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SURGICAL ENDOSCOPY
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Sequence and task analysis of instrument use in common laparoscopic procedures

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Abstract
Background: In the area of instrument evaluation, one aspect that still requires objective assessment is the dynamics of instrument maneuver and exchange. If we could gain a better understanding of these phenomena, we could improve the design of the instruments themselves.
Methods: A total of 29 laparoscopic procedures were videotaped and reviewed using time motion analysis. Instrument multifunctionality was determined using a standardized list of laparoscopic maneuvers. State transition diagrams were utilized to document the sequence of instrument exchanges.
Results: The curved dissector, atraumatic grasper, and cautery scissors were identified as the most multifunctional instruments; each was able to perform five distinct maneuvers. Instrument sequences were found to consist of a three-part dissect → clip → cut cycle and a two-part dissect → suction cycle of instrument exchange.
Conclusion: This study demonstrated that laparoscopic instruments are often used to perform a variety of maneuvers in addition to their primary function. Furthermore, there are common patterns in instrument exchange that provide a potential source of design parameters for improved surgical efficiency.

Key words: Laparoscopy — Instrumentation — Multifunctionality — Task analysis — Instrument exchange

In recent years, there has been an explosion of new instruments and techniques aimed at improving the efficiency and outcome of laparoscopic procedures [1, 2, 9, 10, 12]. To accommodate the rapid development of so many new instruments, the design process needs to be reexamined to take future trends into account. The introduction of new instruments usually follows a cyclic process of concept → prototype design → prototype construction → laboratory and clinical evaluation → altered concept [9]. The laboratory and clinical evaluation step typically addresses the issues of postoperative outcome, reduced procedure time, and increased comfort and maneuverability for the surgeon [3, 12, 17]. In addition, specific aspects of an instrument's function, such as cutting, coagulating, or ease of dissection, are also evaluated [1, 2].

A key issue in the analysis of any instrument is its clinical functionality and efficiency. However, in terms of efficiency, one aspect that has not been thoroughly explored is the need to switch from one instrument to another during a procedure. Besides running the risk of trauma, exchanging instruments disrupts the flow of a procedure and increases the operating time [8, 15]. Thus, it would improve operative efficiency if new techniques and instruments that minimize such exchanges were developed. In addition, to understand the functionality of an instrument, we need to know how it is actually used during surgery and what impact its use has on the flow or dynamics of the procedure. Only recently has there been an attempt to create an objective means of instrument and technique analysis that would address these parameters [6, 7, 8, 15]. One such method is time motion analysis, which uses videotape and standardized evaluation criteria to analyze a particular aspect of the procedure. The use of evaluation criteria often involves timing the specific actions that make up an operative procedure or assessing the frequency of a given surgical movement [4, 5, 13]. This type of analysis could promote the development of new instruments based on an objective need-based assessment [14].

The dynamics of instrument exchange and functionality have not yet been fully explored. Therefore, this study was designed to use time motion analysis to explore the specific maneuvers that are performed by various laparoscopic instruments as well as the sequence in which they are utilized.

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Table 1. Operational definitions of maneuvers

Maneuver	Operational definition
Retracting with grasping	Maneuvering a tissue or organ that is inside the jaws of the instrument
Retracting without grasping	Maneuvering a tissue or organ while it is not within the jaws of the instrument
Cut ultrasonic	Separating tissue planes using the ultrasonic energy generated by the ultrasonic shears
Dissecting	Separating tissue planes using the blunt end of an instrument
Cutting	Slicing tissue or sutures using sharp scissors
Coagulation	Cauterizing a vessel without cutting
Clipping	Occluding a vessel or connecting latex drains with a metal clip
Irrigation and suction	Clearing the field of view using saline and/or suction
Suturing	Piercing of tissue with the suture needle
Suture tying	Manipulating the needle or free end of a suture to make a knot
Specimen/material removal	Removing an organ, tissue sample, or surgical material
Stapling	Separating tissues with a mechanical stapling device
Cut cautery	Separating tissue planes using electrical cautery

Further, we also assessed the relative complexity or multifunctionality of certain laparoscopic instruments in addition to looking for patterns of instrument use during procedures.

