Development of a Novel Fetal Heart Rate Monitor for Twin Pregnancies

(Technical Paper)

Differences in the Utilization of Doppler Ultrasound Contribute to Racial Disparities in Pregnancy Outcomes

(STS Paper)

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Introduction

In clinical databases, higher risks are linked with deliveries involving multifetal gestations compared to single births (Root & Tonismae, 2024). Increased maternal age and use of reproductive technology in recent years have led to increased frequency of twin pregnancies (Martin, Hamilton, & Osterman, et al., 2017). Within the United States, twin births occurred at 21.3 per 1000 live births, while triplet and higher-order births were 80 per 1 million in 2021 (Horon & Martin, 2022). Routine ultrasound surveillance has become a common task to reduce risks of negative outcomes in high-risk pregnancies such as multiple gestations due to the increasing prevalence of multifetal pregnancy complications.

Currently, fetal heart rate (FHR) is the sole basis for fetal monitoring due to the lack of available technology to reliably measure fetal electrocardiogram (FECG) (Bsoul, 2015). In 2017, Dr. Alunaimi and his research team at Khalifa University examined fetal Doppler Ultrasound (DUS) as the preferred clinical technology for recording FHR and monitoring fetal well-being. DUS transducers could introduce discomfort to the patient. It is also considered to be relatively invasive, for its monitoring procedures involve sending a 2 MHz signal toward the fetus (Alnuaimi, Jimaa, & Khandoker, 2017). The biggest pitfall of DUS lies in its difficulty in monitoring FHR in multiple gestations. Multiple independent DUS transducers must be manually positioned on the maternal abdominal with high erroneous FHR registration. To resolve the problem of DUS transducers' deficiency in accurately measuring multiple heart rates, my technical projects aim to construct a novel FHR monitoring device that can differentiate multiple heart rates within the vicinity of each other by testing on a gel phantom system that mimics a maternal womb carrying multiple gestations and processing FHR signals using a triangulation algorithm. Beyond being an acute medical issue, technologies associated with FHR monitoring inevitably impact disparities in pregnancy care. Minority groups within the United States, such as Black American women and American Indian and Alaska Native (AIAN) women, have higher rates of pregnancy-related death compared to White women (Hill, Artiga & Ranji, 2022). Non-White women with twin pregnancies have an increased risk of adverse outcomes, such as preterm birth, preeclampsia, and gestational diabetes (Soffer, et al., 2018). I will investigate the role of DUS in contributing to disparities in pregnancy care in my STS project and explore how the novel device of my technical project could contribute to reducing those disparities.

Technical Topic

The Doppler Ultrasound (DUS) transducer changes its location relative to the moving fetal source, which allows it to change fetal cardiac signals on a beat-to-beat basis. Due to the non-stationary nature of the current DUS approach, precise measurement of time intervals in the cardiac cycle introduces several difficulties, especially in cases of multiple gestations. Common clinical problems in twin pregnancies include: A) erroneous FHR registration when both hearts lie in the same sample volume of the same transducer, B) both DUS transducers aim at the same heart and measure only a single FHR (Hamelmann, et al., 2018). My project aims to create novel devices for FHR monitoring that can measure, differentiate, and present distinct heart rates when multiple are present in the same sample volume. The first part of my project will focus on creating a gel phantom system that mimics the material uterus with multiple fetuses. Gelatin phantom is commonly used as tissue-mimicking material for its acoustic ability and high fibrous structure. However, limited studies have experimented with modeling the beating heart of an intrauterine pregnancy (Rathbun & Zweig, 2021). For this preliminary study on the gel phantom, we assume the total thickness of the main layers from the uterus outward to be 5-8 cm (Mota et al., 2015).

To collect sound waves emitted by the speakers with a maximized signal-to-noise ratio, we will place a circular array consisting of six piezoelectric sound vibration detectors with an additional one in the middle on top of the gel phantom in the center of the two gel phantom heartbeat generators. After collection of the sound waves given by the gel phantom, we will pre-process the sound wave signals using the Fast Fourier Transform in MATLAB and filter the 50-800 Hz frequency to get rid of the noise in the heartbeat sound signal (Raza et al., 2019). As multiple piezoelectric sensors detect heartbeats at slightly different times due to their distance

from the fetal heart, triangulation algorithms can use the time difference of arrival from multiple sensors to estimate the separate positions of the two fetal hearts. Once the fetal heartbeat's location is determined, the algorithm filters out signals not originating from that area including potential maternal heartbeat or noise in this context. Although this preliminary study has a long journey ahead to reach the clinical application phase, the last part of the project evaluates and compares the accuracy of heart rate measurements output by the novel design to one of the clinical standard DUS with an expected systematic error of the novel design to be 6% or less.

