The Makings of Effective Research!

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The pace of technological change requires an agile R&D process where high level requirements are quickly, almost instantaneously defined, refined and articulated. Contrary to the view of the solitary mad scientists in the secret back room, effective and timely research requires a robust team, stable funding, innovative scientists, disciplined processes, a user community identifying the technology gaps, and of course visionaries to describe what the future might look like. This paper will leverage the experiences from over twenty years of Department of Defense research to describe the attributes of successful research, testing and transition. The DoD's seven budget categories of R&D (6.1 to 6.7) as well as the nine Technology Readiness Levels will be explored and discussed as they relate to the progression of projects moving from basic research to successful transitions. Several successful examples from the medical modeling and simulation community will be cited and discussed in detail.

Additionally, methods to describe and evaluate proposed research programs, such as the often used "Heilmeier Catechism" eight questions will be discussed. Appropriate testing for different technology readiness levels will be explored including from simple usability assessments to Training Effective Evaluations and how these compare to operational testing. A few pitfalls of unsuccessful research efforts will also be described, citing specific examples. Finally, a timeline will be presented for beginning a successful research project, including funding and transition strategies.

ABOUT THE AUTHOR

Dr. Beth Pettitt is the Chief for the Medical Simulation Research Branch at the Army's Simulation and Training Technology Center (STTC). Dr. Pettitt is actively involved in pushing research frontiers, testing, evaluating, and transitioning relevant technologies quickly, as well as managing the cost, schedule and performance of the multi-million dollar research efforts. Dr. Pettitt has a BS in Mechanical Engineering from Old Dominion University, an MBA from Webster University and a PhD in Modeling and Simulation from the University of Central Florida. She is Program Management Level III certified through the Defense Acquisition University and is a member of the Acquisition Corps. Dr. Pettitt has been applying creative innovations to medical simulation and training technologies for over 20 years. Her current research is focused on optimizing and applying the correct level of fidelity according to the level of medical care.

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INTRODUCTION - What is research?

Research often begins with an exciting idea or capability that demonstrates how something can be improved. Meriam Webster defines research as “investigation or experimentation aimed at the discovery and interpretation of facts, revision of accepted theories or laws in the light of new facts, or practical application of such new or revised theories or laws” (Research, 2019). Creativity is also a critical part in any true innovation (OECD, 2015). In the case of simulation and training, innovative solutions related to “higher fidelity”, lower bandwidth, and a higher entity count are always sought. These challenges are typically solved through near term product improvements or longer term research and development (R&D) efforts.

Occasionally improving the current capability is adequate or at least adequate for the near term. Product improvement is exactly what the name implies, improving aspects of an existing product to address performance gaps. This improvement requires little new scientific discovery. In the medical simulation and training arena, adding a new type of simulated injury to an existing group of simulated injuries is typically a product improvement. If the new type of injury, however requires new manufacturing techniques or materials, research is likely required. An example of this might be improving burn injury fidelity by creating simulated burned tissue materials that closely mimic burned human tissue characteristics.

The first formal step in research is the development of a hypothesis. In the simulation and training domain, the hypothesis is typically driven by the need to do something that has not been done before to address a performance gap. For example, a long standing research hypothesis is that physical exertion will affect performance. In dismounted soldier virtual simulations, movement and exertion are not present in the exercise due to space and technological constraints. Since the 1990’s, this broad hypothesis has inspired research efforts to indicate position, direction, and speed, such as pressure pads in the trainees’ shoes and the omnidirectional treadmill (ODT) which can be seen in Figure 1 (Boyton, Kehring, & White, 2011). Both of these technologies allowed participants to run in place while wearing a head mounted display system, immersed in a synthetic environment. These technologies allowed the trainee to change directions physically while the virtual representation responded naturally to the direction change. That same physical exertion hypothesis continues to inspire research today into augmented and mixed reality solutions with see through head mounted display systems, allowing individuals to move freely in a physical space, where some of the current research challenges involve registration, occlusion, and scaling (see Figure 2).