Methods

Laparoscopic procedures were viewed to assess the array of unique instruments and maneuvers used in their performance. An objective scoring system was then created to annotate all procedures. In all, 16 distinct instrument maneuvers were identified. The operational definitions for these maneuvers are given in Table 1.

Twenty-nine laparoscopic procedures performed by eight different surgeons were reviewed. The procedures were videotaped in the operating room from beginning to end through the endoscopic video system. Tapes were recorded at super long play speed (SLP) using VHS. A single observer (NYM) reviewed the videotapes using a TV/VCR monitor with a built-in time counter that continuously displayed the time of the tape in minutes and seconds.

An operation was considered to have begun when the first instrument was inserted through a laparoscopic port. At this instant, the time counter was reset and the instrument, port location, and insertion were noted. Tapes were then viewed at normal play speed. For the remainder of the procedure, each new maneuver was recorded with reference to the instrument, port, and time within the case. The recording of this information was simplified by assigning each instrument and maneuver a unique numeric code. Port designations were standardized within a particular type of operation.

The insertion and removal of each instrument were noted for timing purposes. The instrument was considered to be inserted when the it became visible in the videoscopic field. The removal of an instrument was recorded when it was withdrawn through the port. If the port tip was not visible, rapid withdrawal of the instrument toward the port with the subsequent insertion of another instrument constituted a removal. The beginning time of an instrument maneuver was defined as the moment when the instrument made tissue contact and began performing the maneuver. The end time of a particular maneuver was defined as the moment when a new maneuver was initiated or the instrument was removed.

Idle time was also taken into account to better estimate the actual usage time of an instrument or maneuver as well as the total working time of an operation. Idle time was recorded when all the instruments in the surgical field were inactive for a period of ≥ 30 sec or when all the instruments had been removed from the patient. Idle time could not be assessed qualitatively because the etiology of each idle-time occurrence was unknown to the tape reviewer.

Collectively, these data allow a reconstruction of the sequence of instrument exchanges, as well as the relative frequency of a particular instrument change during a given procedure. The sequence of instrument exchanges was displayed using state transition diagrams [11, 13] created by Visio software (Microsoft, Redmond, WA). Individual instruments were compared on the basis of the number of unique maneuvers each could perform; in this way, we were able to quantify the level of multifunctionality of the instrument.

Results

A total of 29 videotaped procedures were reviewed. Procedure types included laparoscopic cholecystectomy ($n = 11$), Nissen fundoplication ($n = 6$), adrenalectomy ($n = 4$), appendectomy ($n = 4$), splenectomy ($n = 2$), and donor nephrectomy ($n = 2$).

Individual instruments were analyzed for the number of distinct maneuvers each could perform. This assessment of multifunctionality is summarized in Fig. 1. The atraumatic grasper, cautery scissors, and curved dissector had the highest level of multifunctionality, each having been used for five different maneuvers across all the cases.

A comparison of overlapping and unique instrument maneuvers is shown in Fig. 2. The atraumatic grasper and curved dissector were both used for the same five maneuvers. Both of these instruments and the cautery scissors were used for retracting with grasping, retracting without grasping, and dissecting. Unique to the atraumatic grasper and curved dissector, as compared to the cautery scissors, was their use to suture and tie sutures. The cautery scissors differed from the atraumatic grasper and curved dissector in their use to cut with the blades and also to cut with electrocautery. Two instruments were forward to have the versatility to perform four distinct functions each.

The ultrasonic shears and the right angle dissector were both used to retract with grasping, dissect, and retract without grasping. The ultrasonic shears, however, had the unique use of cutting with high-frequency energy, whereas the right angle dissector differed with its use of suture tying. The suction/irrigator was used for three separate maneuvers. It is designed to perform irrigation and suction, but it was also used for retracting without grasping and dissecting purposes.

