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REVIEW ARTICLE

VIRTUAL REALITY SIMULATORS: CURRENT STATUS IN ACQUISITION AND ASSESSMENT OF SURGICAL SKILLS

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Medical technology is currently evolving so rapidly that its impact cannot be analysed. Robotics and telesurgery loom on the horizon, and the technology used to drive these advances has serendipitous side-effects for the education and training arena. The graphical and haptic interfaces used to provide remote feedback to the operator – by passing control to a computer – may be used to generate simulations of the operative environment that are useful for training candidates in surgical procedures. One additional advantage is that the metrics calculated inherently in the controlling software in order to run the simulation may be used to provide performance feedback to individual trainees and mentors. New interfaces will be required to undergo evaluation of the simulation fidelity before being deemed acceptable. The potential benefits fall into one of two general categories: those benefits related to skill acquisition, and those related to skill assessment. The educational value of the simulation will require assessment, and comparison to currently available methods of training in any given procedure. It is also necessary to determine – by repeated trials – whether a given simulation actually measures the performance parameters it purports to measure. This trains the spotlight on what constitutes good surgical skill, and how it is to be objectively measured. Early results suggest that virtual reality simulators have an important role to play in this aspect of surgical training.

Key words: clinical competence, computer-assisted instruction, computer simulation, educational measurement, equipment design, medical education, medical errors, motor skills, needs assessment, surgery education.

Abbreviations: FrameSET, Framework for Simulation, Education and Training; MIST-VR, Minimally Invasive Surgical Trainer-Virtual Reality.

HISTORICAL PERSPECTIVES

> Life is short, the Art long, opportunity fleeting, experience deplorable, and judgement difficult.
>
> Hippocrates, Aphorismi, I, i

This incisive apophthegm from the father of bedside medicine is particularly relevant to the present situation of surgical training. It has frequently been stated that the fundamental format of surgical training has not changed in a long time.[1] To appreciate the length of time, it is necessary to consider that the preceptor or apprenticeship model has enjoyed a monopoly on surgical training since the earliest known records of surgical practice. The *Edwin Smith Surgical Papyrus* dates back to 18th century BC, and gives an account of surgical standards accepted at that time.[2] Indirectly, it relates the traditional methods of surgical training – entrusting a young apprentice to the care and knowledge of a master of the craft – and these do not appear to diverge greatly from current methods of training.

The characteristic feature of this model is a teacher-centred approach to teaching, an approach conducted in a loosely structured manner, whenever appropriate opportunities should happen to present themselves (an aspect sometimes dubbed 'education by random opportunity'). The mentor-student relationship is characterized by close supervision in a series of one-on-one situations, in which principles and procedures are taught on the basis of the mentor's interpretation of current standards of practice.[3]

This model has worked well in the past, but a number of recent developments threaten its utility. Among these is the elucidation of the fundamental principles of adult education, which emphasize individual development and a learner-centred approach in an environment conducive to learning with almost continual high-quality feedback on performance. The fundamentals of adult education have been adopted widely in various circles, and reforms under way in Australia should see these principles applied to the curricula of surgical training. As outlined in the Calman Report on specialist training in the United Kingdom, adoption of these principles is recommended in order to streamline training and to make it more efficient.[4]

Several investigators have alluded to the notion of dwindling exposure – over the past three decades – of trainees to an adequate spectrum of operative procedures during the course of their training.[5–7] The reasons for this are many, and include, among others: (i) the rise of interventional radiology and procedural medicine; (ii) a continuing trend towards superspecialization; (iii) increasing skill in the use and availability of minimally invasive techniques; (iv) growing evidence for conservative management of many disorders; (v) rising support for 'graded responsibility' in surgical training; and (vi) changing demographics and disease prevalence.[8–10]

With the recent – and ongoing – explosive expansion of surgical knowledge, the apprenticeship paradigm is no longer able to deliver as adequate an education in the surgical craft as it has in the past. Never before has life been so short, the art so long, the

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opportunity so fleeting, experience so deplorable, and judgement so difficult.[11–18]

CURRENT SOLUTIONS

The current paradigm of an initial, loosely structured apprenticeship in surgery is no longer capable of sustaining a surgeon for the duration of his practicing career.[8,19] As a result, other avenues of training are being sought and developed to supplement the traditional method of training in surgery. In this regard, Kirk goes so far as to say: 'Recent changes in practice and organisation of surgery make it even more important than formerly to focus attention on the acquisition of operative skills.'[8]

One proposed method involves instruction in surgical skills by using virtual reality simulators. This has some clear advantages over other methods of instruction, not only in terms of teaching operative skills, but also in terms of assessing those skills.

