SPECIAL ARTICLE

Surgery and Ergonomics

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This article will provide the reader with an overview of ergonomic issues relevant to the operating room environment. Minimally invasive surgical technologies have increased the therapeutic value of surgical procedures by allowing operations to be performed with less trauma to the patient. At the same time, the surgical team—and particularly the surgeon—have been further removed from direct interaction with the patient's tissues. A scientific and ergonomic approach to the analysis of the operating room environment and the performance and workload characteristics of members of the modern surgical team can provide a rational basis for maximizing the efficiency and safety of our increasingly technology-dependent surgical procedures.

Arch Surg. 1999;134:1011-1016

Although surgeons have undoubtedly had a long-standing interest in the design and efficiency of their tools, Frank Gilbreth, a pioneer in the field of time and motion study, noted in 1916 that " . . . surgeons could learn more about motion study, time study, waste elimination, and scientific management from the industries than the industries could learn from the hospitals."[1] Gilbreth observed that surgical practices and instrumentation varied greatly throughout the country, leading to inefficiency and the lack of a "best" approach to each treatment modality. This mindset reflected the growing interest in the method of scientific management in industry[2] during the early part of this century. Despite some early efforts at objectively studying surgical operations,[3,4] objective work analysis was not widely applied to surgical procedures.[5] Indeed, only 20 years ago Dudley[6] noted that " . . . looked at from the ergonomic point of view most major operations are, at first sight, a mess."

This state of affairs is curious, for there are, in effect, many mental and physical similarities between a surgeon's work and skilled industrial and military jobs. Surgery requires a high level of intellectual preparation, an efficient and controlled workspace, fine motor skills, physical endurance, problem-solving skills, and emergency response skills. Moreover, surgical care is expensive and the costs of errors or delays in surgical treatment are substantial in both economic and human terms. Ergonomic methods would thus seem well-suited to the analysis of surgeons' work. That this has not occurred is probably the result of many interrelated factors, some unique to the field of surgery.

Surgeons train in an environment that discourages complaints about stress and fatigue. The inherent drama of surgical work, coupled with surgeons' historically high social standing, is likely to have encouraged them to see themselves as elite craftsmen and to be reluctant to have their unique work habits analyzed or criticized by others. The relatively low technological demands of surgical operations (with the exception of cardiac and orthopedic subspecialties) until the recent advent of video endoscopic surgery (VES) may also have been a contributing factor to this lack of interest in medical ergonomics. Perhaps most importantly, under a fee-based and physician-driven health care compensation system, surgeons and

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administrators may well have thought of work analysis as an unnecessary annoyance that could be financially counterproductive. In today's highly competitive and cost-conscious health care system, it is likely that our technical progress toward the full potential of less-invasive surgical techniques will be substantially moderated by cost and human performance issues.

HISTORY OF ERGONOMICS

Ergonomics as a science is relatively new. This field, also called "human factors," has to do with designing machines and tools that optimize the performance of the user.[7] The first modern ergonomic studies were Frederick W. Taylor's time study[2] and Frank B. and Lillian M. Gilbreth's motion study.[8] Between 1900 and 1940 there was a growing interest in scientific management, but the availability of cheap labor and the scarcity of funds limited research into this area. World War II created a new interest in the measurement of operator performance in skilled military jobs, providing the impetus for the development of the field of "engineering psychology."[9] As the demands of work-related machinery increasingly exceeded the intuitive human ability to cope with them during the next 3 decades, the field of ergonomics developed into a science of its own. Ergonomic analyses are widely applied today in industry,[10] the military,[11] and sports training[12] to help people achieve optimum performance with a low risk of error and injury.

In the field of medicine, there has been an increased awareness of the importance of ergonomics[13] and the applications of systems analysis.[14] Ergonomic problems have been investigated in relation to intensive care units,[15] gastrointestinal endoscopy,[16] back injuries in health care workers,[17,18] and job difficulty in medical-surgical staff nurses.[19] Anesthesiologists, perhaps more than any other medical specialty, have addressed the important information display and equipment design factors that affect their work.[20-22] In a related specialty, the higher incidence of occupational cervicobrachial disorders among dentists[23] has prompted improved designs of the dental operatory.[24] Despite the increasing attention to ergonomics in health care, it is sobering to read a recent report by the Food and Drug Administration that estimates that poor design of medical instruments may account for half of the 1.3 million unintentional patient injuries in US hospitals each year.[25]

A REVIEW OF ERGONOMICS IN SURGERY

Visualization

Under open conditions surgeons can view their work directly. The main visual ergonomic considerations are the adequacy of the exposure of the operating field to direct viewing and the quality and intensity of lighting on the field. Exposure is greatly aided by proper positioning of the patient and the application of mechanical retractors to the wound and internal tissues. Retractors with various shapes have long been in use but there has been little formal evaluation of their performance.[26] For example, a comparative study of different retractor handles[27] concluded that a hand-held abdominal retractor handle with a vertical "T" handle configuration was preferred by almost all users, yet this information has had no effect on retractor design. Although there are numerous self-retaining retractor designs available today, there are no objective data to support the choice of one design over another. The proper lighting of the surgical field has been the subject of several reviews,[28,29] and detailed recommendations for optimum lighting during open surgery have been published.[30] However, uncertainties still remain regarding the optimum size, location, and number of surgical lights and the most efficient type of controls.