Another way to quantify multifunctionality was to measure the frequency of different maneuvers that were performed by a particular instrument. Figure 3 shows how the ultrasonic shears were utilized in the Nissen fundoplications.

The sequence of instrument changes was analyzed using a state transition diagram. An example of a laparoscopic cholecystectomy is shown in Fig. 4. The most common instrument exchanges for all procedures are listed in Table 2. The probability of an instrument exchange was calculated

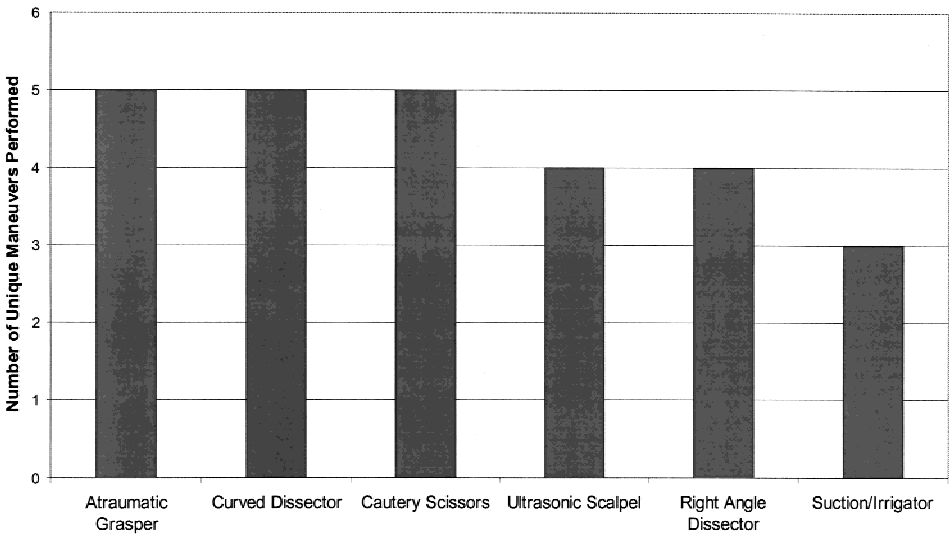

Fig. 1. Assessment of instrument multifunctionality based on the number of unique maneuvers performed by the instruments.

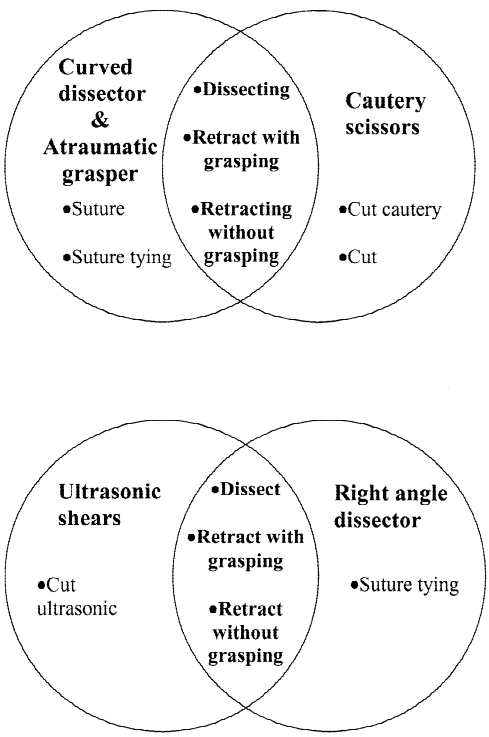

Fig. 2. Overlapping and distinct maneuvers performed by multifunctional instruments.

