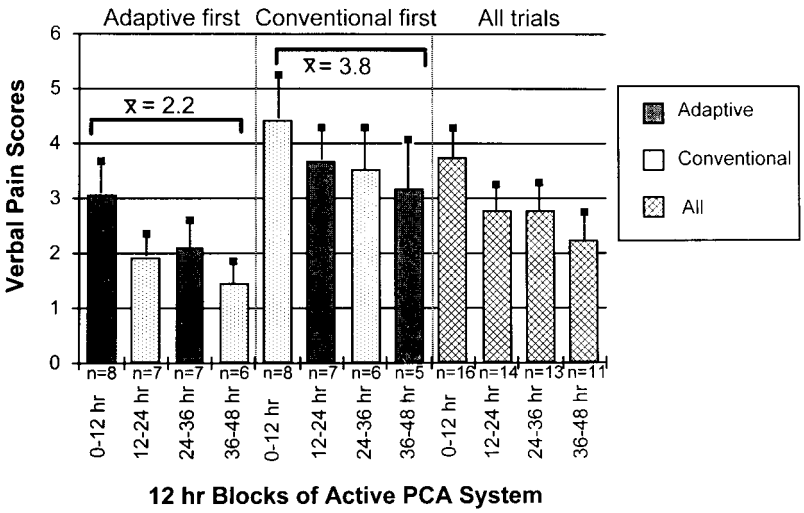

Figure 3. Verbal pain scores recorded on the routine ward chart of acute pain medication infusion at approximately 1-h intervals and averaged over 12-h blocks. Values are mean and SEM.

65% were male, and body weights were 54–91 kg (mean, 77 kg). There were no statistically significant differences between the two treatment groups for any of these variables, for intraoperative narcotic dosage, or for type or duration of surgery.

It was expected that changes in assessment variables would be noted at 12 hourly intervals when the active systems were interchanged. However, it became apparent that the active system used to start a trial had a dominant influence on the subsequent assessment variables, so that formal analyses were performed on the basis of which system was used in the first 12 h.

Hourly Verbal Pain Scores

The hourly verbal pain scores over 48 h recorded on the routine nursing observation chart are shown in Figure 3 in 12-h blocks. The scores for the adaptive-first group were significantly lower than for the conventional-first group ($P = 0.004$).

12 Hourly Pain Questionnaire

The scores from the 12 hourly pain questionnaires are shown in Figure 4 in 12 h blocks. Significantly lower pain scores were observed when the adaptive system was active ($P = 0.048$). In addition, the 12 hourly values in the adaptive-first group seemed to indicate more consistent control compared with the conventional-first group.

Hand Set Pain Scores

Pain scores recorded from the hand set are shown in Figure 5 in 12-h blocks. There was a trend toward lower hand set scores in the adaptive-first group compared with the conventional first group ($P = 0.07$). Unlike the other pain scores, the hand set pain scores did not decline over the 48 h of the study.

Bolus Requests

The median number of bolus requests for analgesia per 12 h in the adaptive-first group was lower than in the conventional-first group for each 12-h block (Figure 6). The median number of bolus requests decreased from 11 in the first 12 h to 5 in the fourth 12 h in the adaptive-first group, but remained almost constant in the conventional-first group with a median of 14 requests per 12 h over the entire 48 h. The difference in bolus requests per 12 h was significantly lower in the adaptive-first group compared with the conventional-first group ($P = 0.023$). The number of bolus requests also progressively decreased in the adaptive-first group, whereas there was no such trend in the conventional-first group (Figure 6).

Analgesic Consumption

Significantly more morphine was administered by the adaptive system than by the conventional system (median, 32 vs 8 mg/12 h, $P < 0.0001$). A significantly higher amount of morphine was administered by bolus by the adaptive system than by the conventional system (median, 22 vs 8 mg/12 h, $P < 0.001$). No patients were prescribed a background infusion for conventional PCA, so that patients received morphine via infusion only when the adaptive system was active.

Adverse Effects

No patient in either treatment group developed an abnormally low respiratory rate or increased sedation