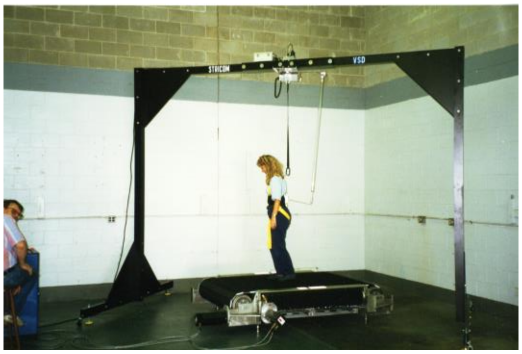

Figure 1: Early Version of the ODT

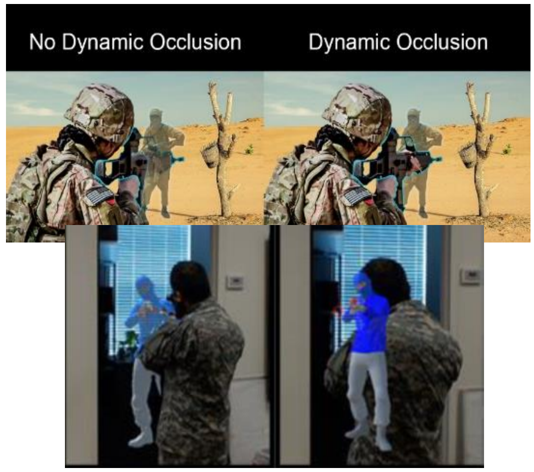

Figure 2: Dismounted Soldier Research

Research has many parts besides identification of the hypothesis or research problem (Creswell, 2008). Good research should also include:

- a literature review and or a market survey
- tracing the research to an identified need or gap, or a formal requirement if it exists
- determining specific research questions
- experiment design
    - determining a data collection methodology
    - insuring locations and capacities
    - following proper protocols, including human protections
- data collection
- analyzing and interpreting the data
- reporting and evaluating research
- publishing the research findings
- transitioning the prototype as appropriate

This paper will focus on an effective research process as it relates to the timely transition of research into usable prototypes.

EFFECTIVE AND TIMELY RESEARCH

With over 20 years of experience in simulation and training R&D, the Simulation and Training Technology Center (STTC) has learned there is no magical formula to determine how long it will take to move a project from early R&D, to advanced development of a capability that is ready to transition to a fielded product. Historically, the fastest R&D effort takes about five years from the birth of the concept to an initial fielding of a training capability; more realistically a R&D effort takes eight to ten years. There are activities, attitudes, and partnerships that facilitate an easy and faster transition. Activities include securing funding, early coordination with the transition partner, early identification of requirements (formal or informal), user tests, training effectiveness evaluations, and demonstrations. Attitudes address the need for partnerships, in regards to testing and transition, as well as a need for trust across the acquisition community. Aligning the different perspectives and missions within the project team requires good communication and patience. For example, R&D will not solve a problem in a year but the transition recipient needs a quick resolution. These conflicts are present in every R&D project.

Innovative research does not always directly match or fulfill an existing requirement. Truly innovative research often defines a future requirement by demonstrating the art of the possible. An example from medical is the Tactical

Combat Casualty Care Simulation (TC3Sim) environment. The TC3Sim R&D effort began in 2008. Numerous versions have transitioned directly to military training locations and to the Virtual Battlespace System (VBS) 2 and VBS3 deployments. A formal requirement for virtual training was finally included in the Medical Simulation Training Center Capabilities Development Document (MSTC CDD), Increment 2 in 2019 (DA Draft, 2019).

