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Describing A Latent Design Cycle In 100 Years Of Innovation And Adoption In Anesthesia Equipment: The Origin Of Awkwardness

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Abstract

Much is understood about the human-technology relationship and the importance of user focused design. This is well recognized in anesthesia with human factors investigations leading to patient safety awareness, regulation, and workload management. Conversely, this has inspired little change in the design of equipment to reduce the awkwardness in providing anesthesia. In fact, it has increased it by not discriminating between normal use and adopted use where the anesthesia profession has, over time, created habits to overcome and accommodate design deficiencies. This study examines past and present anesthesia equipment and use methods to deduce the origin of awkwardness. By describing the latent design cycle in the evolution of anesthesia equipment, a prediction can be provided for the application and acceptance of future technologies in anesthesia. The anesthetic profession may continue with standardized equipment design; conversely, the benefits of innovation in digital technologies to reduce awkwardness will probably be associated with significant change in the convention of use.

BACKGROUND

In the early 1900s, anesthesia equipment consisted predominantly of small hand held devices, the simplest being a folded cloth and bottle. By the 1920s, these designs had progressed to technical apparatus, and then in the 1930s to table based machines. Whilst on the surface, today's anesthesia machines mirror contemporary products, portraying a symbol of progress and technological efficiency, they retain the 1930s table format. With the application of new digital technologies superseding mechanical tradition, a prevalence of screen based activity has now arisen (Drews 2006). This progressive refinement of devices over the last 100 years can be looked upon as a repeating design cycle when components are integrated, added, organized, and recently digitized into a system. This cycle has slowly eroded the anesthetist/patient relationship in favor of the anesthetist/apparatus and more directly the anesthetist/machine relationship. The current generation of machines have become anesthesia workstations, where increasingly ergonomic position and use methods are applied to observing the patient and monitoring technology (Mcdonald 1990, Weinger 1999, Kiefer 2010).

Since the 1970s, research by Duri (1973) Cooper (1978) Boquet (1980) McIntyre (1982) Decker (2003) and Seagull (2004) has lead to the same conclusion, that the assembled components designated as a machine is adequate for the task but not for the activity or procedural diversity of tasks. Although these studies raised concerns, the design of modern equipment became directed by regulations, standards and guidelines. This has been maintained by the absence of research that investigates the long term relationship between the design and use of anesthesia equipment.

The modern anesthesia machine is awkward. To understand the challenges in measuring, communicating and acting on the awkward workspace of anesthetists, it is helpful to investigate and ascertain the origins of awkwardness. It is important to understand the implications of evolving equipment attributes on behavior, and how they advance innovative design thinking within the constrained and regulated field of healthcare equipment (Woods 2000). The recent addition of digital interfaces and digital interaction to healthcare devices brings a challenge to designers; whether to retain, merge, or reinvent product familiarity, methods of use, and learning, to gain both practitioner acceptance and safe use. Identifying the long term collaborative effect of design in anesthesia is the motivation for this work, as this viewpoint has received little recognition and encompasses a range of disciplines.

Our hypothesis in this study is that historical innovation and design advancements continue to reside in equipment as latent design attributes, becoming progressively adopted and accepted as conventions of use. These conventions, initiated by early anesthetists and modified by industry are now entrenched in a profession's response to iterative design and manifested by laminations of technologies. Their original design objectives are misunderstood by researchers in being measured as awkward attributes (Seagull 2004), whereas beyond human factors they are an anesthetist's response to a design evolution. Once established, these conventions are more difficult to recognize and overcome as they have become integral and habitual to the anesthetist's tasks.

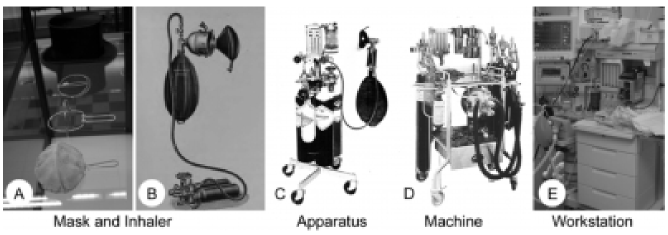
METHOD

To guide this research into understanding the chronological affect of design on ergonomic behavior, literature, photographs, education films and observations of equipment (both static and in use) are examined from a design context. These design characteristics are grouped and compared to identify the following goals:

The design of anesthesia equipment; physical form based changes to prevailing equipment through periods of innovation.