Video endoscopic surgery has introduced the greatest challenge yet to the surgeon's natural view of the operating field. Using current technology, the surgeon views a relatively low-resolution monocular video image of the operating field, which is often degraded by variable lighting inside the body cavities and by the movement of the camera-holding assistant. Under these visual conditions, surgeons require significantly longer times to complete manipulative tasks when compared with direct binocular or direct monocular vision.[31] The lack of depth perception with monocular video systems has been thought to be a significant performance limitation. However, several comparative performance studies of standard monocular and 3-dimensional (3-D) binocular VES systems[32-35] have demonstrated improvement in surgeons' performance using 3-D systems only during complex positioning tasks in a laboratory setting.[32,36] Indeed, a recent randomized clinical study reported no difference in performance or adverse visual symptoms using 2-dimensional or 3-D imaging systems during laparoscopic cholecystectomy.[37] The lack of significant clinical performance enhancement with 3-D VES may be due to a number of factors such as the small distance between the binocular endoscopic channels, the low resolution of current video systems, slow frame refresh rates, and subjects' complaints of eye fatigue and headaches during use of the 3-D systems.[35,37] Others investigators suggest that factors such as background contrast and illumination are equally important 3-D visual cues for the surgeon.[38] The objective performance data regarding the efficacy of 3-D imaging systems is an excellent example of the kind of practical answers one can obtain through ergonomic evaluations of new technology. High technology is not always the answer to human interface problems. For example, in a blinded comparison of several VES camera systems, operating room personnel subjectively preferred digitized video systems but saw no advantage in image quality with the use of 3-chip vs single-chip camera systems.[39]

One basic ergonomic consideration—the correct position of the video display relative to the user's eyes—is almost routinely ignored in VES. Video monitors are commonly placed on top of equipment carts or wherever there is space in the operating room, with the consequence that the image lies at or above the average surgeon's eye level and often to the surgeon's side. Studies of office video terminal display (VDT) users demonstrate that the preferred viewing angle for VDTs is between 10° to 25° below the line of sight.[40] Excessive height of VDTs has been linked to symptoms of neck and back pain in office workers,[41] which may explain why a small but significant number of laparoscopic surgeons complain of frequent neck stiffness and pain.[42] Indeed, Hanna et al[43] have reported an increase in knot-tying performance when surgeons view a monitor placed at hand level instead of at eye level. One approach to improving monitor position has been to install VDTs on ceiling-mounted booms[44] that can be positioned as desired around the operating table. While this approach can facilitate the proper alignment of the surgeon and assistants with the image of the surgical field, the cost of installation remains high and many booms cannot be positioned below eye level. Other innovative approaches to solving the problem of VES display position have included projecting the video image onto a 13-in sterile screen placed in front and slightly below the surgeon within the surgical field (ViewSite display system; Karl Storz Endoscopy, Culver City, Calif) and incorporating the image into a head-mounted display system worn by the surgeon.[45] Clinical and ergonomic studies to assess the effect of these display systems are in progress. Other ergonomic problems with visualization still remain, such as the natural control of the direction of view during VES. Preliminary studies using a voice-controlled robotic assistant suggest this device can facilitate the surgeon's visualization of the field,[46] although savings in actual operating time have not been documented.[47] Achieving adequate visualization in a cost-effective and user-friendly manner will remain a major challenge.

Manipulation

Standard open surgical instruments surgery such as forceps, clamps, and scissors evolved rapidly into standardized designs that accommodated ease and universality of use, mass production, and rapid sterilization.[48] While surgeons have championed the skilled and efficient use of these instruments, there have been relatively little published experimental data describing the biomechanics of open surgical instrument use. Patkin[26] described the power grip and the precision grip used by surgeons. Dudley[6] briefly described the mechanics of passing instruments from the scrub nurse to the surgeon. Tendick and Stark[49] reported a theoretical analysis of surgeons' grasp. Seki[50] published a detailed classification of needle holder grips and an analysis of suturing movements. A recent study reported that surgeons' dexterity was not adversely affected by the use of double gloves.[51]