Another example of R&D affecting training requirements. From 2003-2007, the STTC developed the first rugged, physiology based, wireless patient manikin, designated the Stand Alone Patient Simulator (SAPS) designed to train critical combat medic tasks. At the time, no requirement existed for training on high fidelity trauma manikins in the field. Field training was performed on heavy "dumb" manikins or on other soldiers. After transitioning the SAPS prototypes to the field, the manufacturer commercialized the design and brought it to market as the iSTAN. iSTAN simulators were purchased by military training sites around the world and in 2015, the Army finally began fielding wireless trauma manikins. Figure 3 illustrates the timeline for manikin development. This is a classic example of the time it takes to develop, mature, and field new and novel capabilities.

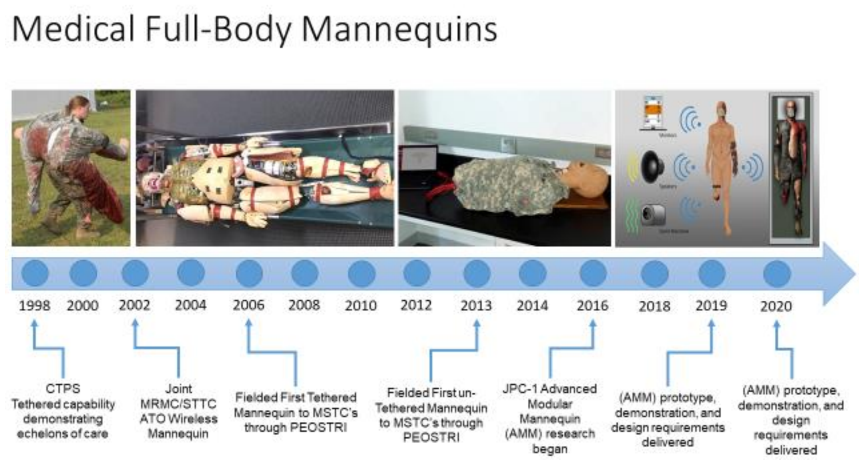

Figure 3: STTC Manikin Development

In the medical simulation domain, one of the current hypotheses is that effective medical training in a virtual or synthetic training environment, needs inexpensive and easily deployed sense of touch to the hands and fingertips. Research to address this hypothesis is multi-faceted and phased over time to provide near, mid, and long term capabilities. There is no requirement for a solution that involves a manikin or a solution that involves a haptic glove. It becomes the research community's challenge to define the problem and demonstrate viable solutions or series of solutions given the time, technology and dollar constraints. To help the broader community understand what a future solution might look like, far out technologies are sometimes pursued. Future haptic feedback in medicine could be provided by the tried and true manikin type devices, or by emerging technologies such as haptic gloves, wrist worn haptic devices or ultrasonic waves. In this case haptic gloves were investigated to demonstrate the ability to actually feel, assess and care for specific combat injuries. The prototype gloves chosen provided extremely realistic finger-tip sensations, however, in their current state, the gloves are a little cumbersome and expensive (see Figure 4). Haptic gloves for medicine, however, do allow the visionary user to imagine what training in the future might look like in an austere environment. It suggests a virtual training capability with no physical training devices (such as a manikin or task trainer) allowing training to occur anytime and anywhere. It also allows new wound patterns and new treatment protocols to more easily be introduced into the training, conceptually only requiring a software update. In this example, demonstrating the ability to train without a manikin or task trainer, should help to define the new requirement. Acceptance of this or any other new simulation capability requires rigorous testing. In R&D, these tests include the less formal user tests and usability testing, often followed by the more formal technical tests and training effectiveness evaluations or TEE's.

Figure 4: Haptics Research for Medical Training

RESEARCH TOOLS AND DESCRIPTORS

The Kirkpatrick Model (Educational Technology, 2020) for testing has been used extensively in the Army's medical simulation research efforts at the STTC. This is a formal process best known for analyzing and evaluating the results of training and educational programs. There are four levels in the model. Level 1 measures how participants react to the training (e.g., user and usability testing). Level 2 analyzes if the training is understood, and is often associated with TEE's. Level 3 examines whether or not there was training transfer (e.g. is the knowledge used outside of the classroom). Level 4 determines if the material had a positive impact and often requires a longitudinal study. Level 4 also includes impacts of time and cost.

