Optimizing the Integration of Computational Tools in Routine Clinical Cardiology

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

Vignesh Valaboju
Spring, 2021

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

Introduction

An engineer can spend decades developing the most innovative piece of technology to change modern medicine, but if a physician cannot use that piece of technology, then the innovation will be lost in the history books. There have been several recent advances in cardiac computational tools that have allowed for personalized medical solutions that cardiologists alone cannot provide (Trayanova et al., 2012). Unfortunately, many of these new computational tools are not being used in routine clinical cardiology due to hindrances that make it difficult to integrate new technology into hospitals. For instance, there are several software, hardware, and implementation barriers ranging from poor hospital infrastructure to the sheer cost of computational resources needed (Lee et al., 2014). Cardiologists also must show a reasonable demand for the technology and actively go out of their way to request for the adoption of new technology. In addition, hospitals have been known to face organizational distress and gridlock when adopting new technology (Coye & Kell, 2006).

Computational tools such as biomechanical simulations allow cardiologists to predict the outcome of heart surgery without ever making a single incision in the patient, leading to better patient health (Lee et al., 2014). To integrate clinical cardiology and the use of computational tools that improve healthcare, there must be overall integration guidelines for engineers, cardiologists, and hospital administrators. Thus, this thesis uses sociotechnical frameworks such as Actor Network Theory (ANT) and technological momentum to answer the following research question: how can cardiologists and engineers increase the use of computational tools in routine clinical cardiology to aid in the diagnoses and treatments of cardiovascular diseases? ANT provides insight into what actors are present and affected by new computational tools in cardiology. Technological momentum helps analyze what societal factors determine the success of computational tools and how computational tools affect doctors, patients, and hospitals. The thesis provides a detailed list of guidelines that will aid the integration of computational tools in routine clinical cardiology.

Methods

To design clinical integration guidelines for engineers working on cardiac computational tools, documentary research methods and network analysis were used. Documentary research methods were used to analyze several journal articles to identify the state-of-the-art computational tools in clinical cardiology, obstacles present when using cardiac computational tools in the clinic, and factors that inhibit physicians and hospitals from adopting new technology in general. Analysis of these areas led to a comprehensive understanding of what clinical cardiac computational tools are in development and in use.

Two main sociotechnical frameworks were used throughout the thesis: ANT and technological momentum. ANT suggests there are actors are human and non-human entities that are part of a complex network where each actor has unspecified relations with another. ANT helps understand how actors interact with each other inside complex networks (Cressman, 2009). Technological momentum is described as the process where society's development shapes technology and technology itself shapes society's development simultaneously. Technological momentum is a combination of social and technological determinism; thus, the theory argues that both social and technological determinism affect how society interacts with technology (T. P. Hughes, 1994).

ANT was employed to determine the key actors present in the development and use of the cardiac computation tools. Experts in research and development (R&D) of computational tools, experienced cardiologists, and hospital administration authored the journal articles analyzed.

Next, network analysis was used to understand how hospital hierarchy functions when new technology is adopted. The analysis provided insight into how financial and organizational factors determine whether a hospital accepts new technology into their pipelines. ANT was used to dissect the complex hospital financial and organizational network. Consequently, technological momentum was used to determine how the complex hospital network affects how engineers develop their tools. The opposite social dynamic was also analyzed to see how tools engineers developed affect the social construction of the hospital network.

Lastly, to obtain a deeper understanding of how hospitals integrate computational technology, a case study analysis on how a new computer information system (CIS) was implemented into a hospital network was analyzed. The case study by Lapointe and Rivard provided detailed information about how physicians reacted to the new CIS. In the case study, ANT was used to analyze the actors in the network created by the new CIS. In addition, technological momentum was employed to understand how the new computer information system influenced physician behavior and vice versa. The results from the study provided insight into what physicians like and do not like about new software integration. The results can be extrapolated to cardiology-specific technology implementation.

The information retrieved from documentary research and network analysis was then used to frame integration guidelines that engineers, cardiologists, and hospital administration can use when developing computational tools for routine clinical cardiology.

