Automatic Time–Motion Study of a Multistep Preoperative Process

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Background: Hospitals use time–motion studies to monitor process effectiveness and patient waiting. Manual tracking is labor-intensive and potentially influences system performance. New technology known as indoor positioning systems (IPS) may allow automatic monitoring of patient waiting and progress. The authors tested whether an IPS can track patients through a multistep preoperative process.

Methods: The authors used an IPS between October 14, 2005, and June 13, 2006, to track patients in a multistep ambulatory preoperative process: needle localization and excisional biopsy of a breast lesion. The process was distributed across the ambulatory surgery and radiology departments of a large academic hospital. Direct observation of the process was used to develop a workflow template. The authors then developed software to convert the IPS data into usable time–motion data suitable for monitoring process efficiency over time.

Results: The authors assigned tags to 306 patients during the study period. Eighty patients norecorded or never had their tag affixed. One hundred seventy-seven (78%) of the remaining 226 patients successfully matched the workflow template. Process time stamps were automatically extracted from the successful matches, measuring time before radiology (mean ± SD, 77 ± 35 min), time in radiology (105 ± 35 min), and time between radiology and operating room (80 ± 60 min), which summed to total preoperative time (261 ± 67 min).

Conclusions: The authors have demonstrated that it is possible to use a combination of IPS technology and sequence alignment pattern matching software to automate the time–motion study of patients in a multidepartment, multistep process with the only day-of-surgery intervention being the application of a tag when the patient arrives.

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PEOPLE have come to expect that it will be simple to track the locations of things. Global positioning systems–enabled devices track where we are, our credit card and automatic teller transactions track where we have been, and a simple Internet search can locate the items we have bought as they are shipped to their destination. In fact, many shipping companies turn the flow of information around and actively send tracking information to the recipient. By using these information sources, businesses and government agencies can reconstruct a person’s activities, creating a time–motion map supporting inferences about what they have done based on where they have been.

Medicine would benefit greatly from similarly potent means to track patients and processes. Clinical processes in a healthcare setting can span several departments. These may encompass not only different physical spaces but also different clinical, administrative, and scheduling information systems. Tracking patients on their physical trajectory in such a setting is difficult; it is similarly difficult to reconstruct the patient’s clinical trajectory—the clinical events and their order—during their stay. An acceptable level of detail may possibly be reconstructed by using the myriad digital information bits distributed between numerous existing electronic data sources, presuming they exist. However, this approach may be complicated by problems with data access, multiple data representations, the need to create custom interfaces between systems, and corruption of the data by poor documentation practices.1,2 Alternatively, the implementation and use of a location tracking system can provide the data to easily identify, monitor, and record patient progress through clinical processes.3–5

Location tracking systems, while not yet commonplace in the healthcare setting, have been used in pilot and research settings to evaluate potential applications.6 These range from simple asset tracking to surrogate record keeping of event time stamps and integrated, smart systems that can detect when process exceptions occur and take appropriate action.7–9 It follows that a location tracking system could be used to monitor the time–motion performance of a clinical process, although this has not yet been demonstrated. Our hospital is interested in monitoring the time patients spend in the facility, particularly when they may be waiting excessively. When combined with knowledge of clinical workflow processes, a location tracking system can be used to automatically provide such temporal information.
In this article, we describe a system that automatically provides temporal process information for time-motion studies using a location tracking system and a custom software application. The system cleans raw location data from a location tracking system and compares the location data to an established clinical workflow template to automatically extract time stamps for process steps in the template. We piloted the system on location data streams from patients undergoing needle localization and excisional biopsy (NL/EB) of a breast lesion, an outpatient process spanning multiple departments and multiple physical locations over a short time span. Our goal was to demonstrate that the system could automatically track the time performance of the preoperative process.

Materials and Methods

The study was conducted with approval of the Massachusetts General Hospital Institutional Review Board (Boston, Massachusetts). Patient observation and tracking were limited to the preoperative processes on the day of surgery. Presurgical tasks before the day of surgery were not evaluated. Similarly, events pertaining to the patients after they entered the operating room (OR) were not included in the study.

Before installing the tracking system, we observed the NL/EB workflow to determine the clinical areas and workflow steps involved in the process. A dedicated observer familiar with the workflow shadowed 15 NL/EB patients longitudinally as they moved through the preoperative process. The observer noted each clinical activity and change in patient location to develop a gross understanding of each step of the workflow process.

