Min Invas Ther & Allied Technol 2001: 10(3) 121–127

Hierarchical decomposition of laparoscopic surgery: a human factors approach to investigating the operating room environment†

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Summary

Hierarchical decomposition of complex behaviour and systems is a valuable research methodology from human factors and information-processing psychology that can be applied to laparoscopic surgery. This article describes results of research on surgeons performing several different laparoscopic procedures, conducted in Vancouver, Canada 1995–98. Through top-down analyses of surgical procedures and bottom-up analyses of tool motions, results included detailed decomposition of the procedures through surgical steps, sub-steps, tasks, sub-tasks and tool motions. Analyses at all levels provided valuable information. In addition to specific surgeon- and technology-related observations, such as the effect of dividing the short gastrics on performance of Nissen fundoplication, gaze patterns of surgeons and factors related to patient safety were analysed. The hierarchical decomposition approach can be extended to other aspects of the complex system that consists of the surgeon and operating room team, the technologies and the operating room environment. Other frameworks for assessment are also considered.

Keywords

technology assessment, task analysis, video annotation, human performance, collaborative work, human error, ergonomics of surgery.

Introduction

In the last 10–15 years, surgical technologies and techniques have evolved at an unprecedented, accelerating pace. Minimally invasive therapy includes camera-based procedures, digital medical image-guided procedures, and robotics for surgical guidance, manipulation and other precision tasks. New technologies have been introduced for medical education, telemedicine, surgical training, pre-operative planning, intra-operative execution and post-operative quality assurance of surgical procedures. New methods are needed to assess these technologies and a human-factors approach is a valuable addition to surgical research. Human-factors research studies the interaction between humans and machines, and has its origins in the optimisation of design of aeroplane cockpits to make the layout and function of the displays and controls more effective and usable for the pilot.

The three aims of this paper are to:

- Highlight approaches to our human-factors research on laparoscopic surgery.
- Present selected analyses and results of our observational research in hospitals.
- Identify the advantages and limitations of our observations to date.

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In addition, we believe that there should be increased dialogue and commitment among researchers, clinicians and industrial partners to the development of frameworks for systematic, objective assessment of technologies and techniques in minimally invasive therapy. Finally, we outline the implications of our research for the development of frameworks and methods for the assessment of the technologies, techniques, surgeons and surgical team performance. We then make recommendations for future human-factors, systems and technology assessment research on minimally invasive therapeutic interventions.

Observational research of laparoscopic procedures

Extending earlier studies on human manipulation and remote manipulation [1], our initial research focussed on the surgeon as a user of tools for visualisation and manipulation. Our motivation was to examine laparoscopic surgery (from Greek: *cheir* = hand + *ergon* = work, literally the work of the hand) as one example of a challenging remote manipulation task for humans. During minimally invasive surgery surgeons are required to manipulate scissor-like handles on the outside of the patient's body, while watching the tools' end-effectors and internal environment on a video monitor displaced from the operative site. Thus, both vision and action are indirect. By using a triangle strategy to study the user–task–tool in the frame or context of the operating room (OR) environment [2], we began to identify constraints and make recommendations on the design of laparoscopic tools. Our research on endoscopic surgery has grown into a major research programme and has broadened to consider the entire operating room and team, across numerous surgical specialties.

Materials and methods

Three distinct methodologies were employed. First, controlled experiments were conducted in the Human Motor Systems Laboratory at Simon Fraser University [3]. Second, we surveyed surgeons in British Columbia, Canada [4]. Third, observational studies were conducted of laparoscopic training workshops and surgical procedures performed in the operating rooms of urban teaching hospitals. The observational studies in the operating rooms form the basis of this report. In particular, we developed a hierarchical framework for assessment based on the plans and structure of goal-directed human behaviour [5].

Over a two-year period (1995–96) we videotaped 24 laparoscopic procedures (cholecystectomy, inguinal hernia repairs, Nissen fundoplication) on split screen, including both the endoscopic camera view and our camera view of the primary surgeon and OR staff. Videotaping the surgeries in the operating rooms allowed for observation of expert surgical skills and spontaneous responses to live situations, in the context of actual operations. The research on human subjects received Ethics approval from the University and Hospital boards. Informed consent was obtained from every individual on the videotape. This included the patients, surgeons, all participating OR personnel, as well as those attending the surgery for training or learning purposes.