Results

Current Advances in Computational Tools

Computational tools in cardiology include artificial intelligence, biophysical and mechanistic computational models of the heart, cardiac drug kinetic models, and computer assisted decision-making tools, and computer-assisted therapy (Cuocolo et al., 2019; MEHTA et al., 1994;

Niederer et al., 2019; Trayanova et al., 2012). The goal of computational tools in cardiology is to combine physiological and physical principles to understand what is happening during pathophysiological states of the heart (Niederer et al., 2019). Artificial intelligence can be used for predictive analysis and risk assessment of various disease conditions, automatic image segmentation of cardiac images, analysis of electrocardiograms, and genomics analysis (Cuocolo et al., 2019). A computer-aided decision support system can analyze vast amounts of patterns and make detailed accurate diagnoses which can aid physicians (Cahan & Cimino, 2017). Advances in medical imaging and catheter measurements have allowed engineers to build computational models of the heart that allow researchers and physicians to understand what happens to the heart during various disease states and interventions. For instance, cardiac resynchronization therapy is a treatment for patients with dyssynchronous ventricular contractions, which is a disease state that often leads to heart failure. Unfortunately, 30% of patients who get pacing therapy do not respond well to it (Thomas et al., 2019). An electromechanical computational model of the heart can be used to determine what are the precise locations for the cardiologist to pace the heart for each patient. The result is a much better treatment success rate and alleviated pressure on the cardiologist to choose the right spot to pace (Sermesant et al., 2009).

In cardiac surgery, finite element models of the heart, detailed computational models of the geometric and mechanical properties of the heart, are used to simulate different types of surgery. For instance, in mitral valve surgery, where the mitral valve of the heart is repaired, the interventions a surgeon might introduce to the mitral valve can be simulated. The results of the surgery can be predicted without ever making a single incision in the patient (Lee et al., 2014).

Using ANT, we can determine one of the main networks in play: the R&D network. The R&D network is important because it contains the actors that create novel advancements in cardiac computational tools; thus, these actors have the power to shape their computational tools in a way that they can integrate seamlessly into routine clinical cardiology. The key actors are engineers, scientists, cardiologists, and the computational tools themselves. Since the thesis is focused on the high-level integration of computational tools in the clinic, the intricate details of the computational tools will be black boxed to avoid convoluted analysis of what is "under the hood" of the tools such as algorithm structure. ANT suggests integration guidelines developed must be targeted toward the actors present in the R&D network.

Integration Issues

Although cardiac computational tools seem great in theory and experimental trials, there are several barriers to integrate these tools successfully into clinical cardiology for routine use. In general, hospitals have a difficult time integrating new technology into their workflows. From the physician's standpoint, two of the main obstacles are physician preferences and reactive posture (Coye & Kell, 2006). The physician must prefer the new technology for it to be adopted. In cardiology, the cardiologist must know about the new technology and actively show a patient and/or community need for it. It is difficult for cardiologists to be on top of the new R&D, since their main job is patient facing, and not the backend like the actors in the R&D network. Physician preference relates to reactive posture, which is that for a hospital to adopt a new technology a physician must request it, or other hospitals must request it for a planning process to start. Coye and Kell emphasized that adopting the new technology often leads to organizational distress and gridlock.

Physician reactive posture is an example of a microcosm of technological momentum. Physician preferences greatly affect the actions of a hospital that in turn determine the success of a computational tool. A cardiologist with no preference for a computational tool will result in the computational tool not being used clinically. In the opposite direction, a computational tool with innovative and useful features will lead to greater physician preference if the physician knows about the existence of the computational tool.

In a study about computational tools in cardiac surgery, Lee et al. 2014 discusses three technical challenges of integrating surgery simulation tools in the clinic: software, hardware, and implementation issues. In terms of software issues, the finite element simulations are computationally expensive and take a long time to run. For time sensitive surgeries, it is difficult to get timely results from the model. In terms of hardware issues, it is difficult to run these complex simulations on hospital desktop computers due to poor infrastructure. In terms of implementation issues, the author mentions that cost effectiveness is a key factor for hospitals. The computational tools are costly, and the hospital also must pay to train and educate the cardiologists on the new tools (Lee et al., 2014).

Hospital Network's Effect on Engineering Development

We already defined above the R&D network. The other important network is the hospital. A hospital is a complex network where several parts affect the integration of clinical cardiac tools. As the number of novel advancements in R&D increases, it becomes increasingly difficult for hospitals to evaluate and accept new technology since much of the technology is disruptive. Disruptive technologies effectively change the status quo workflow and business models in a hospital (Coye & Kell, 2006). The change can be positive or negative.