As outlined by this model, evaluation needs to progress through each level as appropriate. Data from all of the previous levels can be used as a foundation for the analysis at the next level. Each subsequent level provides an even more accurate measurement of the usefulness of the training, yet simultaneously calls for a significantly more time-consuming and demanding evaluation. These levels are also associated with readiness levels.

Technology Readiness Levels (TRL's) (see Table 1) are used to describe the progression of the technology as it matures (DOD Deskbook 5000.2-R). Knowledge Readiness Levels (KRL's) are also sometimes used to describe maturation when the product is a report, analysis or a study, but will not be focus of this discussion. The TRL scale ranges from one to nine, where a TRL 1 is basic science and TRL 9 is a completed project. Most simulation and training research starts at a TRL 3 with the R&D of a system prototype. The completion goal is often a TRL 6 or 7, with system testing in an operational environment.

Table 1: DOD TRL Descriptions

Technology Readiness Level	Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept
4	Component and/or breadboard validation in a laboratory environment
5	Component and/or breadboard validation in a relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in an operational environment
8	Actual system completed and qualified through test and demonstration
9	Actual system proven through successful mission operations

Another method used to describe research in the Department of Defense is to define the type of funding used, which is Research, Development, Test and Evaluation (RDT&E) 6.1 to 6.4. RDT&E 6.1 refers to basic research, so for medical simulation it could be developing a new material to represent synthetic tissues. RDT&E 6.2 is applied research and means a 6.1 capability such as a new material is applied to an existing problem and studied. For example, 6.2 research would take this new material and apply it to a specific procedure or type of wound, such as a burn. It also includes obtaining feedback from subject matter experts on potential usability. RDT&E 6.3, refers to an Advanced Demonstration Phase, where the feedback from the 6.2 phase has been incorporated into a prototype that is more complete. For the burn tissue example, this phase would include incorporating the burned tissue into a more complete training system, to allow a more robust usability evaluation. RDT&E 6.4 is normally the last phase where traditional R&D occurs. Again, lessons learned from the previous phases are incorporated into this new design and the system is tested at a training site with high student throughput to do a complete TEE. The TEE typically assesses educational changes with the new 6.4 technology compared to current instructional methods. Figure 5 illustrates how testing, TRL levels and RDT&E indicators relate to each other.