A further 2 years of extensive video annotation (MacSHAPA, Sanderson, 1994) and statistical analyses were performed (1996–98), to describe the precise timing and location of OR events, surgical events, tool insertions, removals and motions as well as interactions of eyes–hands–tools–tissues, with respect to surgical goals. Through iterative top-down analyses of surgical procedures and bottom-up analyses of tool motions, we provided detailed decomposition of the procedures to the level of tool motion. From observable surgical events on our research video, we operationally defined the beginnings and endings of surgical steps, sub-steps, tasks, sub-tasks and motions. Using times for these events, we examined durations at each hierarchical level and relative timing among the interacting components. We also analysed gaze and communication patterns in the OR and transcribed conversations related to teaching, technology, surgical planning and execution.

Results

Top-down analyses of surgical procedures and bottom-up analyses of tool motions provided detailed decomposition results for each of the procedures. For example, the cholecystectomy procedure was divided into surgical steps (e.g. isolate gall bladder), sub-steps (e.g. dissect surround), tasks (e.g. tease tissue), sub-tasks (e.g. snip tissue), and tool motions (e.g. open jaws). Some components of the decomposition were serial, that is they unfolded in sequence (e.g. steps such as isolate gall bladder, then remove gall bladder; and motions such as reach, then orient, then open jaws, then close jaws), while others were parallel and iterative (e.g. sub-steps such as locate and dissect surround of gall bladder; tasks such as poke and tease tissue). Regardless of the serial or parallel nature of the components in the decomposition, the operational definition of the ending was always in terms of the observable achievement of a specific surgical task, or motion goal.

In this paper, we detail the Nissen fundoplication procedure. The operational definitions for the surgical steps are presented in Table 1. Note that the beginnings and endings for each step can be identified by specific, observable surgical events on the video. Two independent annotators assessed the times of the events defining these fundoplication steps based on the operational definitions, for one randomly selected fundoplication procedure. Using Kendall's Rank Order Correlation Coefficient T, and Freidman's Rank Test for Correlated Samples, the inter-rater reliability showed significant agreement between the two annotators. Also, on two separate occasions, one annotator performed video analysis of the steps for a particular procedure and showed high intra-rater or day-to-day reliability in identification of the surgical steps. Only this individual analysed the majority of the videotaped surgical procedures, over an 8-month period.

Figure 1 represents the hierarchical decomposition of the Nissen fundoplication procedure. When the step of dividing the short gastric is included there are seven surgical steps making up this anti-reflux procedure. The steps are: prepare patient, divide peritoneum, expose crura and GE junction, repair crura, divide short gastrics, wrap fundus, and close patient. The steps were divided into sub-steps, also with operationally defined beginnings and endings. For example, the 'wrap fundus' step included the following sub-steps: elevate oesophagus, pull fundus under, anchor fundus and suture wrap.

Each surgical sub-step is composed of a number of tasks. In the fundoplication we chose to examine four of the tasks regularly performed in a number of the surgical steps. The tasks were dissect, suture, anchor suture, knot and cut suture. These tasks were performed using the laparoscopic scissors/dissector, harmonic scalpel, endostitch tool and grasper (usually a Maryland dissector). The 'dissect' task was quite complicated because there were a number of tools and techniques used to separate different types of tissue. It was found that, on average, there were four sutures, one anchor suture, three-and-a-half knots, and five cut sutures in every fundoplication procedure. The durations of these four tasks indicate that the knotting task takes the longest, followed by anchor suturing, normal suturing and cutting suture tasks.

At the lowest level of the hierarchy in Figure 1 are sub-tasks, depicted only for the suture task. Examining Figure 1, we follow down the hierarchy: repair crura step, join crura sub-step and suture task. The sub-tasks making up the suture task are position jaws, bite, pull needle through, re-position, re-bite, re-pull needle through, re-re-position, re-re-bite, re-re-pull needle through and pull suture. Operational definitions of these sub-tasks for the suturing task using the endostitch tool are provided in Table 2. The first sub-task requires the surgeon to get oriented within the internal abdominal space and then to locate the precise location of the suture. The subsequent position sub-tasks take less time because the surgeon is already oriented in the internal environment. The 'pull suture' sub-task takes a longer time because the surgeon is ensuring that the suture is secure and will hold the wrap adequately.