First, let us understand the organizational structure of a hospital and use ANT to dissect the network and its actors. The main actors, from the top to bottom in hierarchical order, are board members, executives, department administrators, patient care managers, and service providers (*Hospital Organizational Structure*, n.d.). The board members at the top of the structure often will not deal with niche technology such as computational tools in cardiac care; thus, they are black boxed. The hospital executives manage financial and business-related decisions. These people have large input on whether a new computational tool can be accepted due to financial reasons. The department administrators and patient care managers oversee daily activities in departments and direct patient care (*Hospital Organizational Structure*, n.d.). In cardiology, these actors include chief of surgery and cardiology. The two groups play a vital role in determining the effectiveness of and need for new computational tools. Lastly, the service provider actors include doctors, nurses, and other essential hospital workers (*Hospital Organizational Structure*, n.d.). The actors of interest here are the doctors and nurses since they will interact with the computational tools the most daily.

The executives have financial considerations for hospitals such as the pay-to-performance ratio and the input of stakeholders (Coye & Kell, 2006). Ultimately, a hospital is still a business. The lack of capital is often a barrier in hospitals adopting new technology. Executives need cost-effectiveness analysis on new technology to ensure that there is a good reason for healthcare spending on the new technology (Coye & Kell, 2006; Lee et al., 2014).

Hospitals currently use a capital-budget to purchase new hardware and software (Haas et al., 2018). Computational tools in cardiology include several hardware advancements, but are largely focused on perpetually updated software (MEHTA et al., 1994; Niederer et al., 2019). Perpetual software is constantly updated based on empirical and theoretical data as it comes in real time. Haas et al. argues that capital-budget allocation for perpetual software is outdated because hospitals have to pay a large upfront fee for software that must be updated frequently (Haas et al., 2018). Cardiac computational tools often must be constantly updated to perform the best. Haas proposes using a subscription payment system to buy perpetual software. This not only saves money for the hospital, but it also improves the quality of computational tools since a hospital can stop the subscription service if the computational tool is not performing up to standards (Haas et al., 2018). Under the capital-budget allocation system, if a computational tool does not keep performing well, the hospital must take its losses since everything is paid up front. Technological momentum in this case highlights how a hospital network and computational tool performance determine the financial successes of each other. Social determinism is key here because consistent purchases from hospitals encourage constant innovation of computational tools.

There is currently a lack of financial backing for new, clinical computational tools. Federal funding for private hospitals to purchase new clinical technology will also release the burden upon executives to shift budget allocation from existing therapy technology to new and unproven therapy technology (Coye & Kell, 2006). Thus, the government is also introduced as an actor into the hospital network. A greater financial backing for new and upcoming cardiac computational tools encourages executives to take chances on new cardiac computational tools. There is currently a lack of effort to support healthcare leaders to introduce new clinical technology (Coye & Kell, 2006).

***Accepting New Technology* Case Study**

A study by Lapointe and Rivard was published in 2006 analyzing how well a CIS was implemented in a hospital. The authors focused on understanding how physicians accepted or resisted the implementation of the new CIS. Lapointe and Rivard defined resistors that vary with levels of resistance over the course of product implementation. Using ANT, we can define resistors as physicians, nurses, and implementors. The study defines implementors as people who led the implementation of the new CIS, which included head of physicians, head of nurses, hospital CEOs, and project managers. Physicians, nurses, and implementors each played a critical role in determining the success of the CIS. Three cases were analyzed where CIS was implemented in a community hospital and two university hospitals. Two of the three cases had such high levels of resistance, that the CIS had to repealed (Lapointe & Rivard, 2006).

In the community hospital, physicians valued their relationship with nurses (Lapointe & Rivard, 2006). Network analysis suggests that there is a hierarchy between the nurses and physicians. The physicians have authority over the nurses and can tell them what tests and procedures must be done for patients. Originally, physicians directed nurses by giving them directions orally; however, the new CIS required physicians to document all their actions and requests in the CIS. For instance, nurses would refuse to give a patient an IV if the physician did not put it in the system. The CIS required physicians to spend up to 1.5–2 hours a day managing patient records (Lapointe & Rivard, 2006). Thus, in this case, the physicians refused to use the CIS and provided a high level of resistance. Originally, the hospital CEO kept forcing the CIS onto the physicians, but the CEO was eventually threatened by the high level of resistance since physicians at one point refused to see patients. Consequently, the system was pulled from the hospital network (Lapointe & Rivard, 2006).

In one of the university hospital cases, similar conflicts between nurses and physicians arose. Physicians found it arduous to enter prescriptions into the CIS and felt like they were doing nurses' work. When physicians asked nurses to place prescriptions in the CIS, the nurses refused to (Lapointe & Rivard, 2006). Due to the lack of clear-cut responsibility guidelines when using the CIS, the implementors tried mitigating the situation with temporary fixes. None of the temporary fixes worked leading to the dismissal of the CIS from the university hospital (Lapointe & Rivard, 2006).