After mapping the process, we deployed an indoor positioning system (IPS; Radianse, Lawrence, MA) to cover the patient care environments visited by patients during the NL/EB process as determined by observation. Our hospital had previously deployed this IPS throughout the perioperative environment, but additional receivers were needed in radiology and certain transit points between the two clinical areas for this study. The IPS has a 10-s temporal resolution and room-level spatial resolution. The IPS uses small transmitters, or tags, whose room-level location is continuously detected by wall-mounted receivers that reside on the computer information system local area network. The tags for this particular IPS use active radiofrequency identification and infrared light (i.e., dual emission) to communicate with the receivers. Because the IPS uses the existing local area network infrastructure, hardware costs for the system included only the additional receivers, the new network connections, and 20 additional tags dedicated to the project. A server hosting the IPS software and database was already present.

Location information for each tag is stored in a structured query language database on the IPS server. The tags transmit only their serial numbers. The tag serial number is associated with patient identifiers by the IPS server. No patient information is transmitted, and the IPS server sits behind the hospital information systems firewall, so risks to patient privacy are eliminated. We assigned a tag to every NL/EB patient during the pilot period, with the exception of periods when the research assistant was unavailable because of illness or vacation.

Our tag management strategy had important implications for the scope of the patient pathway that could be monitored. The research assistant manually assigned a tag to each NL/EB patient on the afternoon before the scheduled procedure. The tag was then placed in the patient’s chart, which was then stored in the same-day surgery unit (SDSU) check-in facility. The tags remained there overnight. The next day, clerical personnel were intended to affix the tag to the patient’s garb when they checked in. The tag would communicate its position—and hence the apparent location of the patient—to the IPS from the point of assignment onward. Tags were removed by clinical staff as patients completed the NL/EB process and were placed in a drop box in the recovery room. Again, the tags continued to communicate their position—and the apparent location of the patient—until they were reassigned by the research assistant.

The IPS generates “events” that are stored in the database. The events of interest for this study denote location changes. However, there are many other events pertaining to tag or receiver status. In total, there are 23 potential events in the system, many of which are uninformative for our purposes (battery low, battery high) or do not apply to our study (location time-out, receiver initialization). We therefore developed software to clean the data stream resulting from the IPS. We selected eight events to maintain in the data stream. These included tags changing locations, being assigned, and timing out. A tag time-out means that before this event, the IPS asserts that a specific tag is found near a specific receiver, but after the tag times out, the system no longer makes this assertion until the tag is found again, either at the same receiver or a new one. During the tag time-out period, the IPS is no longer tracking the tag but will reacquire it upon a change in location or after the time-out period in the same location. We assume during analysis that a tag that is timed out remains in its previously known location until the tag is reacquired. The cleaning software then eliminates duplicate location entries, maintaining the event where the system first saw a tag in a particular location and eliminating all subsequent location entries until a new location is found. What results is a data stream showing, in sequence, the changes in location of a tag over time with no uninformative events and no two adjacent entries being the

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same location. Each location, initially designated by the location name of a receiver, is then mapped to the area to which it belongs (radiology, OR, or SDSU).

We then applied a modified sequence alignment algorithm to the location data to match it to an established clinical workflow template for an NL/EB patient. This template was derived from the previously mentioned observation of the process and early inspection of the data stream for these patients. Because of noise in the data stream, periodic instability of the IPS, and the proof-of-concept nature of the study, a simplistic workflow template of (SDSU → radiology → SDSU → OR) was used in this pilot. All patients whose time-motion trajectory matched this template were considered to have undergone the NL/EB process. An example of the data handling from raw data to final template matching can be found in figure 1.

When a patient’s time-motion trajectory matched the template, the algorithm then calculated dwell times in each location. Four time intervals were calculated:

- The time between the start of the first SDSU period and the radiology period (SDSU before radiology)
- The time between the start of the radiology period and the second SDSU period (radiology)
- The time between the start of the second SDSU period and the OR period (SDSU after radiology and before OR)
- The total of the preceding three time periods (total time).

We calculated individual patient dwell times and average dwell times per month for the entire duration of the pilot. All tagged patients whose time-motion trajectory did not match the expected template were rejected as not following the expected trajectory, despite being scheduled for NL/EB. For these patients, we manually investigated the data stream to determine where the time-motion data diverged from that expected based on the template.