The major drawback of the project includes the lack of fetal movement due to the immobilized heartbeat generators and the limitation of the gel phantom to only represent twin pregnancies. Future iterations of this project could integrate motion-tracking technologies or machine learning models capable of distinguishing between the expected movement patterns of both the fetal heart and surrounding structures. These enhancements could improve accuracy and reliability, ensuring that the device maintains high precision in measuring and separating heart rates in real-world clinical settings. Additionally, future designs might explore multi-angle sensor arrays or even wearable configurations, allowing a flexible response to the natural, three-dimensional movement of fetuses within the womb.

STS Topic

My STS research paper will investigate the question, "How do differences in the utilization of Doppler ultrasound (DUS) contribute to racial disparities in pregnancy outcomes?" During my literature reviews for the technical project, I found that the pregnancy-related mortality rates for Black women and American Indian/Alaska Native (AIAN) women are more than three times and twice as high, respectively, compared to White women (41.4 and 26.2 versus 13.7 per 100,000). Infants born to women of color are at higher risk for mortality compared to those born to White women, with the primary causes of infant mortality being birth defects, preterm birth and low birth weight, maternal pregnancy complications, sudden infant death syndrome, and injuries (Hill et al., 2022). DUS, a key tool in assessing fetal well-being by measuring blood flow in the umbilical artery, can help detect issues like fetal growth restriction (FGR) and placental insufficiency. However, there is very little research that aims to elucidate the role of Doppler ultrasound behind the disparity in pregnancy care. The worse pregnancy outcomes faced by minority populations further underscore the need for a clear understanding of why race is an indicator of one's likelihood to have an adverse pregnancy outcome when national medical institutions widely implemented standard fetal monitoring devices such as DUS.

In 2020, Dr. Stewart and his research team found that the availability and usage of Doppler ultrasounds vary by socioeconomic and racial lines. Specifically, the systematic review highlights the unequal access and inconsistent use of DUS in low and middle-income communities (LMICs) (Stewart et al., 2020). In 1997, the World Health Organization (WHO) estimated that half of the developing world lacked access to ultrasound imaging, and in areas where it was available, much of the equipment was either outdated or non-functional (Mindel, 1997). In addition, fetal growth standards determine which fetuses are diagnosed with FGR and are candidates for enhanced fetal monitoring. These standards can be customized based on race and other characteristics. Likely, as a result, race-based growth standards associated with DUS introduce potential biases in the interpretation of DUS results and increase racial disparities in obstetric care (Ramesh & Larkin, 2022). My STS research aims to connect the experiences of minority groups in both the United States and globally with known risk factors for adverse pregnancy outcomes, shedding light on the well-documented disparities in maternal and infant mortality (Hill et al., 2022).

Methods and Frameworks

My analysis will begin with historical case studies and documentary research to contextualize the current state of racial disparities in pregnancy care. I will analyze key texts that document these disparities, such as Medical Apartheid by Harriet Washington and Killing the Black Body by Dorothy Roberts. This examination of historical records on the dark history of medical experimentation on Black Americans from colonial times to the 21st century and reports on actions done to extend reproductive justice to all women will provide a nuanced understanding of the historical factors contributing to adverse pregnancy outcomes among different racial groups.

A critical component of my analysis will involve a comprehensive review of peer-reviewed medical literature that addresses racial disparities in pregnancy care. This will include studies focusing on the challenges faced by minority communities in accessing quality prenatal care and the efficacy of various monitoring technologies, including Doppler Ultrasound (DUS). By synthesizing findings from these studies, I will be able to draw connections between socioeconomic status, psychological stress stemming from racism, education level, and the established disparities in pregnancy care.

To explain the disparity in pregnancy care by drawing on the broad spectrum of available research and information, I will apply Actor-Network Theory (ANT) in my research. ANT seeks to identify all actors involved with a given technology and analyze their interactions with one another and with other technologies (Cressman, 2009). A key feature of this theory is that it treats human and non-human actors equally, enabling the inclusion of technology, policies, and groups of people as relevant factors (Rodger et al., 2009).