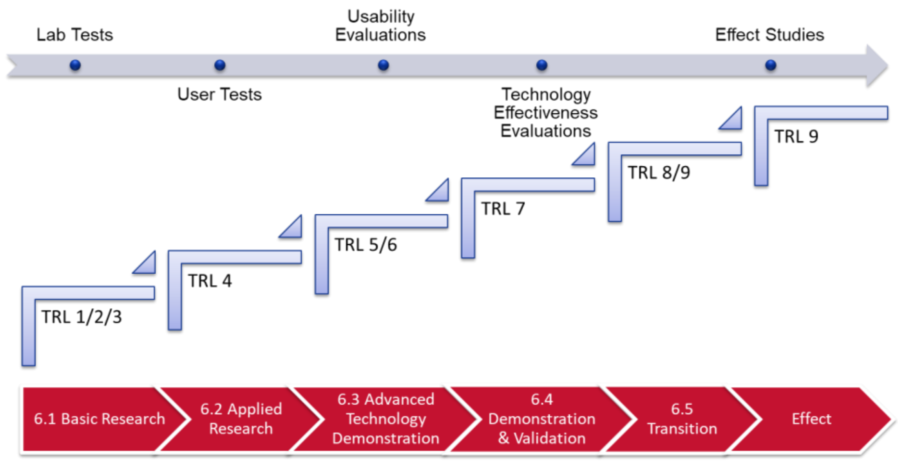

Figure 5: Testing, TRL Levels and RDT&E Funding

One other tool that is often used to describe and help evaluate new research efforts is the "Heilmeier Catechism" (DARPA, 2020). In use since the 1970's, this set of questions defines in simple language, the objective, how the problem is addressed today, the new approach, what difference will it make, the risks, costs, schedule, and metrics for success. The content of these questions is most often succinctly included on one chart and orally defended to determine whether or not a program will receive funding. Figure 6 shows two examples of quad charts used to secure funding and brief the progress of research, that follow the guidelines of the Heilmeier Catechism. Again, the goal of the chart is to describe the overall research effort and why it matters, including cost, schedule and evaluation criteria on one chart with no jargon. Objectivity and the ability to quantify data and dollars are critical as the researcher responds to these questions.

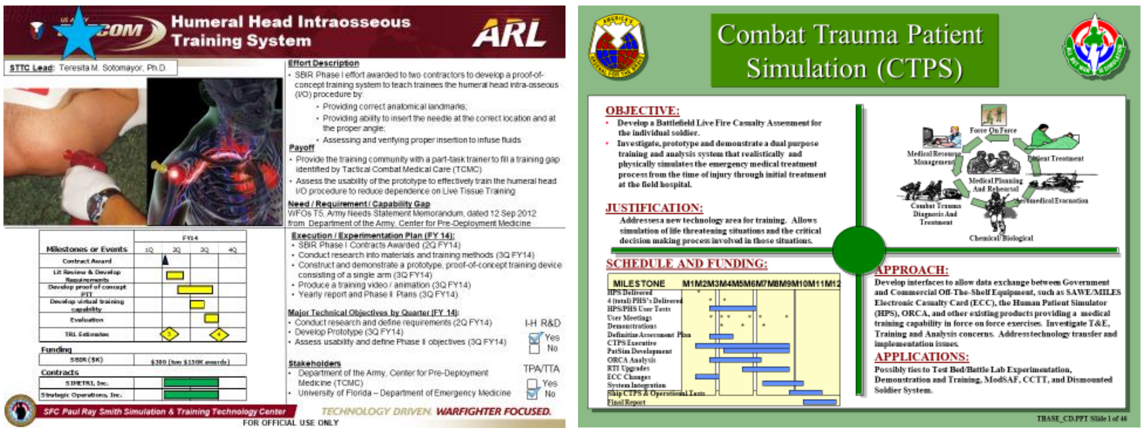

Figure 6: Examples of Heilmeier Catechism Styled Charts

FUNDING CONSTRAINTS!

Research funding has been casually mentioned several times throughout this paper. There is nothing casual about ensuring and securing an appropriate budget for the desired research goals. Once again, there is no magic formula to determine how much a particular research objective will cost. There are numerous mechanisms to securing funding. These include Small Business Innovative Research (SBIR) efforts, competition for intramural funding opportunities, and numerous Broad Agency Announcements (BAA), to name only a few.

Experience has shown that progress can be made with very small funding amounts (approximately $150K/year). However, typically, to really solve the larger problem, shorten the fielding time, and produce a viable solution, much larger investments over several years are required. Additionally, it is impossible to constrain true research with a fiscal year schedule. Research can and should reveal options and challenges not originally envisioned, although it cannot go on forever! The goal of all research should be to transition a new product or capability to the broader community. This requires discipline, focus on achieving the original goal and independent evaluations, while simultaneously identifying future research vectors.

The importance of stable and consistent funding for a research effort cannot be overlooked. Breaks in funding can be catastrophic to research teams as critical skills are lost through personnel reassignments. Most research projects continue for many years: three to five seems to produce a viable capability. Of course, like all efforts, comprehensive annual or bi-annual reviews are essential to insure that the research is progressing and is on track toward accomplishing the desired outcomes.