In the case where the CIS succeeded, resistance levels increased from resistors temporarily, but ultimately declined as the implementation process continued. When the physicians encountered problems for a pharmacy module in the CIS, they sent letters to the hospital management, the implementors, asking for necessary changes. The hospital management responded promptly and withdrew the pharmacy module until requested improvements were made. The CIS fared well at this university hospital. Physician-nurse conflict was not identified in this case (Lapointe & Rivard, 2006).

In the case study, the technological determinism portion of technological momentum is evident. The nature of the CIS changed the social interactions within the hospital network. When the CIS caused resistance, it resulted in escalating conflicts between physicians, nurses, and hospital administration. These negative social interactions often led to poor patient outcomes, especially when physicians refused to see patients in the small hospital case. The social determinism portion of technological momentum is also evident. In one of the university hospitals, the physician interactions with the pharmacy modules identified holes in the CIS leading to improvements within the pharmacy module of the CIS. First, technology determined physician reactions to the pharmacy module. Then, society, the hospital network, determined what changes needed to be made to the CIS. This back-and-forth was repeated creating a feedback cycle, which led to the success of the CIS in the hospital.

Discussion

Documentary research methods and network analysis suggest that engineers and scientists developing cardiac computational tools for routine clinical cardiology need clear-cut development guidelines for their computational tools to succeed in clinical cardiology. In addition, hospitals must adapt accordingly to be receptive of new computational tools. As a result, guidelines will allow for an increase in the use of computational tools in routine clinical cardiology. Two professors at the University of Texas at Austin famously state that engineering methods are the future of medicine and that the noninvasive nature of computational tools in medicine has been very effective in bettering patient outcomes (T. Hughes & Taylor, 2015).

The sociotechnical analysis from ANT and technological momentum shaped four main integration guidelines that are key to increase the use of computational tools in cardiac care. First, R&D networks must create teams to constantly educate cardiologists and cardiac department administrators on the new cardiac computational tools being developed. The increased education from the teams will increase physician preference for new computational tools in development. The education will also reduce physician reactive posture since both the cardiologists and the hospital administration become well versed on the new computational tools. The guideline increases the strength of technological momentum since R&D networks strengthen their relationship with the hospital networks. Thus, there is expected to be more efficient social and technological determinism between the hospital and R&D networks.

Secondly, engineers must keep in mind software and hardware infrastructure challenges hospitals face. Hospitals do not always have the necessary infrastructure to keep up with modern computational advancements. R&D networks should also develop clear reports of what infrastructure is needed for their computational tools to succeed in clinical cardiac settings. In addition, engineers must understand that hospitals have limited budgets and should consequently prioritize cost-effectiveness of their tools. Lower cost products can result in the opportunity for engineers to sell their computational tools to a wider array of hospitals.

Thirdly, hospitals must modify their capital-budget to include a subscription-based budget for perpetual software. A subscription-based budget, originally suggested by Haas et al., reduces stress from the capital-budget and is better suited for perpetual software since the software is frequently updated. The computational tools in the clinic must be frequently optimized to ensure best patient outcomes. In addition to the subscription-based budget, hospital board members must advocate for greater government funding to back new computational tools in cardiology. The federal-budget backing will encourage cardiology departments to increase the use of new computational tools since they can afford them more easily.

Lastly, engineers must consider cardiologist-nurse dynamics present in the hospital. The CIS case study analysis through the lens of technological momentum highlights that technology can interfere with social dynamics present within service provider actors of the hospitals. Preserving these social relations is vital to ensure that a computational tool is not kicked out clinical cardiology due to integration flaws. Thus, engineers must develop clear guidelines for how nurses and cardiologists can both benefit from new computational tools.

Conclusion

The use of ANT and technological momentum helped dissect and solve integration flaws present with new computational tools in routine clinical cardiology. The results highlight that computational tools in cardiology are advancing quickly and are vital to improving patient outcomes. However, without proper implementation of these novel computational tools in hospitals, the tools will have trouble succeeding as seen in the Lapointe and Rivard case study. Integration guidelines must address software and hardware infrastructure issues, implementation barriers such as hospital finances, physician preference issues, and social dynamics within the service provider group. The thesis suggests the following guidelines to increase the use of computational tools in clinical cardiology: R&D networks must allocate resources to educate cardiologists about new computational tools, engineers must design computational tools compatible with modern day software and hardware infrastructure in hospitals, hospitals must implement a subscription-based budget, and most importantly, engineers must consider how computational tools may disrupt social dynamics between cardiologists and nurses. The guidelines proposed are ultimately targeted at improving patient outcomes in routine clinical cardiology. It is important to note that the guidelines produced are only suggestions hypothesized to increase the use of computational tools in clinical cardiology based on documentary research and network analysis. Real world trials of these guidelines in the R&D and hospital networks are vital to further develop a detailed list of guidelines for engineers, cardiologists, and hospital administration to abide by. Engineers and cardiologists have an ethical and social obligation to prioritize patient outcomes, and guidelines to best increase the use of routine clinical computational tools have the power to positively affect patient outcomes.