The suturing task and the knotting task act together to effectively approximate tissues (crura and fundus). The knotting task is made up of nine sub-tasks: loop, needle under loop, anchor knot, twist and loop, needle through loop, pull knot tight, re-twist and loop, needle re-through loop, and re-pull knot tight (not shown in Figure 1 due to space constraints.) The sub-tasks taking the most time to complete are loop and anchor knot, taking > 50% of the total time of the

Table 1. Operational definitions of surgical steps in Nissen fundoplication

Surgical steps	Beginning	Ending
1. Prepare patient	Moment the insufflation needle contacts abdomen	Liver in place and liver elevator is stable
2. Divide peritoneum	Moment the tool moves towards the peritoneum to cut	Last cut of peritoneum
3. Expose crura and GE junction	Last cut of peritoneum	Last cut of tissue and when scissors are removed
4. Repair crura	Moment the endostitch contacts abdomen	Completion of cut suture and removal of endostitch
5. Divide short gastrics	Moment scalpel contacts abdomen	Last cut and scalpel removed
6. Wrap fundus	Moment oesophageal elevator contacts abdomen	Completion of last suture — endostitch is removed
7. Close	When endostitch is removed	Completion of last open suture

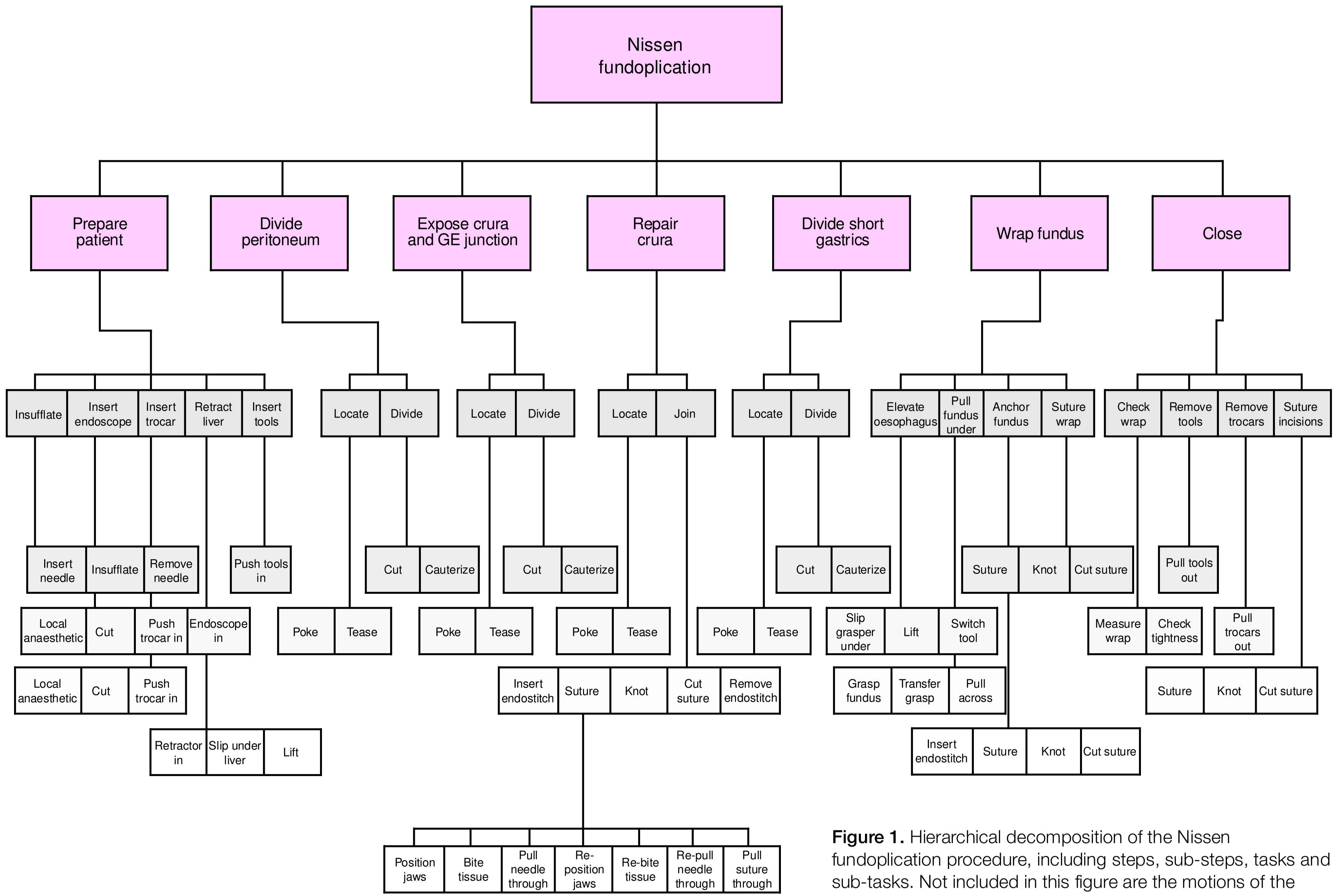

Figure 1. Hierarchical decomposition of the Nissen fundoplication procedure, including steps, sub-steps, tasks and sub-tasks. Not included in this figure are the motions of the laparoscopic tools. See text for details.