Figure 1

Fig.1 Stages of equipment design (source: A-C-D Geoffrey Kaye Museum of Anaesthetic History, Australian and New Zealand College of Anaesthetists, Melbourne, Australia. B (Boyle 1907)



Device name and type is an established method of cataloguing anesthesia equipment and four stages are commonly applied (Figure 1).

First, from the mid 1800s, a folded towel, cloth or 'rag' was held over the patients face to administer chloroform or ether from a drop bottle, by the late 1800s the cloth was supported by a wire mask in a range of formats. This method led to the more complex inhaler that combined mask and bottle as one.

Second, the apparatus was developed by integrating inhaler technology into a portable or floor mounted system where multiple anesthetic agents and gas flows could be controlled.

Third, the machine was developed by physically integrating the table holding anesthetic agents and inhalers with the apparatus (Wilkinson 2002).

Fourth, the workstation, where devices for patient monitoring and ventilation are integrated into the machine format.

Disassembling 100 years of innovation into stages presents design as an integrator of technology.

The use of anesthesia equipment; design stages identified above were aligned to changes in use methods, providing a correlation between activity and design.

While stages of equipment development are well documented, use methods are more difficult to ascertain. Therefore, a diagrammatic analysis of technology integration and use method was devised. This method correlates how initiatives for design change leads to the implementation of new technologies and how clinical procedures are both affected and effect work methods in the progressive development of current anesthesia practice. To catalogue the technological and behavioral changes to anesthesia delivery as a design cycle, the following criteria were used:

In the development of equipment, what design attributes changed use methods?

What was the effect of design changes on behavior and ergonomics (use methods)?

What was the effect of innovative new concepts and human factors research into awkwardness?

RESULTS

EXAMINATION OF USE METHODS

HAND HELD (CLOTH, MASK AND INHALER)

Early methods of anesthesia delivery provided a total dose of anesthesia agent. More sophisticated inhalers used mechanical indicators to preset flow, providing a limited measure of safety and control. Mask and inhaler were diverse in design. They ranged in acceptance and evolved in a parallel timeframe; a commonality was the requirement to be portable, allowing early anesthetists to take their practice to the patient. Primarily these devices were designed by anesthetists around their own anthropometric capability, requiring the practitioner to observe the patient whilst controlling the mask or inhaler. Symmetry in use and close proximately to the patient is identified as a predominate design criterion that allowed for personal comfort and control (Figure 2).

Administration required two handed use; being a symmetrical system, either hand could be used. This freedom in administrative positioning, patient viewing and handedness required skill and control, a dexterity only gained from experience. Observation of archived equipment reveals that these early devices could be used either left or right handed, however with a need for a precise and controlled seal over the patients face, instructions (Boyle 1907), publications (Thomas 1975) and an early ICI training film (Thomson 1944) show the right hand was to dominate the mask. The patient's physiology was representative of today's monitoring interface, all in the visual field of the anesthetist. While cloth, mask and bottle, and equally the inhaler, are no longer used, their influence on design is marked by their duration of use into the 1950s.

APPARATUS

The second stage of evolution occurred in replacing the hand held craft of anesthesia with scientific apparatus and mechanical interaction. Similar to inhalers, these were designed by anesthetists. These were portable devices more suitable for hospitals and the operating theatre; comprising standalone rather than hand held technology. By transferring anesthesia administration from the drop bottle and inhaler, to calibrated flowmeters and vaporizers, anesthetists were able to control more complex technology. While the design of these was flawed in mis-connections, poor calibration, and materials that perished, wore and failed, the ergonomics and positional activity was an anesthetist derived carryover from mask and bottle behavior. The diversity and experimental nature of the majority of apparatus conceived between 1900 and the 1930s continued the provision for established methods of use in line with the practitioner as designer. The apparatus remained biased to the tradition of close proximity to patient, symmetry, retention of the mask and predominantly left handed use, i.e. right hand on mask and left hand available for equipment.