Advantages

Skill acquisition Because simulators are potentially available at all hours, training in operative technique may be tailored around work and other commitments and incorporated into a programme of instruction designed to facilitate progression from novice to expert. A particular skill may be rehearsed over and again, so that an individual's problematic areas may be addressed before approaching a patient. An additional advantage of reproducible simulations is the ability to standardize assessment of trainees for valid and objective comparison of performance in operative skills.

Conversely, by registering images obtained from real patients, the simulated tasks may be varied in order to avoid learning of the simulation, and to expose the trainee to a variety of anatomical variations under various physiological conditions. It also allows for practice of a particular therapeutic procedure on a simulation of a particular patient's pathology prior to laying hands on the actual patient in the operating theatre.

Virtual reality simulators have, in the past, repeatedly proven their value in training for high-risk, mission critical tasks for which training is required, but opportunity limited by danger, prohibitive cost, or extreme impracticality. In these situations, simulations allow for risk-free training, providing a non-threatening environment in which trainees, not yet achieving proficiency, may practice a skill with the freedom to fail, without entailing unpleasant consequences, or squandering consumable training materials.

Just as flight simulators allow pilots to be trained in the skills of aviation without endangering the lives of their passengers, surgical simulators can provide novice surgeons with the opportunity to acquire new skills without threatening the well-being of their patients.[20,21] With the perennial danger of communicable disease being acquired by means of sharps injury, virtual reality simulators provide a training environment free of such risks. In short, simulators have the potential to save patients from trainees, and trainees from patients.

Studies of surgeons' physiological parameters while operating indicate that this activity is associated with a degree of psychological stress.[22–24] If the operating surgeon happens to be a trainee, learning diminishes dramatically in such a non-conducive environment.[25] This is especially the case with junior trainees who may be unfamiliar with the routine and team dynamic within the operative suite, and who are highly conscious of their lack of skill. Simulators can provide an avenue by which this anxiety may be alleviated, being a non-threatening learning environment in which basic skills may be acquired. When the time comes to transfer these skills to the operating theatre, the trainee's confidence in their own ability ought to dispel some anxiety, and facilitate learning on a cognitive axis.

Skill assessment By its very nature, virtual reality simulation depends on tracking measurements of instrument movement which may easily be extracted from the simulator platform to provide objective measurements of the user's performance in executing the simulated task. This represents the first time in the history of surgical training that entirely objective assessments of psychomotor skills have been possible.

Apart from the obvious advantage of objectivity, direct assessment of a trainee's psychomotor skills will no longer mandate the substantial resources, human or otherwise, which would be required were assessment to be undertaken by currently available means. It is the impracticality, as well as the low reliability, of observed assessment of surgical skills that have prevented it from assuming its rightful role in the trainee selection process.

Using a simulator, performance data is, of course, recordable for comparison over a period of time, which means that a trainee can instantly obtain objective feedback on their performance compared to past performance in a variety of tasks. The importance of constructive feedback provided on demand has previously been demonstrated.[26]

Objective comparison of trainees has not been possible in the past, but the reproducible and impartial conditions generated by virtual reality simulators represent a positive step in this direction, allowing the skills of one trainee to be directly compared with those of another. This has implications for the norm-related assessment of trainees, as well as for selection of candidates for surgical training. While technical ability is only one predictor of success as a surgeon, its importance as a selection criterion has been undermined by lack of a feasible, objective means of measuring it.[27]

This also has important implications for ongoing, regular recertification throughout the surgeon's career. Current sentiment is driving policy towards compulsory, periodic accreditation of surgeons, and – as official proceedings in Australia,[28] the UK,[29] and the USA[30] state, at least implicitly – if doctors do not take this responsibility upon themselves, other groups are standing by all too eager to impose it upon them.

Additional advantages Surgery itself is becoming increasingly enhanced by technological interfaces.[31,32] During the career of many currently practising surgeons, these advances have forced them to learn new sets of fundamental psychomotor skills in order to be able to undertake procedures previously accomplished only by open surgery, and to remain up to date in their field of practice.[33] Laparoscopic surgery limited the three dimensional, exquisitely tactile operative field to an abbreviated two dimensional image, manipulated by means of cumbersome instruments at a distance.[34] Fibre-optic endoscopy paved the way into organs previously inaccessible except through large incisions, but restricted surgeons to operating at a distance with long, flexible implements that were difficult to control. In the 1970s, microsurgery dramatically expanded the scope of surgical intervention, as did, most recently, the incorporation of robotics. Each of these places a unique interface between the operating surgeon and the tissues of the patient.[35] The introduction of each of these surgical modalities was accompanied by steep learning curves,[36] because they each added an additional, novel dimension to the traditional interaction between surgeon and patient.