**Statistical Analyses**

All statistical analyses were planned in advance of the study. Results are reported as frequency, median, mean ± SD, or mean and 95% confidence interval for the mean as appropriate throughout the Results section. Data were tabulated and analyzed using Excel (Microsoft, Redmond, WA).

**Results**

The perioperative process for NL/EB in our hospital involves the coordination of multiple personnel in different areas and protocols. Each location, initially designated by the location name of a receiver, is then mapped to the area to which it belongs (radiology, OR, or SDSU). We then applied a modified sequence alignment algorithm to the location data to match it to an established clinical workflow template for an NL/EB patient. This template was derived from the previously mentioned observation of the process and early inspection of the data stream for these patients. Because of noise in the data stream, periodic instability of the IPS, and the proof-of-concept nature of the study, a simplistic workflow template of (SDSU → radiology → SDSU → OR) was used in this pilot. All patients whose time-motion trajectory matched this template were considered to have undergone the NL/EB process. An example of the data handling from raw data to final template matching can be found in figure 1.

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different departments. Needle localization is performed in the radiology suite, whereas the subsequent excision occurs in the OR. The two departments do not use the same scheduling system. The layout of the preoperative area used for the preoperative NL/EB process is illustrated in figure 2. Note that the process that was tracked is spread over two floors and multiple locations.

We assigned tags to 306 patients scheduled for NL/EB between October 14, 2005, and June 13, 2006. Of these, the data streams of 177 patient trajectories matched the workflow template using the sequence alignment algorithm, giving a raw success rate of 58%. The remaining 129 patient trajectories did not match the workflow template, for an apparent failure rate of 42%. Reviewing the location data streams for each of these cases revealed a variety of reasons for not matching the workflow template. These are shown in figure 3, with additional details below.

Fourteen of the patients did not have breast surgery, did not have the needle localization procedure, or did not have surgery on the day for which the tag was assigned to them. Sixty-six patient tags never left the first step of the template, the SDSU. We interpret this to mean the tags were never affixed to the patient, because each of these patients did actually have NL/EB of a breast lesion on that day. These 80 cases could reasonably be excluded from the assessment of the system’s technology success because there was no opportunity for the system to function.

Manual review of the IPS data from the remaining 49 rejected patient tags indicates that they did, in fact, at least partially map onto the NL/EB workflow. Nine patient tags first appeared in radiology, missing the initial SDSU step, and 11 patient tags never appeared in radiology at all. Review of medical records for these patients

![Fig. 2. Layout of areas used for the needle localization and excisional biopsy (NL/EB) process in the same-day surgery unit (SDSU) (third floor) and radiology (second floor) suites. The arrows indicate patient flow. Patients enter the SDSU for registration at the check-in area, change into hospital garb, and are led into a holding area for a preoperative evaluation and intravenous catheter placement (green arrow to SDSU_pre-Op & PACU). When called for, patients are then transported to radiology for needle localization (brown arrows). They are then transported back up to a different holding area directly outside the operating rooms for further assessment and reconnection of the intravenous (orange arrows to SDSU_OR Holding), before they enter the operating room (OR). PACU = postanesthesia care unit.](image-url)

![Fig. 3. Breakdown of patient tags that did not match the needle localization and excisional biopsy (NL/EB) workflow on the scheduled day of surgery.](image-url)
confirmed that needle localization had been performed. Nineteen patient tags were never localized to a specific OR, although frequently they were sensed by receivers near the assigned ORs. Again, review of medical records ascertained that a specific OR had been used for excision. Six patient tags were detected neither in radiology nor in a specific OR, although transit points were visited, indicating that the tags moved in a pattern consistent with the NL/EB process. Two patient tags had an OR location before radiology, and 2 patient tags were never detected in the SDSU after radiology but before an OR, both of which prevented a successful template match. Therefore, the IPS with our custom software algorithm was able to successfully track patients through the complete clinical workflow process in 177 (78%) of 226 cases where the system had a chance of a successful match. Of the remaining tags that moved from the initial location, the match was fragmentary and so the case was rejected by the system.

For the 177 patients that successfully matched the workflow template, the individual time stamps for each patient and each step in the workflow template are presented in figure 4. Each patient is represented by four points showing the intermediate times spent in the three preoperative locations, and the total time for the process. The black bars along the x-axis indicate patients who underwent needle localization and excisional biopsy but whose trajectory as detected by the tracking system only partially matched the workflow template. The scale for the bars (in number of patients) is shown by the right side y-axis. OR = operating room; SDSU = same-day surgery unit.