The early apparatus designs were the results of innovation and modification amongst many practitioners, Wilkinson (2002) describes the origins of the popular Boyle apparatus, as an adaption of the Marshall apparatus that in turn had been influenced by Gwathmey's designs. These early machines were mounted on a stand to be at a comfortable working height, and demonstrated a direct correlation between technology innovation and the transfer and acceptance of earlier use methods. This is ascertained firstly from the placement of apparatus components in a comprehensible left handed flow pattern from left to right to the outlet. Secondly, the mask was a continuation of earlier designs that still required dexterity and control to place appropriately. This design stage retained an established use method originating in right hand in control of the rag, mask or inhaler and typically left handed operation (Figure 2). The success of the Boyle apparatus may partially reside in anesthetists' acceptance of their own iterative design and an evolutional approach to use methods based on normal use and recognition of ergonomic consistency.

MACHINE

The third stage occurs when the apparatus technology became a table based system, a consolidation that offered the anesthetist a work surface, with drawers; a workplace. To accommodate the table, the apparatus equipment was mounted at the rear, leading to a design where established technology becomes standardized through design integration. This created a workspace in the operating room and promoted a change in equipment positioning from the left of the patient to the right. This changed established methods of use, handedness and reach. The table based design dictated a behavioral change that opposed the flexibile use of the mask, inhaler and apparatus. In the case of the anglo-commonwealth Boyle machine, this was compounded by retaining a traditional left handed component arrangement to a machine that was situated and used on the right. Component arrangement was later revised to suit right hand use in the 1950s and illustrates how standardization and reliance on slow iterative change became a hallmark of the anesthesia machine. The Boyle machine focused on providing a design solution to the earlier diversity of individual practitioner arrangements in a multiple user hospital setting. The machine format biased normal use to the chassis or furniture rather than the practitioner's anthropometrics. The right handed position that opposes the use methods of earlier devices is a direct result of compromise in integrating technology with furniture. The table defines an area for auxiliary equipment and a workspace dominated by the prevalent right handed. This contradicted the established method of mask application, leading to anesthetists creating, conforming and adopting a new awkward use method.

During this period, the table based format was adopted in the USA (Thomas 1975). One example exists of practitioner design that questions industry consensus and demonstrates a personal wish to mitigate behavioral change. Illustrated in A.G.McKenzie's (2008) historical note, the Gillies machine of 1951 shows the interface and controls centered and brought to the front of the table.

WORKSTATION

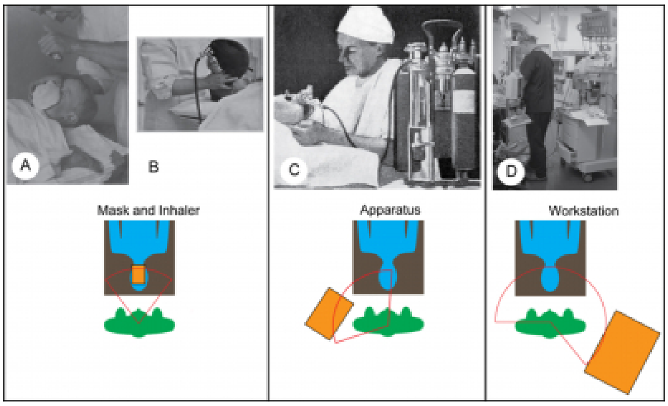
The workstation differs little in physical form from its predecessor. While continuing to retain the table, its increased size, the addition of mechanical ventilation systems with long breathing circuits, and workplace congestion has forced placement further away from the patient (Figure 2). Its inception is marked by a 30 years design hiatus that established an awkward yet familiar convention in use methods aligned to the table based machine design. Weinger (1999) examined studies that led to awareness of patient safety during the 1980s, including anesthetists' contributions to patient monitoring technologies, pulse oximetry and capnography. These additions are described by Cooper (1978) and Westhorpe (1992) as a haphazard application, in turning the simple machine format into a "Christmas tree".