This is an important point for two reasons. Firstly, initial familiarization with these novel modalities may be undertaken on a simulator rather than a patient, allowing for a less turbulent *in vivo* learning curve. The importance of a complication-free learning curve was emphasized by the Royal Colleges of Surgery in their reply to the General Medical Council's determination on the Bristol case,[29] wherein they state: 'there should be no learning curve as far as patient safety is concerned.' This is restated a little more clearly by Hasan: 'there is a lack of professional or public tolerance for suboptimal results due to a learning curve.'[37]

Secondly, new surgical modalities increasingly depend upon an electronic interface, which lends itself to simulation of these procedures. It is easier to design and implement a simulation for robotic surgery, for instance, than for open surgery. A new human computer interface is not required; all that is required is the removal of the effector unit of the surgical robot, and its replacement by a simulated unit – a patient is no longer required for teaching or learning the requisite skills.[38,39]

Virtual reality simulators are, therefore, in a position to form the basis of a programme of familiarization, whereby surgeons may become acquainted with the skills required to master new surgical modalities. This has obvious implications for accreditation, continuing medical education, and recertification.

Without simulators, this process will become more difficult as animal workshops become ethically untenable, and cadaveric facilities diminish in number and resources.

Already in New South Wales, the Human Tissue Amendment Bill 2001 is before the Legislative Assembly, seeking to modify the *Human Tissue Act 1983* and the *Coroner's Act 1980* to make it illegal to use human tissue obtained during the course of a post-mortem examination for any purpose – including educational purposes – not directly related to conducting the examination unless specific written permission is given by the deceased prior to their death. Should this amendment be passed by Parliament in its present form, it will severely limit human tissue availability for research or education. A sting in the tail of the proposed amendment makes it imprudent to assume that the deceased did not verbally revoke consent prior to death and this will further limit access even to the tissues of those who 'donate their bodies' to medical science. Other states will undoubtedly follow.

The measure of this shortfall may be filled, at least in part, by introducing appropriately designed simulators.

Beyond the advantages bestowed upon trainees, virtual reality simulators are also of benefit to mentors and teachers at a time when educators are required to display a degree of accountability both to their creditors and to their students. The financial cost of any educational intervention must be weighed against the benefit derived from it. Similarly, educators and mentors owe their students an efficient education of the highest possible standard.

Virtual reality simulations of surgical tasks meet these criteria in a number of ways. First of all, they make the tasks of assessment and feedback somewhat easier and decidedly more objective, thereby effecting an assessment standard previously unattainable. They are versatile enough to be useful in a variety of settings, and may be tailored into remedial programmes for individual trainees, or for intensive courses in particular skills, whatever the need may be. The majority do not require special conditions to run, as might be encountered when establishing animal laboratories or bench-top exercises utilizing animal products, nor do they require the ongoing cost of consumable materials.

Disadvantages

While the advantages of employing virtual simulations in surgical training may be clear to some extent, the disadvantages are not altogether obvious. Foremost among these is their availability, or more correctly, the lack thereof. Most of the simulators - described in the literature are still in development phase, and most of the commercially available simulators are not suited to surgical tasks.

At present, most commercially available simulators enable training in a single task only, mostly of needle-insertion or suturing types. Some of these incorporate force feedback, but this remains rudimentary. It has not yet been determined whether this feature enhances learning on such simulators, although this seems intuitively to be true. Haptic feedback adds substantially to the cost and complexity of a simulator, and some institutions may have difficulty in justifying such gross expenditure on a simulation of a single task, particularly when it has not yet been demonstrated to be of any greater benefit than cheaper and more accessible, low maintenance alternatives.

Another issue to be considered is that of technical support services for the acquired simulator. In Australia at present, there are no locally based distributors of surgical simulators, and no established avenues for the provision of technical support or maintenance. If this situation persists, the burden of maintaining the equipment will have to be borne entirely by the institution purchasing the simulator.

It must also be clearly stated that none of the surgical simulators described in the contemporary literature, or those available commercially, have been fully validated in adequate trials. Indeed, there are currently no broadly accepted guidelines for the validation of simulators, partly because there is no consensus on useful performance parameters, and no way, at present, to relate performance to ultimate outcome.

FUTURE CHALLENGES

Metrics

Most validation studies to date have been performed on the Minimally Invasive Surgical Trainer-Virtual Reality, or MIST-VR (Virtual Presence, London, UK), a 'bare bones' laparoscopic simulator which utilizes abstracted graphics, making it a worthwhile investment for general, orthopaedic, ENT, and cardiothoracic surgeons, and gynaecologists; in short, it is of potential benefit to any specialty making use of minimal access techniques.