References

Cahan, A., & Cimino, J. J. (2017). A Learning Health Care System Using Computer-Aided Diagnosis. *Journal of Medical Internet Research*, *19*(3). https://doi.org/10.2196/jmir.6663

Coye, M. J., & Kell, J. (2006). How Hospitals Confront New Technology. *Health Affairs*, *25*(1), 163–173. https://doi.org/10.1377/hlthaff.25.1.163

Cressman, D. (2009). *A Brief Overview of Actor-Network Theory: Punctualization, Heterogenous Engineering & Translation*. https://summit.sfu.ca/item/13593

Cuocolo, R., Perillo, T., De Rosa, E., Ugga, L., & Petretta, M. (2019). Current applications of big data and machine learning in cardiology. *Journal of Geriatric Cardiology : JGC*, *16*(8), 601–607. https://doi.org/10.11909/j.issn.1671-5411.2019.08.002

Haas, D. A., Jellinek, M. S., & Kaplan, R. S. (2018, March 29). Hospital Budget Systems Are Holding Back Innovation. *Harvard Business Review*. https://hbr.org/2018/03/hospital-budget-systems-are-holding-back-innovation

Hospital Organizational Structure. (n.d.). Rivier Academics. Retrieved April 2, 2021, from https://www.rivier.edu/academics/online/resources/program-resources/hospital-organizational-structure/

Hughes, T. P. (1994). Technological Momentum. *The MIT Press*.

Hughes, T., & Taylor, C. (2015, February 25). *What physicians can learn from engineers*. Science Node. https://sciencenode.org/spotlight/what-physicians-can-learn-engineers.php

Lapointe, L., & Rivard, S. (2006). Getting physicians to accept new information technology: Insights from case studies. *CMAJ : Canadian Medical Association Journal*, *174*(11), 1573–1578. https://doi.org/10.1503/cmaj.050281

Lee, L. C., Genet, M., Dang, A. B., Ge, L., Guccione, J. M., & Ratcliffe, M. B. (2014). Applications of Computational Modeling in Cardiac Surgery. *Journal of Cardiac Surgery*, *29*(3), 293–302. https://doi.org/10.1111/jocs.12332

MEHTA, V., DEB, P., & RAO, D. S. (1994). APPLICATION OF COMPUTER TECHNIQUES IN MEDICINE. *Medical Journal, Armed Forces India*, *50*(3), 215–218. https://doi.org/10.1016/S0377-1237(17)31065-1

Niederer, S. A., Lumens, J., & Trayanova, N. A. (2019). Computational models in cardiology. *Nature Reviews. Cardiology*, *16*(2), 100–111. https://doi.org/10.1038/s41569-018-0104-y

Sermesant, M., Billet, F., Chabiniok, R., Mansi, T., Chinchapatnam, P., Moireau, P., Peyrat, J.-M., Rhode, K., Ginks, M., Lambiase, P., Arridge, S., Delingette, H., Sorine, M., Rinaldi, C. A., Chapelle, D., Razavi, R., & Ayache, N. (2009). Personalised Electromechanical Model of the Heart for the Prediction of the Acute Effects of Cardiac Resynchronisation Therapy. In N. Ayache, H. Delingette, & M. Sermesant (Eds.), *Functional Imaging and Modeling of the Heart* (pp. 239–248). Springer. https://doi.org/10.1007/978-3-642-01932-6_26

Thomas, G., Kim, J., & Lerman, B. B. (2019). Improving Cardiac Resynchronisation Therapy. *Arrhythmia & Electrophysiology Review*, *8*(3), 220–227. https://doi.org/10.15420/aer.2018.62.3

Trayanova, N. A., O'Hara, T., Bayer, J. D., Boyle, P. M., McDowell, K. S., Constantino, J., Arevalo, H. J., Hu, Y., & Vadakkumpadan, F. (2012). Computational cardiology: How computer simulations could be used to develop new therapies and advance existing ones. *Europace*, *14*(Suppl 5), v82–v89. https://doi.org/10.1093/europace/eus277