AVOIDING THE VALLEY OF DEATH

Referring to Figure 5, RDT&E 6.4 funding is intended for the development of advanced prototypes and RDT&E 6.5 funding is intended for System Development and Demonstration. RDT&E 6.4 and 6.5 facilitate transition from the R&D to acquisition and fielding, effectively bridging across the proverbial valley of death. Without RDT&E 6.4 and 6.5 funding, transition is difficult, but is possible.

Transitioning any research into an actual fielded product or system, is an art that requires discipline! The "art" or creative part of the transition process refers to the ability to forecast what technologies have the potential to solve a milestone objective. It also refers to the innovation required to take basic technologies, apply the appropriate R&D and produce a desired outcome. The discipline comes through formal transition agreements and continual communication between the researchers and the acquisition and fielding group. The discipline is also applied through understanding of a program's milestones and successfully determining where a specific research effort can best be incorporated. The communication requirement cannot be understated… Regular meetings to share program goals and research outcomes can be effective. A promising way to facilitate transition is to assign research personnel to work part of their time in the acquisition offices and vice versa. This type of arrangement promotes such close coordination that very few opportunities are missed. The researchers begin to understand the needs of the acquisition group, and the acquisition group gains an appreciation of what it takes to completely research and develop a prototype capability.

Transition occurs through the commercial side as well. Often when research transitions from industry, it is through a product purchase. Commercial products are typically developed through Internal Research and Development (IRaD) and sometimes through government sponsored R&D. When government purchases a capability developed with IRaD, extra testing and assessment measures are warranted to ensure that the item meets the government requirements. When the government sponsors the development, it usually receives a prototype capability that the contractor continues to develop on their own. Once commercialized, the government simply awards a commercial purchase, thus significantly shortening the often decade long acquisition timeline.

ROBUST RESEARCH TEAMS – It takes a Village!!

A robust and successful research effort requires a dynamic, dedicated and multi-disciplinary team. Visionaries and technical writers are critical at the very beginning. Visionaries are also useful at certain critical decision points in the life a research project. Equally important is a proponent and/or user community who must effectively articulate gaps in training capabilities. Proponent and end users do not typically define the candidate technologies or the research, but they can provide invaluable insight in developing a solution. Examples of well-defined gaps could include limited capability to provide prolonged care or limited capability to train burn care. From those simple statements, innovative scientists and engineers begin to break down current and emerging technologies that may be applied to solve the gap and what research is required to meet the training objectives. Effective research teams also require systems engineering process skills throughout the project life cycle. Subject matter experts, whether its seasoned pilots for flight simulators or experienced medics for TC3 simulations are also a critical part of the robust team.

RESEARCH PROJECT PITFALLS

Throughout a researcher's career there are many successful and unsuccessful research projects. From an optimistic viewpoint, research is never totally unsuccessful as there is always some knowledge or insight to gain. The ultimate goal of research is to advance science and hopefully to transition some sort of capability or product. For the purposes of this discussion successful research will be defined as research that produces a tangible software or hardware product, not just a study or report. Seeing the flaws of a research project once the work is complete, is much easier than forecasting the issues beforehand, but there are some general principles that can be learned from failed attempts.

- Sometimes the vision is way ahead of a technologies capabilities! In 2003, the STTC attempted to develop what we now call a mixed reality for an airway management training system (Rolland, 2003). A reflective, see through head mounted display (HMD) and manikin (see Figure 7) were the primary parts of this system, which required a darkened work space for the retro-reflected image to be visible. Although progress was made, registration, occlusion, and HMD limitations made it impossible to fully realize the vision of this effort.