Recognizing the resulting ergonomic inadequacies of stacking new technology, investigations by Duri (1973) Cooper (1978), and Boquet (1980) promoted the argument that the current machine was in need of a complete redesign, resembling an "accident waiting to happen" (Cooper 1978 and Westhorpe 1992). The premise was that in stepping out of the 1950s convention, a new workstation design that both looked and worked differently to resolve ergonomic issues would be accepted as better. Complete redesign rather than integration was applied as a method to resolve the anesthetist's workplace. Novel equipment resulted; the Gambro Engstrom 2000, Engstrom Elsa/EAS, Physio BV Physioflex, Dräger Cicero, and Siemens Kion machines reflected Duri, Cooper and Boquet's research. While advancing capability, technology and patient safety in anesthesia, these designs were not universally accepted by the anesthesia community. In time the technology was iteratively adapted into machines retaining the traditional table based format and awkward use method.

Since the 1990s manufactures have sought to resolve the collection of components by integrating them into one device and mitigating ergonomic difficulties with adjustable screens and left hand versions. Recognition of dexterity in operating knobs, dials and touch screens as opposed to the patient and mask is prevalent in these designs. This places expectations on the anesthetist's physical capability, both in the distance of reach and observation of patient and machine, as machine position in the operating room is not standardized i.e. the patient is in front and the workstation (monitoring and control of anesthesia) is behind (Dalley 2004).

Figure 2

Fig 2 Illustrations of equipment in use and corresponding diagrams of developing workplace awkwardness. source: A Geoffrey Kaye Museum of Anaesthetic History, Australian and New Zealand College of Anaesthetists, Melbourne, Australia. B (Boyle 1907). C (Thomas 1975)



THE SHIFT IN INNOVATION

The move from early hand held devices and apparatus to the table is a result of early boutique designers close to the activity such as Nissen Deacon, Charles King, Coxeter and Sons and Richard von Foregger. With intentions of resolving equipment use and workplace management, their ideals were later purchased and pursued by larger companies. The shift from anesthetist led innovation, to industry led design followed by patient safety, has become a future proofed design methodology. In becoming homogenized and generally congruous, the right hand table based design had become the basis of innovation, standards, regulation and familiarity. In the maturing of a profession, anesthetists became restricted from personally innovating equipment, adopting the awkwardness of the table design and accepted a convention as part of their profession.

The mechanical technology of inhaler and apparatus endeavored to supplement the mechanical capability of the human operator, whereas the machine sought to redefine and organize the anesthetist's workplace. In its initial simplicity this brought a measure of coherency, order and standardization at the cost of individual use methods. 80 years of innovation and growth in components has expanded the user interface exacerbating awkwardness leading to increased demands on the anesthetist's physical capability in the need to interact both visually and physically with technology and patient. This reversal of established behavior placed technology above ergonomics, forcing anesthetists to alter their methods. Therefore, studies are inclined to find awkwardness as a result of machine design and component placement rather than a result of a design methodology focused on familiarity, iteration and safety.

CRITICISM AND CONCEPTS

The critical incident technique was introduced to anesthesia by Cooper, Newbower, Long, & Mc-Peek (1978) identifying the relationship between human error and equipment. Reducing human error has since remained a significant aim in anesthesia, however little consideration is given to pre-machine use methods and the long term impact of inherited habits. Evidence of these is incorporated in drawings, photographs and historical descriptions as legacies of pioneering anesthetists (Thomas 1975 and Maltby 2002).

Challenges to a convention that united workplace analysis with design, were initiated by the predesign investigation by Duri (1973), who promoted the role of the anesthesiologist in design and used human factors methods to examine the environment of the anesthetist. In an attempt to provide useful information for the redesign of the complete man-machine system, Duri quantified awkwardness in a series of link analysis diagrams of machine placement, and the time the anesthesiologist's attention was distracted from the patient. A similar study by Seagull (2004), termed awkwardness as "dispersion of attention" and proposed that these measures are conspicuously absent in research but useful to designers. Duri's investigation used memomotion filming, [1] timings and link analysis including interviews, whereas Seagull used eye tracking video to analyze task related events. These two investigations span 30 years, have similar hypotheses, and while allowing for technical advances they also share methods and comparable results.