The main drawback of ANT is its inherently infinite nature in searching for a wide range of actors and the level of subjectivity that it allows. Since ANT treats all components equally as actors, the approach can introduce ambiguity, as it sometimes overlooks power imbalances or the historical and social context of these actors. Recognizing these challenges not only provides a balanced approach to the theory but also underscores the importance of critical reflection when using ANT as a methodological tool.

The key actors that appear to impact the disparity in pregnancy care involving the use of DUS include low and middle-income communities, healthcare providers, DUS technicians, insurance companies, and institutions such as education and the government. ANT will be applied to characterize the interaction between the aforementioned groups with the goal of elucidating the driving interactions behind racial disparities in pregnancy care.

In addition to using ANT as a methodological lens, I will also incorporate Critical Race Theory (CRT) to explore how both racism and classism have shaped the development of DUS and broader healthcare systems for fetal monitoring, particularly in the context of pregnancy care. CRT provides a powerful analytical framework for understanding how racial and social inequalities are embedded within systems and structures. One of the key advantages of using CRT is that it allows for a deeper understanding of how racism and classism are not merely individual biases, but are systemic forces that are built into the very fabric of societal institutions like healthcare. CRT emphasizes the concept of "intersectionality," which looks at how race, class, gender, and other identities intersect and create unique forms of oppression. Applying this framework to my research can help reveal how marginalized communities, particularly women of color, face compounded barriers when it comes to accessing prenatal care, undergoing ultrasound screenings, or receiving adequate follow-up care during pregnancy. This framework

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STS Prospectus

also encourages a critique of the dominant narratives in healthcare that often portray technological advancements as neutral or inherently beneficial, revealing how these innovations may inadvertently reinforce existing inequities.

However, one limitation of CRT is that it can sometimes be criticized for focusing heavily on racial and social justice issues, which may not always align with purely technical or clinical discussions. In the context of my research, this could mean that CRT might overlook some of the more technical aspects of DUS development or fail to account for how other factors, such as technological limitations or medical training, also contribute to racial disparities. Additionally, emphasis on structural critique of CRT may lead to a focus on systemic problems without offering as many immediate, actionable solutions for addressing these inequities at the micro-level of clinical practice.

Nevertheless, integrating CRT with ANT can help bridge these gaps: ANT explores the technological and networked aspects of the healthcare system, while CRT provides a critical framework for understanding the broader societal forces that shape these technologies. Together, these methodologies will enable a comprehensive investigation into how DUS and fetal monitoring technologies have been influenced by, and continue to perpetuate, racial and class disparities in pregnancy care.

Timeline

I aim to finish the historical studies and literature review before Thanksgiving 2024, which will give me a head start in applying ANT and CRT methodologies and frameworks to systematically analyze how each identified factor contributes to the racial disparity in pregnancy care over the winter break. I aim to finish the ANT and CRT analysis by the end of March 2025. I also plan to reach out to Dr. Christopher S Ennen, who is an obstetrician-gynecologist at the University of Virginia Hospital, for a scheduled interview in early February 2025 to gain perspective from a clinician on the current challenge in fetal heart rate monitoring using DUS and how it contributes to the racial disparity in pregnancy care. Interviewing in February will place me in a good position to finish the STS research paper by the end of next semester.

STS Prospectus

Key Text

1. Cressman, D. (2009). A brief overview of Actor-Network Theory: Punctualization,

heterogeneous engineering & translation. Retrieved from <u>https://summit.sfu.ca/item/13593</u>.

- Main Argument: This piece explains the core concepts of Actor-Network Theory (ANT), focusing on how networks of human and non-human actors come together to shape outcomes through processes like punctualization, translation, and heterogeneous engineering.
- **Importance to Project:** ANT provides the STS framework for my research by helping explore how race as a sociotechnical construct influences pregnancy outcomes. It enables the analysis of how systemic factors, such as medical technologies and institutional practices, interact with social and racial dynamics.
- 2. Lawrence, S., & Hylton, K. (2022). Critical Race Theory, Methodology, and Semiotics: The

Analytical Utility of a "Race" Conscious Approach for Visual Qualitative Research. Cultural Studies \leftrightarrow Critical Methodologies, 22(3), 255-265. <u>https://doi.org/10.1177/15327086221081829</u>