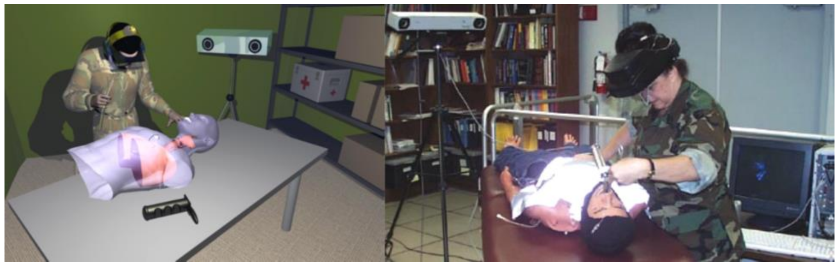

Figure 7: Early Mixed Reality Research

- The technology needs to present an easy to use solution. In 2008, an early version of a virtual patient system was researched and developed (Kenny, 2010). The goal of the system was to provide an immersive patient for a health care provider to train on taking a patient history. The visuals (see Figure 8) were good, however the natural language processing frustrated many users. The software required a voice training session, to help the virtual characters understand the trainees' speech, and if there was an accent of any kind the system really struggled. Because of the complexities of using the system, it never fully transitioned to the intended user.

Figure 8: Early Virtual Patient Research

- The solution must fit the budget of the training audience. There are countless examples of this! For example, surgical simulators cost thousands of dollars but are designed for a single use before requiring expensive manufacturer refurbishment. These surgical simulations have been tried and then dismissed at many military training sites. It is easy for the industry and the research community to design the ultimate and perfect solution. It is much harder to make it cost effective.
- Sometimes a promising technology is combined with the wrong use case. An example of this can be seen in an early attempt to incorporate inexpensive, flexible sensors in the skin of a manikin. For the sake of easy construction and demonstration, the abdominal area was chosen (see Figure 9). Although the technology showed promise, it proved difficult for the user community to envision how this technology would transition to more relevant scenarios dealing with the head or extremities.

Figure 9: Prototype Flexible Sensors and Automated Palpation Research

- A training system must be extremely durable! Again there are numerous examples of prototype systems that fail basic durability testing in an operational environment. One of note in the medical simulation research community, are the joints on training manikins. Countless manikins, which were advertised as capable of field training, and purchased for use in outside training lanes are no longer allowed out of a lab or classroom. Joints breaks while dragging the simulated casualty to safety. R&D was actually conducted to fix this deficiency, but the solution has not been implemented across the manikin industry.

- Timing is critical! Research can be a year or two early, which can make it challenging to pull it out of the archives and transition the relevant parts across the "valley of death". On the other hand, sometimes by the time research is complete, it starts to seem irrelevant. Female trauma may end up falling in this category. Because researchers are eager to share their early findings through conferences and publications, industry will also sometimes start to work on a solution. Even though the R&D may be perfect and complete, many of the critical training challenges have already been solved.

AGILE RESEARCH AND DEVELOPMENT

Typically, when the word "agile" is used, everyone thinks only of software development. However, many of the principles in agile software development easily translate to R&D (Hazzan, 2014). A few principles of Agile development are examined more closely below:

- "Satisfying the customer" is essential for R&D to gain user acceptance and to end with a successful transition.
- "Welcome changing requirements, even late in development" is critical to the success of R&D as the prototype goes through the testing, revision, and retest phases. Not only will users recommend changes, but fundamental changes are often a necessity as the testing progresses. There is no room for the R&D team to hold on to their unique ideas, if they no longer meet the need.
- "Build projects around motivated individuals" has already been discussed with the importance of building a visionary, multi-disciplinary team.
- "The most efficient and effective method of conveying information to and within a development team is face-to-face conversation": this principle is accomplished both through regular R&D team meetings as well as the exchange of personnel across R&D and acquisition groups.
- "Working software is the primary measure of progress" is translated in R&D to a prototype that performs as desired and expected.
- "At regular intervals, the team reflects on how to become more effective, then tunes and adjusts its behavior accordingly"… this principle could be viewed as one of the most important for R&D in the simulation and training domain. Technological advancements are often happening at such a fast pace that researchers must adapt and change quickly. This requires an open mind to new ideas and new processes that support changing directions. This principle also points to the need to always identify new research needs and ideas in the midst of delivering a needed research outcome.