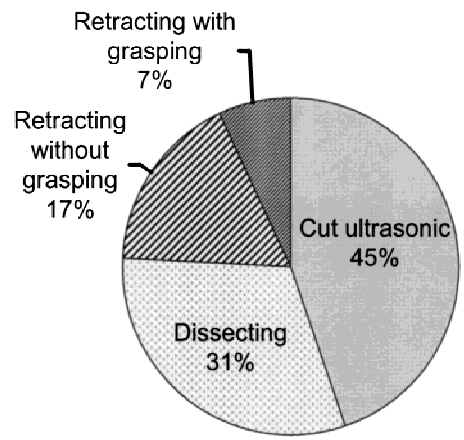

Fig. 3. Less than half of the maneuvers, actually done with the ultrasonic shears were performed to utilize the designated function of cutting during Nissen fundoplication. The shears were also used as an alternative instrument for dissecting, retracting without grasping, and retracting with grasping.

based on all the possible subsequent instruments after removal of the initial instrument. Two- and three-instrument cycles were used in the cholecystectomy. The three-instrument cycle involved the curved dissector, clipper, and scissors. Removal of the curved dissector was followed by the insertion of a clipper 58.7% of the time. Subsequent removal of the clipper was almost always (89.7%) followed by insertion of the scissors. Finally, the scissors were most often (66.7%) exchanged for the curved dissector again. The two-instrument cycle describes exchanges between the hook cautery and the suction/irrigator. Almost every time the suction/irrigator was used, it followed the hook cautery (87.5%). Reciprocally, most hook cautery removals gave rise to suction/irrigator insertions (68.8%).

In the adrenalectomies, two- and four-instrument cycles were observed. A four-instrument cycle was identified for the ultrasonic shears, right angle dissector, clipper, and scissors. The right angle dissector was always preceded by the ultrasonic shears; this was a rare example of two dissecting instruments with a clear temporal relation. Following use of the right angle dissector, the clipper was usually (80.0%) the next instrument. As in a cholecystectomy, scissors often (47.0%) followed the clipper but not with the same predictability as in the cholecystectomy (89.7%). Finally, the scissors were most often removed (75.0%) for use of the ultrasonic shears. Both of the two-instrument cycles involved the suction/irrigator in combination with the ultrasonic shears and the clipper, respectively (Table 2).

Donor nephrectomy had a similar three-instrument cycle consisting of the ultrasonic shears, clipper, and scissors. We also identified an ultrasonic shears/suction/irrigator cycle. The relative probability of instrument exchanges is shown