The simulation – which comprises 12 tasks to teach the skills of laparoscopic manipulation, diathermy, and clipping – is run within a customizable teaching and assessment database called FrameSET (Framework for Simulation, Education, and Training). The hardware interface is the Laparoscopic Frame (Immersion Medical, Gaithersburg, MO, USA), which emulates the real laparoscopic interface, but without force feedback. The entire simulation runs on a graphically accelerated IBM compatible PC using Windows 2000/NT.

The most significant feature, from a training perspective, of this simulator is its ability to provide immediate feedback and performance analysis. For each task, a performance database records time to completion, number and type of errors performed, and economy of movement. Results are separated into scores for the right and left hand. It is this which makes MIST-VR such an advanced and useful simulation.

The challenge lies in determining which of the potentially measurable parameters are useful for predicting performance in a real laparoscopic environment, and this is the crux of evaluation studies. The importance of this kind of research is only just beginning to be realized. With the addition of haptic rendering, additional parameters will be assessable, such as extent of tissue damage, errors of force, and errors of alignment. Other possible parameters await further elucidation, and it must be kept in mind that, at this stage, the science of psychomotor skill acquisition and assessment is still relatively nebulous.

Haptics

One obvious question which surfaces whenever haptic interfaces are considered is that of instrument-tissue force interactions. It is important for the overall success of a simulator to render haptic feedback in such a way that it reflects the real forces experienced by a surgeon at operation. Problems arise when one considers the methods of force measurement for this purpose.

Various proposals include using instruments with force and torque sensors to measure interactions at the instrument-tissue interface in either live animal or human cadaver models. The fact is, however, that there are real differences in the tissue properties between these models and living human tissue. Another alternative would be to measure the tissue properties of living organs as surgeons actually operate on them, using instruments modified to include sterile force and torque sensors. The caveat here is that few such sensors exist which are capable of being sterilized, and those that are amenable to sterilization cannot be modified for inclusion into surgical instruments without considerable financial input, and various ergonomic obstacles. Further deliberation brings light to bear on the variations in measurement between individual patients, and between various stages of pathology. These issues remain to be addressed.

Another challenge facing researchers working on haptics projects is the development of an adequate haptic interface for open surgical procedures. At the present time, this has been relegated to a position further away towards the horizon, as the complexity of designing such an interface increases exponentially with the increased degrees of freedom within which force interactions take place, when compared to the more limited arena of laparoscopic surgery. Computing power has not yet achieved this level of sophistication.

Graphics

As simulators evolve, their fidelity increases considerably; that is, they begin to look and feel more like the real thing. The minimum threshold for task fidelity, however, is yet to be determined, and will be different for simulations of different tasks.

Various issues need to be addressed in terms of registration. This is the way computers recognize objects, their boundaries, and their volumes. Challenges need to be faced in areas such as detecting collisions between objects and the graphical representation of tasks such as tissue dissection and cutting which change the topology of the simulated organs. The solution to these problems depends on the computational algorithms used to model organs, instruments, and materials, and finding the right solution for a specific simulation is largely a matter of trial and error. Perhaps further elucidation of the physical properties of organs and materials will help to minimize the heuristic element in this area of development.

CONCLUSION

Where is the knowledge we have lost in information? Those responsible for designing and implementing the use of simulators in surgical education ought to pay heed to this lament by T. S. Eliot. Surrounded by the state of the art in technological wizardry, it is possible to be carried away by what is technically possible, and to forget that the real task at hand is one of educational development. This is achieved by adhering to the principles of curriculum design: training needs analysis, training programme design, and training media specification. Efforts in developing simulators should be paralleled by research in the techniques and processes of validation; we must be sure, as we climb the ladder of success in surgical simulator development, that it is leaning against the right building.

Examples from its short history demonstrate the importance of this kind of research in simulation development. What might initially seem intuitive may not necessarily turn out to be true on empirical examination. For example: the MIST-VR simulator discussed above which, at first sight appears to be too abstract to be useful, on closer scrutiny is proving otherwise; while on the other hand, nursing students using CathSim – an intravenous cannulation simulator developed by Medical Immersion with realistic graphics, audio output, and haptic feedback using a unique hardware interface – failed to demonstrate improvement in cannulation of real patients when compared to controls, despite the high level of realism of the simulation.[40]

There is no doubt that simulators will play a role in the training of future generations of surgeons. It is our duty to investigate thoroughly all the issues associated with this exciting new field to ensure that the education of surgeons does not fall below the current high standard, and that the many pitfalls associated with new technologies and educational interventions are avoided.

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