Table 2. Operational definitions of sub-tasks in the suturing task using the endostitch tool in fundoplication

Sub-tasks	Begin	End
1. Position jaws	First movement of endostitch towards target tissue	Ready to pass needle through tissue (i.e. tissue between open jaws)
2. Bite tissue	Closing movement of jaws to pass needle through tissue	Opening movement of jaws with needle passed over through tissue
3. Pull needle through	First movement of pulling suture through tissue (i.e. jaws opening after bite)	End of first pulling movement with needle through tissue (i.e. jaws close)
4. Re-position jaws	First movement of endostitch towards target tissue	Ready to pass needle through tissue (i.e. tissue between open jaws)
5. Re-bite tissue	Closing movement of jaws to pass needle through tissue	Opening movement of jaws with needle passed over through tissue
6. Re-pull needle through	First movement of pulling suture through tissue (i.e. jaws opening after bite)	End of first pulling movement with needle through tissue (i.e. jaws close)
7. Pull suture through	End of first pulling motion	Completion of pulling suture through (i.e. small grasper is reaching for end of suture)

entire knot. These sub-tasks occur early in the knot task and are essential for a good knot. They provide the secure base for the knot. Subsequent sub-tasks simply strengthen the knot.

It was found that all tasks and sub-tasks could be broken down into five basic motions [6]. These motions were: reach and orient; grasp and hold/cut; push; pull; and release. The descriptions and coordinate axes for these motions are summarised in Table 3. These motions were found from observing the video and annotating the motions of the tools occurring during certain tasks and sub-tasks. When two tools were being used, they were analysed separately so the different motions for each were known.

Both the endostitch and laparoscopic grasper were used for the tasks examined. The tasks of anchor suture, normal suture and knot were all analysed down to the motion level. At the lowest level in the hierarchical decomposition (not shown in Figure 1), the motions did not occur in the same organised pattern over all procedures, or even tasks or sub-tasks. The motions were not timed, but were looked at in terms of a frequency count. The frequencies at which the motion occurred were placed within the context of the higher levels, such as sub-task and task. This provided a measure that helped determine quantitatively how complex certain sub-tasks and tasks were for the surgeons, i.e. the more complex tasks and sub-tasks contained a greater number of tool motions.

Analyses of event timing and durations of hierarchical components at all levels provided interesting results, not reported in detail here. The hierarchical decomposition approach allowed the durations of larger and progressively smaller units to be determined and compared across surgeons, surgical experience, patients, particular tools, viewing conditions and procedural variations. For example, in Nissen fundoplication, we compared whether or not surgeons divided the short gastrics. In the initial surgeries we observed, the short gastrics were not

Table 3. Description of motion and movement coordinate axes [6]

Motion	Description	Movement coordinates
Reach and orient	Movement of tool in any direction towards or away from target	Translation along z-axis
	Rotational movement of tool about tool insert point	Rotation about z-axis, x and y axes
Grasp and hold/cut	Open and close movement of jaws	Open/close about the jaw coordinate system
Push	Movement of tool into target tissue, usually with end-effector closed	Translation along z-axis Rotation about z-axis, x and y axes
Pull	Movement of tool away from target tissue, usually with object in stable grasp	Translation along z-axis Rotation about z-axis, x and y axes
Release	Open jaws	Open/close about the jaw coordinate system

cut. The harmonic scalpel then became available to our surgeons in 1996. Although adding the step of dividing the short gastrics with a harmonic scalpel took time, this dramatically shortened the time taken for the next step (wrapping the fundus around the oesophagus), compared to not dividing the short gastrics. Demonstrated in Figure 2, this comparison shows the power of the hierarchical decomposition as an assessment tool.

Analysis of gaze patterns revealed that the surgeon's gaze was directed primarily to the monitor (about 80% of the operative time), with the remainder of the time spent looking at the hands/tool handles or away from the monitor and hands. Gaze patterns varied systematically with transitions between surgical tasks, tool insertions and removals [7]. Results of our video analysis also indicated those factors that were potentially critical to patient safety and error in this complex system [8]. Aspects of viewing systems (interference), tools (faulty end-effectors), equipment layout (too many cables) and communication varied with the chronological context of the hierarchical decomposition.