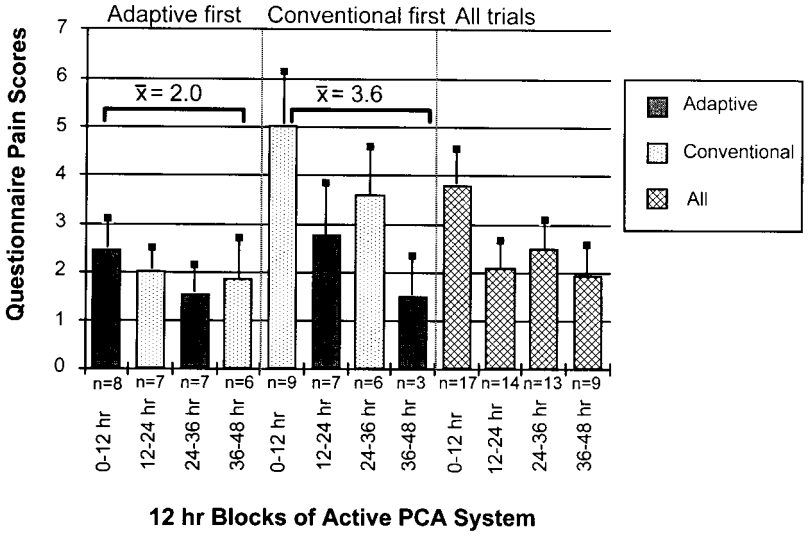

Figure 4. Pain scores from the 12-hourly questionnaires, with 12-h averages for each active system shown as blocks. Values are mean and SEM.

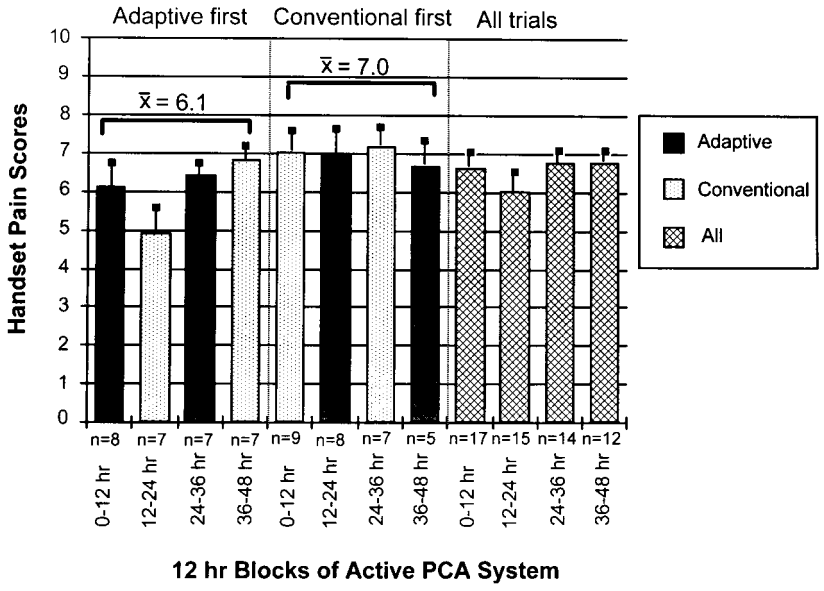

Figure 5. Pain scores from the patient-controlled analgesia hand set. Values are mean and SEM.

scores. The adaptive PCA and the conventional PCA groups had similar respiratory rates (18.1 ± 1.2 vs 18.3 ± 1.7 bpm, mean ± SEM, respectively) and similar sedation scores (0.4 ± 0.4 vs 0.5 ± 0.5, mean ± SEM, respectively). No reversal drug (naloxone) was required by or was given to any patient. No episodes of desaturation were detected. No itching was reported.

The adaptive PCA and the conventional PCA groups had a similar incidence of postoperative nausea and vomiting, with 7 vs 5 12-h blocks with episodes of nausea, 3 vs 1 12-h blocks with episodes of vomiting, and 17 vs 15 doses of antiemetic (metoclopramide 10 mg IV), respectively. One patient experienced severe nausea and slight incontinence during vomiting when the adaptive PCA was active after he was inadvertently instructed by a junior nurse in the postoperative ward to press the highest value on the hand set if he felt any pain at all.

Discussion

In conventional fixed-bolus PCA systems, the analgesic prescription has to accommodate patients that may be more opioid-sensitive, and thus the bolus sizes that are generally selected are expected to be safe in all likely circumstances. However, analgesic requirements vary greatly, especially among patients but also within patients over time, and are difficult to predict. For these reasons, the optimum fixed-bolus dose has been the subject of debate, though a commonly prescribed range is 1–1.5 mg of morphine (3–8). The