Similar hypotheses exist in Boquet's 1980 analysis of the anesthesia workplace, however Boquet uses human factors analysis, advanced techniques in eye tracking, and industrial design methods to create design prototypes. Comparing the illustration of Boquet's 1980 prototype to Wilkinson's 1930s description of joining the table to apparatus, it would seem Boquet has separated the machine back into table and apparatus and reversed 50 years in search of normal behaviors to resolve his design. Boquet's task and link analysis and the recording of interactions is a reactive design method. Therefore, any design conclusions are based purely on the individual tasks, sequence and frequency constrained by the studied machine format. Consequently Boquet's conclusion of an apparatus type layout as better, implies that anesthetist's use methods were only new habits to overcome design deficiencies in the machine.

The technology inspired design of Cooper's (1978) Boston Anesthesia System (BAS), differs from Boquet's industrial design bias and the notion of understanding compositional interaction through task analysis. Cooper's hypothesis applied research 'by design', starting with an indictment of the mechanical anesthesia machine as unsafe where as digital electronics were potentially safer. A comparison can be made to the Siemens Kion workstation (released in 2001) a radical ergonomic layout consisting of three independently rotating parts: column, user interface, and trolley. Effectively a product designer's intuitive hypothesis that does not communicate a practitioner centered use (Liu 2003). Neither of these concepts acknowledged the prior or established behavior of anesthetists as important precedents, but instead presented a compromise in physical format, endeavoring to coerce a new use method that was yet be established or understood.

Recently David Liu (2010) evaluated head-mounted display technology as a means to resolve awkwardness by providing the anesthetist with continuous visual information while monitoring the patient. Liu's study has in effect returned the anesthetist's positioning back more than 100 years, to the mask and bottle pose and normal behavior aligned to the activity rather than to the machine.

Studies of the anesthesia workplace, and the questioning of established convention through new designs, exhibit the perceived importance of human factors study. On a micro level much has been achieved through iterative design, new technologies and attention to detail, conversely these endeavors have inspired little change in the man-machine relationship. The scales remain tipped in favor of patient safety and information management, with the anesthetist progressing from normal use positioning where patient and device are one, to covering and monitoring more than 180 degrees. The anesthesia machine, as a table based system, bred an expertise and acceptance for a format that disregards awkwardness by favoring convention and safe change. This can be substantiated by the demise of novel machines discussed earlier that invested in human factors and challenged tradition yet suffered limited acceptance.

DISCUSSION

Over the last century anesthesia equipment has matured out of practitioner inspired needs, leading to a manufactured consensus of best design; and in the last 40 years, an engineered lamination of advancement. Within this field, human factors has focused on attending to use methods as a reaction to contemporary iteration rather than reflect on practitioners altered behavior generated through incremental change. This study contrasts equipment and use methods to describe the evolution of anesthesia equipment from the perspective of design changes that have impacted on the behavior of the anesthetist. A slow transitional effect of historically evolving equipment design that harbors a hidden capability to convey a professions' needs whilst restricting greater innovational exploration.

Early anesthesia devices were developed and customized for personal use, diverse in comparison with today's technology and workplace standardization. Methods of use are now constrained by anesthesia's complex, dynamic and critical interactions alongside an engineering led design approach and the influence of safety orientated regulations. These evolving criteria have promoted an iterative design methodology that has maintained the table based format of the anesthesia machine designed nearly 80 years ago. This maturity is part of a latent design cycle where changes are small or imperceptible. The requirement of familiarity and standardization, fostered by these iterations, has encumbered the anesthesia machine within an evolving design cycle based on a convention of use. This study proposes that the origins of awkward use methods are rarely recognized in research and are implicit in the diminishment of ergonomics and usability from normal use to forced adoption and the generation of workaround habits.