Discussion

Hierarchical decomposition is a powerful analytic approach that offers one framework for structuring the complex environment within which the surgical team and technology interact [9,10]. The hierarchical decomposition approach can be used and extended for numerous applications in minimally invasive surgery which include:

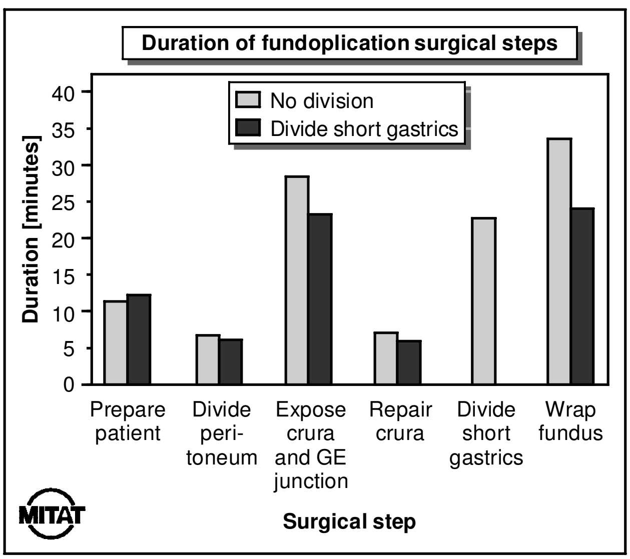

Figure 2. Contrasting the durations of the steps of the Nissen fundoplication procedure, depending on whether or not the short gastrics are cut with a harmonic scalpel.

- Designing and evaluating the effectiveness of new tools for visualisation and manipulation [11].
- Evaluating different aspects of operating room layout, e.g. monitor display position.
- Designing training for surgery through modular sections corresponding to our hierarchical decomposition. Such training could be implemented with physical or animal models, augmented or virtual environments [12,13].
- Evaluating surgeons' performance, assessing skill levels and learning curves in modular, manageable units.
- Planning customised patient-specific surgery prior to the operation.
- Analysing changes in the surgeon's focus of attention, at each step or level in the hierarchy.
- Understanding what information is used and required by the surgical team, and the optimum ways to present this information during the procedure.
- Improving patient safety and decreasing errors, by assessing in the hierarchical context [14].
- Improving the technology in general. Making a better 'fit' between the technology and the surgeon, given human user characteristics and constraints.

The hierarchical decomposition approach gives the above activities a framework for assessment. Most importantly, it has the advantage of allowing comparison of similar components of different systems, or comparison of variations in certain components of the same system, at many levels of analysis. It can be used to evaluate variations in technique or technology, as well as experience, learning and skill level of the surgeon. Since the functional goals at each level of the hierarchy are explicit, the behavioural effects are clearly attributable to the changed constraints resulting from the new technique or technology. This makes for a simple, objective, yet elegant way of analysing task and function in a complex system. However, it does not lend itself to inferences about the cognitive aspects of the performers (surgical team) within such a system. The hierarchical decomposition approach is focused on the functional aspects of the task, i.e. the behaviour of the user in executing the task with the specific tools, and the underlying constraints within the operating room environment. It is, therefore, limited in its application for elucidating human cognitive processes underlying the performance of complex surgical tasks.

In summary, we have presented a hierarchical framework for the decomposition of laparoscopic surgical procedures, from a surgeon-centred, human-factors perspective. This framework enables both qualitative and quantitative analyses of surgeon–task–tool interactions, and could be extended to all members of the OR team. Given the complex environment of the hospital OR, other frameworks for assessment of surgical techniques and technologies are needed. To develop such frameworks, we must cross disciplinary boundaries and levels of analysis, bridge medical/health, educational and industrial sectors, and build collaborative national and international networks. These new frameworks will lead to evidence-based decision-making for: the purchase, implementation and integration of new surgical technologies in the ORs of hospitals; the planning and execution of surgical and other therapeutic interventions; and the improvement of patient health and safety.

Acknowledgements

This research, 'Remote Manipulation in Endoscopic Surgery', was funded by the British Columbia Health Research Foundation (BCHRF), Canada. Preparation of this manuscript was funded by the Institute for Robotics and Intelligent Systems (IRIS3) in Canada, 'Intelligent Tools for Health Care' project, to C.L. MacKenzie as Principal Investigator. Thanks go to the patients, surgeons, and OR staff for cooperation and informed consent. Thanks also to Elaine Lee, Sarah Manske and Bin Zheng for assistance with the figures in this report.

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