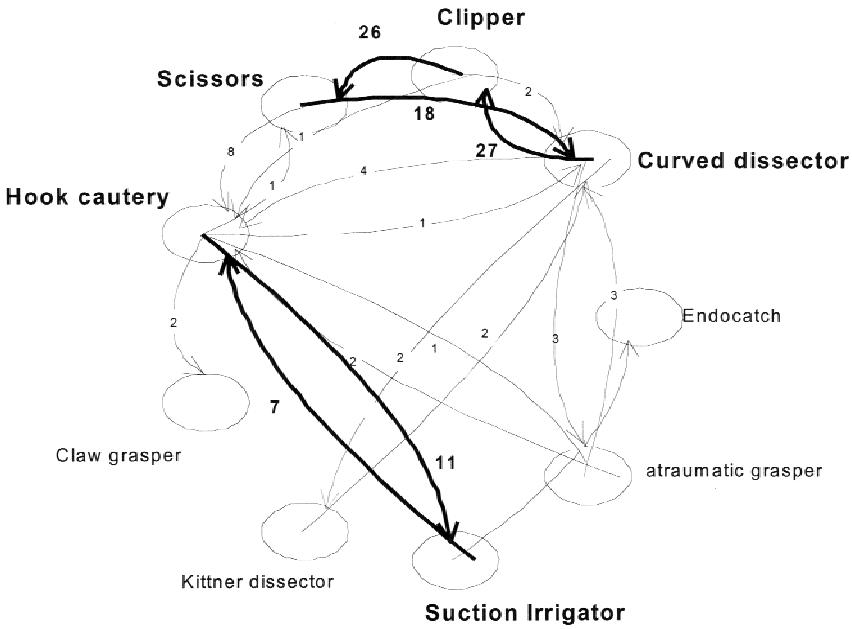

Fig. 4. Instrument exchanges at port three in 11 cholecystectomies. Each oval represents an instrument; as labeled. Each arrow represents removal of the instrument at the arrow's tail and its replacement with the instrument at the head. The number associated with each arrow is the number of times that specific instrument exchange occurred (in total) in the 11 cases. In seeking ways to reduce the number of instrument changes, it is useful to look for repetitive cycles of instrument use. The curved dissector → clipper → scissors cycle and a hook cautery → suction irrigator cycle are the most prevalent patterns of instrument exchange in the example.

Table 2. Common instrument exchanges in laparoscopic procedures

Procedure	Initial instrument	Subsequent instrument	Probability of exchange (%)[a]
Cholecystectomy	Curved dissector	Clipper	75.0 (27/36)
	Clipper	Scissors	89.7 (26/29)
	Scissors	Curved dissector	66.7 (18/27)
	Hook cautery	Suction/irrigator	68.8 (11/16)
	Suction/irrigator	Hook cautery	87.5 (7/8)
Adrenalectomy	Ultrasonic shears	Right angle dissector	22.7 (5/22)
	Right angle dissector	Clipper	80.0 (4/5)
	Clipper	Scissors	47.0 (8/17)
	Scissors	Ultrasonic shears	75.0 (6/8)
	Ultrasonic shears	Suction/irrigator	45.5 (10/22)
	Suction/irrigator	Ultrasonic shears	57.9 (11/19)
	Clipper	Suction/irrigator	41.1 (7/17)
	Suction/irrigator	Clipper	36.8 (7/19)
Donor nephrectomy	Ultrasonic shears	Clipper	27.3 (9/33)
	Clipper	Scissors	70.6 (12/17)
	Scissors	Ultrasonic shears	57.1 (8/14)
	Ultrasonic shears	Suction/irrigator	27.3 (9/33)
	Suction/irrigator	Ultrasonic shears	69.2 (9/13)
Nissen fundoplication	Atraumatic grasper	Mechanical suturing device	32.1 (9/28)
	Mechanical suturing device	Atraumatic grasper	66.7 (10/15)

[a] Proportion of times following removal of the initial instrument that the subsequent instrument was inserted

in Table 2. In the Nissen fundoplication, there were no three-instrument cycles. The only noticeable two-instrument cycle was the switch between the atraumatic grasper and the mechanical suturing device. In all four types of procedures, an instrument exchange that occurred less than four times was considered insignificant and was not considered to contribute to any cycle.

Discussion

Improved efficiency in the performance of a procedure one of the primary goals of instrument design. The dynamics of instrument exchange and functionality are two aspects of instrument design that need to be further explored. This study was undertaken to gain a basic understanding of how certain laparoscopic instruments are used and how they are exchanged for one another. With the growing variety of instruments available to the laparoscopic surgeon, the decision of which instruments to choose during a given procedure is becoming increasingly difficult. One reason often given for why a particular instrument is chosen is the diversity of its functions, or its 'multifunctionality'.

In this study, the instruments with the greatest diversity of function were three types of dissectors and two types of cutting/coagulating device. The features common to all five instruments were their ability to retract tissue with and without grasping and their ability to dissect. Dissecting is a

primary function of dissecting instruments, but it was also a common function of the most popular grasping device in our study (the atraumatic grasper) and the two cutting/coagulating devices. Even the suction/irrigator was used to dissect on many occasions. Among these instruments, the suction/irrigator is the least well equipped to dissect; its use for dissection illustrates the surgeon's willingness to use an instrument for a purpose not intended by its designers if the situation warrants it and the instrument is adequate for the task. Similarly, the tasks of suturing and suture tying were accomplished using needle holders, but they were also done using the atraumatic grasper, curved dissector, and right angle dissector. The latter three instruments indicate once again that secondary uses of instruments are common in laparoscopic surgery.