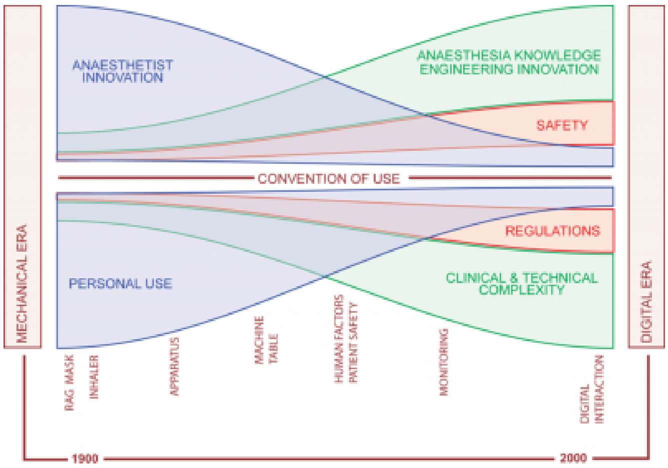
THE INNOVATION EVOLUTION

The diagram in Figure 3 illustrates the evolving constraints on use methods that surround equipment acceptance leading to a convention of use. Early practitioner innovation is represented on the left, evolving and slowly constrained by new knowledge, innovation and safety. This also represents normal use, again progressively restricted as a result of new knowledge's partner, clinical complexity, and safety's partner, regulation. Knowledge, innovation and safety in healthcare design are attained by applying iterative design methods that force compliance and acceptance. Clinical complexity and regulations have encouraged new behaviors, compromised ergonomics, and created awkwardness. Within the evolution resides a convention of use suggesting that anesthetists have adopted technology, rather than adapted to technology. This residue of old designs still exist, embedded as a result of the very methods applied to reduce them.

The gradual reduction and demise of practitioner anesthetist leadership in the physical aspect of design is a result of technological complexity, regulation, patient safety and standards, placing the acknowledgement of behavior, normal use and habits behind technological innovation. In the last 80 years, innovation has encouraged acceptance through a recognizable table based format where practitioners have been forced to adopt, rather than adapt, unwittingly taking responsibility and creating new habits.

Figure 3

Fig 3 The evolving constraints on use methods producing a standardised design format

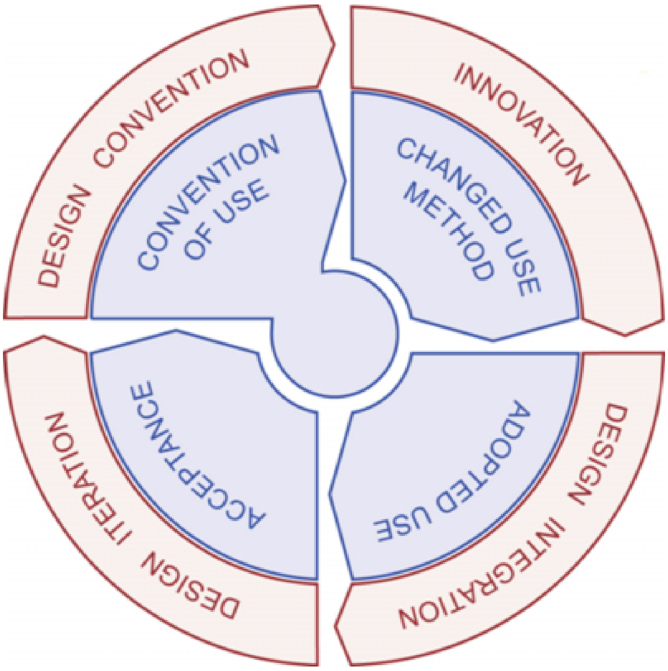


RECOGNIZING THE LATENT CYCLE AND PREDICTIONS

The design cycle can be looked upon as a hypothesis to promote awareness of the current crossroad; a time where new technologies are smaller, faster, and ill suited to past methods of integration, and where habits and conventions continue to reside in the man-machine system. Figure 4 illustrates the latent design cycle where lapses between integration and new innovation have resulted in subtle iterations to produce a standardized format and a convention of use. Suggesting each stage of anesthesia equipment innovation has unknowingly returned to these objectives to allow for equipment adoption, and acceptance. This has resulted in manufacturing the expectation that a design format can safely bridge the "dynamic interplay" (Woods 2000) of cognitive adaption (i.e. learning to use new technology and procedures) and physical adoption (applying, achieving and accepting it).