Fig. 4. The colored dots plot individual time stamps extracted for each successfully matched patient versus calendar date during the automatic time–motion pilot study. Each patient is represented by four points showing the intermediate times spent in the three preoperative locations, and the total time for the process. The black bars along the x-axis indicate patients who underwent needle localization and excisional biopsy but whose trajectory as detected by the tracking system only partially matched the workflow template. The scale for the bars (in number of patients) is shown by the right side y-axis. OR = operating room; SDSU = same-day surgery unit.

The mean preoperative process performance measured by the IPS for each month of the pilot is plotted in figure 5. The mean time over the duration of the pilot period in the SDSU before radiology was 77 ± 35 min (mean ± SD), time in radiology was 105 ± 35 min, time in the SDSU after radiology but before the OR was 80 ± 60 min, and total time was 261 ± 67 min. Medians for each were 72, 101, 64, and 252 min, respectively.

Discussion

We demonstrated a new technology for performing time–motion studies and applied it to a multistep preoperative process. The raw data from the IPS was processed through custom software that allowed us to automatically and continuously monitor three time intervals in patients' preoperative processes, corresponding to three distinct steps geographically separated from each other. The three steps occurred in areas that did not share a common administrative computer database, so the IPS was the only way to easily obtain objective time–motion data that was not subject to biases induced by self-report or the presence of an observer. The sum of these three time intervals given by the IPS-sequence matching system is a measure of our system’s preoperative throughput performance.

Tracking systems such as the IPS can provide valuable information for a variety of applications. Time–motion information, in particular, can be problematic to obtain from the first process step were also evenly distributed over the period of the study (data not shown).
due to the number of observers needed and number of cases that must be observed. Logistically, additional people in already crowded clinical spaces make routine observation less than desirable. It would be hard to avoid an observation bias in a real-world clinical setting where an observer is obvious. On the other hand, tracking systems use small tags whose presence is known but is less intrusive.

Process and time–motion information can feasibly be obtained through other technologies such as bar code time stamps, although such solutions require a commitment throughout the process in that personnel must remember to scan the bar codes during clinical care. Rotondi et al. report a compliance rate of 77–98% for bar code scanning for patient tracking after 3 weeks of staff training for a system deployed for all patients throughout the same-day surgical services. On the other hand, the ability to “set and forget” a location tracking system tag is potentially a simple and effective way to track clinical processes, especially the performance of processes over time. In our study, compliance with affixing the location tracking tag on NL/EB patients was 77% (226 of 292 NL/EB patients had tags affixed) during the pilot period. Before the pilot, the research assistant had educated check-in personnel to affix the tag to the patient’s garb only for this specific patient population. However, the check-in personnel handled approximately 12,000 ambulatory patients during the period of the pilot, of which our patients were a small fraction. Viewed from this perspective, the 77% tagging rate was acceptable for the purpose of a pilot study.

Tag application could undoubtedly be made more reliable if all patients were tagged (i.e., if tagging was the norm rather than the exception) and if the tag were coapplied with the patient’s identification band. Location data visibility would also be helpful to assure tag placement. In a separate pilot project, we have demonstrated that the location data can be made widely visible and integrated with data from other information systems without requiring clinicians to seek the data out. Beyond visual codisplay, integration of electronic clinical data and tag location data would allow creation of “untagged patient” alerts if the clinical data provide location awareness. The feasibility of such added functionalities would be heavily influenced by the local information systems context. For example, in our setting, we have a “location-aware” nursing documentation system in the preoperative holding area (in principle allowing us to create an “untagged patient” alert from the disagreement over location between the tracking and nursing documentation data), but not all hospitals have such systems.

The IPS data stream requires substantial postprocessing to convert the raw location data into a useable form for time–motion studies. Location data from the IPS are noisy, with many events that are either redundant or uninformative for our purposes. These events greatly increase the size of the data stream. Our cleaning application outputs a reduced data stream that eliminates uninformative and redundant events, giving a base set of time stamp/location/event triplets encapsulating the pertinent information needed for a time–motion study. Only 58% of all patients who we intended to track successfully matched the workflow template contained in our software algorithm. However, a large percentage (70%) of the nonmatches could never have matched, either because the patient did not have a procedure on the day for which the tag was assigned or because the tag was never affixed to the patient’s gown on the day of
the procedure. Both of these situations are easily identified and therefore easily and reasonably excluded, resulting in an adjusted successful match rate of 78%. This is a sufficiently inclusive sample to monitor the performance of a patient flow process.