These alternative uses most likely arise due to a number of factors. One is that instrument exchange during laparoscopic procedures is time-consuming [6]. If the current instrument is adequate to complete the new task, then it may be retained to do so. In this decision process, the surgeon must weigh the benefits of saving time through one less instrument exchange vs the potential time savings of exchanging the instrument in hand for a new one that is more ideally suited for the task. Most situations that instigate secondary uses are somewhat transient, so it is often deemed better to simply retain the current instrument. Another possible reason for the alternative use of an instrument is that exchanging instruments poses a safety risk to the patient. Changing instruments disrupts the flow of the procedure [8, 15] and can break the concentration of the surgeon. In addition, due to the limited view obtained with most endoscopes, there may be instances during an insertion or removal when the instrument cannot be seen while it is still inside the patient. These "blind" episodes are potential causes of trauma that can be minimized by reducing the frequency of instrument exchanges; hence, the surgeon may decide to retain his or her current instrument.

The importance of documenting such secondary use is that the data can provide designers with a new perspective on instrument development. For example, if ultrasonic shears are used more often for dissecting and grasping, then newer designs should accommodate these needs. It is unclear how much designers actually focus on multifunctionality, yet multifunctionality clearly plays a role in making an instrument more effective and hence more popular among surgeons. Solely improving the primary function of an instrument at the detriment of secondary and tertiary uses decreases its flexibility and could therefore limit its acceptance.

It is unlikely that any one instrument could be diverse enough to adequately perform every function that is needed in a complex laparoscopic procedure. Since instrument exchanges are inevitable, we looked more closely at the process of instrument exchange, paying particular attention to the sequence followed in instrument changes. Using state transition diagrams, we found that the most common sequence among all types of procedures was a dissect → clip → cut → repeat cycle ("dissect" here is meant to be a broad term comprising previous operational definitions for dissection, ultrasonic cutting, and cutting with cautery). This cycle was most prevalent during a cholecystectomy, where there was a very high probability of being able to predict the next instrument following a particular instrument removal. The purpose of trying to recognize such repetitive sequences was to identify common steps in laparoscopic procedures where instrument exchanges could potentially be eliminated. By somehow combining the function of two of the three instruments in a cycle, the number of instrument changes necessary to complete the procedure could be reduced [16].

This would shorten the operative time and lessen the potential trauma to the patient during an instrument exchange.

Another common cycle that was seen across all of the procedures was the dissection → suction cycle. Attempts have been made to combine these two entities, for example with an ultrasonic aspiration device [1] that fragments collagen-sparse tissue. Most of the applications identified in this study, however, involved the suction of fluids rather than tissues. Without proposing specific designs, we suggest that an instrument that combined these two maneuvers would help to maintain the continuity of a case for the surgeon, thus greatly expediting the procedure.

This study was limited by our lack of knowledge regarding the circumstances surrounding instrument and maneuver changes. Objective observations were made of these two phenomena, but the underlying reasons for their occurrence were not addressed. Certainly some reasons for selecting or exchanging an instrument are more obvious than others. For example, the accidental rupture of a vessel necessitates some form of ligation of the vessel and subsequent cleanup, increasing the chances that certain instruments will be utilized, such as a clipper and a suction/irrigator. Another factor that influences instrument use is the specific instruments that are actually available to the surgeon during a particular operation. If a certain type of dissector that would be ideal for a particular maneuver is not available, the surgeon will be forced to opt for the next best choice among the instruments at his or her disposal. Since not all of the instruments identified in this study were available to every surgeon in every procedure, some compromises in instrument selection must have been made. To understand the context within which certain instruments were exchanged for one another, future studies should be designed to take this aspect into account. Both quantitative and qualitative data on instrument usage are needed so that the instrumentation demands of laparoscopic surgeons can be assessed accurately.

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