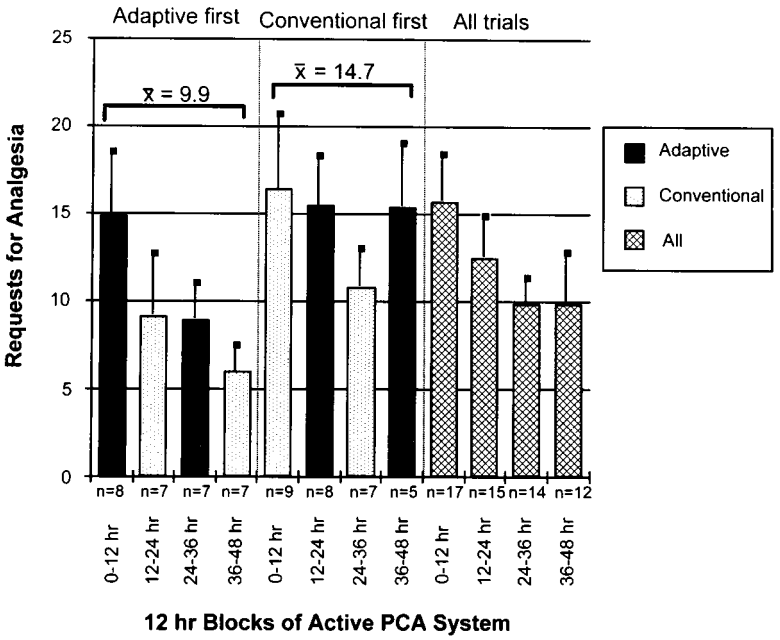

Figure 6. Number of requests for analgesia per 12-h block. Values are mean and SEM.

new adaptive PCA system addresses this limitation through its variable and patient-specific bolus dosing.

The use of a constant background infusion of analgesic in conjunction with conventional PCA is not usual practice, though it is the subject of some disagreement (19–21), again because of the widely varying analgesic requirements of patients, often up to 10-fold. To avoid undesirably high infusion rates, we have used the patient's individual button-pressing profile to adjust the varying background infusion in the new adaptive PCA system. In this pilot clinical study, the background infusion accounted for one third of the total analgesic administerd by the new adaptive PCA.

Analgesic consumption followed a clear 12-hour cycle in synchrony with whichever system was active. Thus, when the adaptive system was active, patients received significantly more analgesic than when the conventional system was active. This increased dose was not associated with an increase in side effects, but rather with lower pain scores, reflecting, we would suggest, a general tendency to underprescribe postoperative analgesia even with conventional PCA.

When the adaptive system was used to start the trials, the number of bolus requests was significantly lower and decreased uniformly over time, and there were significantly lower pain scores throughout the entire 48 hours, even during the subsequent cycles of conventional PCA. We believe these findings probably indicate significant clinical benefits from the new adaptive PCA system and confirm the importance of improved early analgesia (1,13–15).

The absence of a decline over 48 hours of the hand set pain scores suggests that the hand set pain scores are logged differently from traditional pain scores and may represent a different aspect of the pain cycle. Thus, they probably demonstrate a common pain threshold at the moment at which analgesia is requested, though they could also reflect attempts to maintain consistent bolus doses once a satisfactory pain level has been established.

Conventional PCA is not necessarily suitable for all postoperative patients, so a patient selection and education process is required for its successful implementation. For more sophisticated technology, such as the new adaptive PCA system, patient selection and staff training could perhaps, paradoxically, be more simple. In fact, one of the goals of the new adaptive or "smart" PCA was to use its sophisticated program to make its interface easier to use. Thus, there is no programming at all of bolus, lockout, etc. by clinical staff; the patient has only to 'tell' the hand set what he has to tell the nurses, as well as push the usual request button, and the machine's algorithm, which is based on an estimate of best bedside clinical practice, does the rest by rapidly learning the patient's needs and adapting the dosage accordingly.

The new adaptive PCA system lends itself to extension or enhancement in various ways. First, for example, the incorporation of a continuous ventilation monitor could be a desirable safety feature, and, indeed, we have previously explored the feasibility of using on-line information from noninvasive respiratory or carbon dioxide sensors to trigger alarms or to modify the algorithm. However, this technology is currently too unstable to be reliable for this purpose, although if a suitable device became available, it could easily be added. Second, although we excluded patients with a history of drug abuse, because they are

not normally deemed suitable for PCA in our institution and because their button-pushing behavior might not reflect solely analgesic needs, rendering their data hard to interpret, patients with opioid tolerance and higher genuine analgesic needs could be easily accommodated by the new adaptive system. This can be achieved by the use of a specific high range of dosage, with tightened safety and step-down settings. We have not formally evaluated this strategy, but we have found it feasible and effective in two young large male patients with very high analgesic needs.

In conclusion, the new adaptive PCA system described here has a number of features which are significantly different from those of PCA systems currently available. These enhancements include a patient hand set on which different pain intensity levels can be registered, expert system adaptation of bolus delivery to the patient's analgesic need, and a self-adjusting background infusion. Preliminary studies indicate that the new system is technically feasible, is well accepted by both patients and clinical staff, and appears to offer improved analgesia without additional side effects.

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