RECOMMENDATIONS AND CONCLUSIONS

Table 2 presents a notional timeline for moving through the research process and incorporates many of the concepts discussed in this paper. There are several important things to note about this timeline. It assumes no funding delays caused by continuing resolutions, and contracting challenges; and it assumes the project is fully funded from the beginning. It also assumes successfully presenting a research plan without rewrites and delayed committee reviews. On the technology development side, it assumes that all the changes identified in the previous phase can be incorporated into the next version within a year to facilitate the proposed annual testing cycle. It assumes that the technology produced in each phase will be viable, needing very little extra time or manpower for modifications. In short, this timeline represents a perfect situation! Even with this very optimistic view of research, the project lasts almost 5 years.

Table 2: Optimistic Schedule for Research

Time	**Research Project Task**	**Responsible Entity**
Month 0	New capability/training gap identified	User/proponent/scientist
Month 2	Candidate technologies/hypothesis identified	Project Team
Month 6	Literature Review/Market Survey	Scientist
Month 8	Heilmeier Catechism Developed	Scientist
Month 12	Funding Secured for the Entire Project	Scientist
Month 15	Project Begins; Begin transition discussions with acquisition partners	Project Team
Month 18	Experiment Design	Scientist
Month 24	Initial Prototype I (TRL3/4) Lab/User Testing	User/Scientist
Month 27	Analysis of User Test Data Complete	Scientist
Month 36	Prototype II (TRL 5/6) with modifications based on User Tests results; ready for Usability Evaluations	Project Team
Month 39	Analysis of Usability Evals Complete	Scientist
Month 48	Prototype III (TRL 6/7) with modifications based on Usability Eval results; ready for TEE	Project Team
Month 54	Analysis of TEE complete	Scientist
Month 55	Potential Transition	Project Team

Research takes time and requires a patient, persistent vision for the future. R&D has a long history of positively impacting the quality and effectiveness of simulation and training systems. New research must be familiar with formal requirements and gaps but must remain forward thinking and creative. For real progress to occur, scientists, engineers and users must be free to pursue advanced capabilities far beyond what is currently available. In fact, they must not be afraid to fail, for even the worst research results advance knowledge through lessons learned. The best of research provides a vision for the future. Properly resourced research teams possess the capability to create revolutionary change!

REFERENCES

Boyton, A., Kehring, K., & White, T. (2011). Biomechanical and Physiological Validaton of the Omni-Direction Treadmill as Mobility Platform for Immersive Environments. Aberdeen Proving Ground, MD: Army Research Lab.

Creswell, J. (2008). Educational research: Planning, conducting, and evaluating quantitative and qualitative research (3rd). Upper Saddle River, NJ: Prentice Hall.

DA Draft. (2019, May 19). Capability Development Document For Medical Simulation Training Capability (MSTC), Increment 2 Program. MSTC CDD, Inc 2.

DARPA. (2020, June 18). Heilmeier Catechism. Retrieved from DARPA: https://www.darpa.mil/work-with-us/heilmeier-catechism

DOD Deskbook 5000.2-R. (n.d.).

Educational Technology. (2020, June 7). Retrieved from kirkpatrick-model-four-levels-learning-evaluation: educationaltechnology.net

Hazzan, P. O. (2014, May 14). Agile Research. Retrieved from INFOQ: https://www.infoq.com/articles/agile-academic-research/

Kenny, P. G. (2010). Virtual patients for virtual sick call medical training. I/ITSEC. Orlando, FL: NTSA.

OECD. (2015). The Measurement of Scientific, Technological and Innovation Activities. Frascati Manual, doi:10.1787/9789264239012-en. ISBN 978-9264238800.

Research. (2019, June 7). Dictionary, Merriam-Webster. Retrieved from Merriam-Webster Web site: Merriam-Webster.com

Rolland, J. D.-L. (2003). Development of a training tool for endotracheal intubation: Distributed Augmented Reality.