Figure 4

Fig4 The latent design cycle of procedural familiarity and the origin of awkwardness



The cyclic motivation for each stage of redesign has been focused on implementing innovative ideas through integration, in exchange for changed use methods. Although well equipped with research and novel concepts, each stage of redesign has been carried out by a differing and growing body of professions who have perceived technological evolution as continually capable of being anticipated and adapted to. The substitution of all traditional interactive instrumentation (e.g. rotameters, bellows and bypass lever), with digital interfaces is within current engineering capability. However this does not account for how old task behaviors are applied to adopt to new design changes, or how old altered behaviors become established conventions and therefore accepted. In the few cases when novel ideas have been implemented, the results have met with limited success. Traditional controls have design and use behaviors that stem from the inhaler, apparatus and early machines, and are integral to the latent design cycle of procedural familiarity. This implies that anesthetists wish to retain a qualified element of craft; the retention of a long held belief in personal behavior and intuitive decision making, and a trust in mechanically derived machine physiology.

Reflecting on anesthetists' reluctance to give up an adopted and awkward convention, implementing new technologies may widen the gap between the behavioral craft of anesthesia and the requirements for information management and vigilance (Warm 2008), thereby prompting new unanticipated behavior (Woods 2000). This results in a concerned prediction that in retaining the table based system and awkward ergonomics, familiarity can somehow convey safe use thereby facilitating a continuance of adoption. The benefits of any future substantial change to equipment format will impact on established standards, safety and a generation of anesthetists with a significant change in the convention of use. This prediction hinges on the capability of anesthetists to safely adapt outside of the design cycle, requiring innovative solutions that may resemble past use methods.

While the IEC (2007) standards promote usability, using terminology such as learnability, memorizability and satisfaction, (effectiveness, efficiency, ease of user learning and user satisfaction) a significant design approach is required to alleviate the current and developing inadequacies and the impending challenges of design acceptance. This risk in change must be balanced against the profession's diversity in age, culture, experience, habits, technology comfort, and specialty. It is revealed here that anesthetists will adopt new work methods governed by technology that go against previous behaviors if a familiar convention of use is retained. David Liu's study shows how reducing awkwardness involving radically innovative design requires new use methods. It is difficult to anticipate how such changes (or the revision to old, normal use methods) may be universally accepted.

CONCLUSION

By using a design orientated historical viewpoint, our investigation has led to a conclusion that the capability of design and technology to solve social and economic needs has unknowingly and imperceptibly cultured a habit of acceptable awkwardness. The evolutionary approach has endeavored to make the workplace of the anesthetist effective and efficient, and success can be seen if each design step is viewed in isolation. However, bringing 100 years of design together reveals a latent design cycle paved with adoption. Past studies analyzing the task of anesthesia and quantifying awkward placement, have applied human factors methods retrospectively to innovation. While this presents designers with a suitable problem to solve, it ignores the origin. Therefore within the safety conscious and regulated field of anesthesia, the solution remains iterative. Iterative design is a proven method and has demonstrated its ability to make analogue and mechanical equipment safer during the last century. New digital technologies do not 'fit' comfortably into this technology 'genealogy' and require a new approach that encompasses interface, interactions and chassis design.

Anesthetists have not adapted to new equipment changes, instead they have and continue to adopt difficulties as part of their profession and workload, creating and passing on behaviors, habits and shortcuts to mitigate design inadequacies. New methods of equipment introduction, training and supervision may overcome the acceptance of new technologies but the past demonstrates a latent design predicament hiding behind the facade of the anesthesia machine that may prove difficult to overcome, as it resides in familiarity and acceptance rather than good work methods. The greater concern here is that innovation is now bound within a design cycle that restricts ergonomic workplace relevance to a design convention.

As a prediction, this study sounds a warning to the implications and acceptance of new technology and interfaces that do not follow the traditional path of iterative evolution that has seen the anesthetic machine develop within a familiar format over the last 80 years. A design specification that has evolved in a concomitant relationship with patient safety, regulations and education, while awkward, is a convention accepted by anesthetists. The recent technological capability to move from analogue and physical, to digital and screen based interaction presents a revolutionary change and questions how anesthetists will adapt. Or will they adopt as they have in the past?

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