Video endoscopic surgery brought to the forefront new and significant ergonomic problems related to the surgical manipulation of tissues. Instruments for VES generally incorporate a pistol or axial grip handle, a 5- to 12-mm-diameter circular shaft that houses the actuating mechanism, and a rotating double-action tip for tissue manipulation. The fulcrum point created by the trocars inserted in the body wall limits the internal movement of the instrument tip to 4 degrees of freedom.[52] The internal mechanical design of VES instruments results in substantially diminished tactile feedback[53] and an unfavorable force transmission ratio from handle to tip.[54] Laparoscopic instruments have also been shown to have a nonlinear relationship between input and output forces, which further degrades the surgeon's ability to delicately sense tissue characteristics.[55] All told, VES instruments have been shown to require 4 to 6 times more force than open surgery instruments to complete the same task.[56,57] With these less-effective instruments, it is not surprising that surgeons report increased fatigue following VES.[42] Indeed, a recent questionnaire by the Society of American Gastrointestinal Endoscopic Surgeons revealed that 8% to 12% of 149 responding surgeons reported frequent pain or numbness in the arms, wrists, or hands following laparoscopic surgery. There have also been reports of thenar neuropathies from the awkward thumb ring in pistol-grip laparoscopic instruments[58-61] and of pectoralis tendonitis from prolonged use of a bowel clamp.[62] Some alternative laparoscopic instrument handle configurations have been proposed[63] but ergonomic data to support their use are still lacking. Although the axial design handle is generally preferred for suturing, there is no objective evidence that this handle design is superior to the pistol configuration.[57] To address some of these problems, some authors have developed guidelines for skills training similar to those used in microsurgery.[64,65] Other investigators have studied the optimal port locations for endoscopic intracorporeal knotting[66] as well as the best visual angles for the laparoscopic camera[67] based on ergonomic performance studies in an inanimate trainer.

There has been increasing interest in developing telerobotic manipulators for VES applications.[49,68] Such sophisticated robotic instruments can give surgeons increased freedom of movement of the instrument tip, coupled with force feedback and binocular vision. These systems have been shown to be very effective for performing delicate surgical manipulations in animal models.[69,70] Published clinical case reports involving the use of robotic assistants during surgery suggest they can also be very useful and more precise than human assistants in some instances.[71,72] Sensors are under development that can transmit tactile information to the surgeon's hand through tactile "displays."[73] Computerized instrument systems[74,75] have been designed in an attempt to increase the surgeon's efficiency during laparoscopic surgery by automatically coordinating different tasks such as suction, irrigation, insufflation, and coagulation. Proof is still lacking that these relatively expensive and complex systems increase efficiency. However, one recent study did demonstrate a 20% increase in the speed of gynecological operations with the use of a more compact computer-controlled multifunction instrument.[76] The ultimate role that "intelligent" robotic instruments will play in modern surgery will depend on the balance between any ergonomic improvements in surgical performance and the cost of the systems.[77]

Posture

Performing open surgical procedures has almost always required standing, awkward body positions, and the occasional need to exert substantial forces on tissues. In industrial ergonomics it is well recognized that static as well as dynamic postural stress can lead to fatigue and disability.[78,79] Indeed, dentists have a high rate of subjective musculoskeletal complaints and disability claims related to cervicobrachial disorders[23] that are presumably due to the nature of their working posture. There is little quantitative information about the musculoskeletal loads experienced by surgeons. Kant et al[80] studied the posture of physicians and nurses during surgery and found that surgeons and scrub nurses experience substantial stress to the musculoskeletal system owing to their frequent and prolonged static head-bent and back-bent postures. Radermacher et al[81] also reported that during laparoscopic and orthopedic surgery more than 70% of intraoperative work postures are substantially static. Mirbod et al[82] recently surveyed musculoskeletal complaints among orthopedic and general surgeons and found a substantial prevalence of complaints of pain in the shoulders (32%) and neck (39%) among orthopedic surgeons. In the same study, general surgeons reported similar symptoms, with a prevalence of 18% and 21%, as compared with pharmacists at 15% and 18%, respectively. Sitting is more restful during extended periods of suturing and also provides a more stable posture for controlling instruments during microsurgery.[83] Indeed, a sitting posture has long been recognized to be a preferred position for light manipulative work[84] and suggestions have been made to allow surgeons to adopt a sitting position during at least part of an operation.[85,86] In the United States, however, sitting during major torso or extremity surgery remains uncommon.