The remaining nonmatched patients underwent the NL/EB workflow, and their tag was detected at some steps in the process, indicating the tag was successfully affixed to the patient for at least part of the time. A number of contributing factors may result in a patient’s observed data stream not matching the workflow template. During the pilot, the state of the IPS was sometimes in flux. For example, receivers were sometimes off the network, and therefore tags were picked up by the nearest available receiver in range. In this scenario, tags would be seen “nearby” but not actually within a clinical area defined in the workflow template, and so would be rejected as a nonmatch. The tracking process can also fail after the tag is affixed to the patient; a tag may be under the patient, blocking reliable infrared transmission, or a patient’s gown may be exchanged during the day without the tag successfully being transferred as well. In addition, the patient movement process itself may be adjusted in response to day-to-day space constraints. That is, patients may be sent to wait in areas not covered by the IPS, or they may be taken directly from radiology to the OR. Although we attempted to account for such fluidity in the process by using a very general process template and a very broad mapping strategy, it can be expected that not all such exceptions were caught. The overall “health” of the location tracking process is evident in the plot of times extracted from successfully matched patients (fig. 4). The apparent gap in February actually contains patients whose tags moved but were not successfully matched to the workflow template. This suggests a problem with the IPS hardware. The gap in April clearly demonstrates a time when no tags were being applied because the research assistant was unavailable.

Tracking data are limited in that they can only ascertain one’s location and cannot explain what happened during one’s time in that location. Even using temporal–spatial information relating clinician and patient proximity, one must assume that such proximity has a meaning, which it may or may not have. Despite this limitation, the process times that were automatically extracted from the NL/EB time–motion study provide a gross measure of time spent in the hospital and time spent in the nearest available receiver in range. In this scenario, tags were being applied because the research assistant was available. The gap in April clearly demonstrates a time when no tags were being applied because the research assistant was unavailable.

This applies both to the number of patients who can be observed/tracked simultaneously and the ability to track process performance over time. Either requires only the assignment and application of tags, rather than using more observers. In addition, the presence of a tag, especially if the tag becomes ubiquitous in the environment, would minimize observation bias and would feasibly then provide a more accurate representation of process times. This is especially true in an environment where patients are tracked for other purposes or are tracked as part of routine care. In a facility investigating or planning the implementation of a quality improvement initiative that includes patient tracking, this application may be included with very little effort.

The workflow matching algorithm we developed to process the raw IPS data is designed to scale to include multiple workflows. In our pilot, only a small portion of the hospital’s total clinical space was covered by the IPS. We mapped receivers to SDSU, radiology, and OR groups and used a very general template of (SDSU → radiology → SDSU → OR) to track the NL/EB workflow. If more granularity is desired and there are distinct, well-defined physical waypoints in the alternate processes to be monitored, the algorithm distinguishes between workflows automatically. Extending the example of breast surgery patients, if a patient were scheduled for radioisotope lymph node mapping instead of needle localization, these two preoperative processes would be automatically distinguished from each other and monitored simultaneously, provided that the radioisotope injection was performed in a distinct location from the needle localization suite and IPS receivers had been installed.

We have demonstrated that it is possible to use a combination of IPS technology and sequence alignment pattern matching software to automate the time–motion study of patients. The only day-of-surgery intervention is the application of a tag when the patient arrives. The system automatically tracks the time performance of the preoperative process in a multidepartment, multistep process. Although unable to determine exactly what a patient is doing based on location alone, the ease of this intervention underscores the value of the information that is automatically derived from the location data stream for a tagged patient. By simply applying a tag, data for a large number of patients may be used to track processes not only at a point in time, but also longitudinally to study the stability of process times or the impact of process changes.

References

2. Sandberg WS, Sandberg EH, Seim AR, Anupama S, Ehrenfeld JM, Spring SF, Walsh JL. Real-time checking of electronic anesthesia records for documentation
errors and automatically text messaging clinicians improves quality of documentation. Anesth Analg 2008; 106:192–201