Video endoscopic surgery has altered the way surgeons interact with the surgical field, and in doing so has changed surgeons' posture. During transurethral resection of the prostate, the use of a video monitor significantly decreases the physical load on the shoulder musculature by allowing the urologist to view the endoscopic image while sitting upright.[87] Surgeons' axial skeletal posture is also more upright during laparoscopic surgery as compared with open surgery.[88] This upright posture during VES, however, seems to be accompanied by substantially less body movement and weight shifting than during open surgery.[88] This situation could account for increased static postural fatigue during laparoscopic surgery. As is the case with the positioning of the VES monitor, some basic ergonomic rules that affect surgeons' posture, such as lowering the height of the operating room table to accommodate the increased length of VES instruments, are often ignored.[86]

Mental and Physical Workload

As new technology has entered the workplace, there have been increasing psychological demands placed on workers in many fields. Advances in psychology and neurobiology have put forth new concepts of mental workload and stress that have seen widespread application toward critical task analysis in industry[89] and the military.[11] Levey et al[90] were the first to directly measure the energy expenditure of operating room personnel. He found that while activities such as hand scrubbing and the performance of amputations required the greatest oxygen consumption, the average energy expenditure of surgeons in the operating room was not much above sedentary levels. Oxygen consumption measurements, however, are at best only an indirect measure of physical effort and do not accurately reflect cognitive workload. For example, Becker et al[91] reported heart rates in 10 surgeons to be higher than commensurate for the measured oxygen consumption. Chavez-Lara et al[92] reported significantly increased urinary epinephrine and norepinephrine excretion in surgeons before and during surgery. Foster et al,[93] Payne and Rick,[94] and Goldman et al[95] also reported significantly elevated heart rates in surgeons during operations. Czyzewska et al[96] analyzed heart rate variability patterns and correlated decreased heart rate variability during the operation proper with an increased mental workload experienced by the surgeon. Thus, the evidence to date suggests that surgeons experience significant cardiovascular stress during operations and that the magnitude of this stress exceeds the level of aerobic physical work performed. Contemporary behavioral psychology would attribute this differential effect to an increase in mental workload required by surgeons to perform surgery.

Most surgeons admit experiencing higher levels of frustration and tension during complex VES procedures, although there are no objective data to confirm this observation. Cuschieri[97] described a 4-hour performance "wall" that surgeons encounter during long VES procedures. During training for advanced laparoscopic procedures, most surgeons report exhaustion at the end of a 5- to 6-hour training session, despite optimized instrument and equipment conditions.[98] Interestingly, no such sharp performance barrier has been described during open surgery. Although operating times for simple VES procedures approximate those for open surgery, the cost of this performance during VES may be a higher level of adaptive mental stress by the surgeon.

The Operating Room Environment

The efficient design and setup of the operating room has long been a subject of interest to surgeons, architects, and engineers. The optimum design characteristics of an operating room have been widely discussed[99,100] and standards for operating room construction have been published by the American College of Surgeons' Committee on the Operating Room Environment[30] and the American Institute of Architects' Committee on Architecture for Health.[101] While there is general agreement about the proper size of modern operating rooms,[30] some authors[29] have expressed concern about the potential hazard to personnel and equipment from the many cables and tubes present in the operating room. Several solutions have been proposed to reduce equipment crowding and lines crossing the floor in the operating room.[102] Among the most popular are ceiling-mounted movable arms or tracks that can conveniently position equipment near the patient, thus freeing the floor space around the operating table. Increasingly, the usefulness of these and other design concepts will be able to be tested in advance through the use of virtual reality design tools.[103,104]

Video endoscopic surgery requires an increase in the amount of equipment in the operating room and poses a new challenge to optimizing the use of operating room space.[105] Alarcon and Berguer[106] reported that the percentage of total floor space occupied by persons, furniture, and equipment during laparoscopic operations is increased by 10% over open operations. Nonproductive activities can occupy up to 25% of the surgeon's time during VES.[107] Simple aids such as an autoclavable multicompartment sheath can help to organize instruments on the field and a foot pedal template can keep different pedals correctly positioned for the surgeon.[108] Every surgeon and nurse knows that a well-rehearsed operating room team is advantageous in reducing operating time and perhaps even conversion rates during VES.[109] The effects of environmental conditions such as temperature and humidity on the performance of the surgical team are largely unstudied. Excessive noise levels in the operating room may cause distractions and make it difficult for the anesthesiologist to hear alarms and physiologic breath sounds.[110] While there are several collaborative projects addressing the overall design of the operating room of the future,[105,111] the lack of comprehensive task-analysis and time-motion data related to surgical operations continues to hamper the development of objective solutions to the problem of optimum operating room design.

SUMMARY

More than a quarter-century ago, Laufman[99] lamented that "only a few surgeons have made the surgical environment their main research interest." Future efforts to create a more user-friendly operating room environment will require the rethinking of traditional concepts of architecture, asepsis, and staffing. A greater involvement by surgeons and the other members of the operating team in this process can help assure the goals of increased efficiency and flexibility while maintaining patient and staff safety.

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