- **Main Argument:** The authors discuss using Critical Race Theory (CRT) as a methodological lens to interrogate racialized imagery and narratives in qualitative research. They advocate for a race-conscious semiotic analysis.
- **Importance to Project:** This article is vital for my methodology section as CRT aligns with my research goal of uncovering how racial constructs influence maternal health outcomes. It provides insights into analyzing systemic disparities critically and contextually.
- 3. Washington, H. A. (2006). Medical Apartheid: The dark history of medical experimentation

on Black Americans from colonial times to the present. New York: Doubleday.

- Main Argument: This book details the history of unethical medical experimentation on Black Americans and its enduring impacts on trust in medical systems.
- **Importance to Project:** It contextualizes how historical medical racism has led to systemic disparities and mistrust that influence pregnancy outcomes today, establishing a foundational backdrop for my research.
- 4. Murphy, M. (2012). Seizing the means of reproduction: Entanglements of feminism, health,

and technoscience. Durham: Duke University Press.

- Main Argument: Murphy explores how feminist movements have engaged with reproductive technologies and policies, critiquing the medicalization of reproduction and its sociopolitical implications.
- **Importance to Project:** This work is significant for examining how the medicalization of reproduction intersects with racial inequities, providing insights into the sociotechnical dynamics of maternal healthcare.
- 5. Clarke, A. E., Mamo, L., Fishman, J. R., Shim, J. K., & Fosket, J. R. (2010).

Biomedicalization: Technoscience, health, and illness in the U.S. Durham: Duke University Press.

- Main Argument: Clarke et al. discuss the transformation of healthcare through biomedicalization, focusing on how technoscience reconfigures health and illness.
- **Importance to Project:** This framework helps analyze how ultrasound and other prenatal technologies influence racial disparities in maternal health outcomes, linking technological practices to systemic inequities.
- 6. Roberts, D. (1997). Killing the Black Body: Race, reproduction, and the meaning of liberty.

New York: Pantheon Books.

- Main Argument: Roberts critiques the regulation and devaluation of Black women's reproduction in the U.S., highlighting the intersections of race, gender, and reproductive rights.
- **Importance to Project:** This book provides essential context for understanding how societal narratives about Black motherhood shape healthcare practices and outcomes.
- 7. Hill, L., Artiga, S., & Ranji, U. (2022). Racial disparities in maternal and infant health:

Current status and efforts to address them. Retrieved from <u>https://www.kff.org/racial-equity-and-health-policy/issue-brief/racial-disparities-in-mater nal-and-infant-health-current-status-and-efforts-to-address-them/</u>.

- Main Argument: This brief examines current statistics and efforts to address racial disparities in maternal and infant health in the United States.
- **Importance to Project:** It offers recent data on racial health disparities, which will support my discussion of systemic inequities and their impact on pregnancy outcomes.
- 8. Stewart, K. A., Navarro, S. M., Kambala, S., Tan, G., Poondla, R., Lederman, S., Barbour, K.,

- **Main Argument:** This review discusses trends in ultrasound adoption in low- and middle-income countries, highlighting barriers and benefits of use.
- **Importance to Project:** It provides a global perspective on ultrasound technology, contextualizing how its use impacts racialized health outcomes within a broader framework of healthcare disparities.
- 9. Soffer, M. D., Naqvi, M., Melka, S., Gottlieb, A., Romero, J., & Fox, N. S. (2018). The

association between maternal race and adverse outcomes in twin pregnancies with similar healthcare access. Journal of Maternal-Fetal & Neonatal Medicine, 31(18), 2424-2428. <u>https://doi.org/10.1080/14767058.2017.1344634</u>

- **Main Argument:** The study finds persistent racial disparities in adverse pregnancy outcomes among twin pregnancies despite controlling for healthcare access.
- **Importance to Project:** This research underscores how disparities persist beyond socioeconomic factors, supporting my focus on systemic and structural contributors.

10. Ramesh, P., & Larkin, J. (2022). Race-based customization of fetal growth standards-What

is the impact on disparities? American Journal of Obstetrics & Gynecology, 226(1), S61–S62.<u>https://doi.org/10.1016/j.ajog.2021.11.127</u>

- **Main Argument:** The article critiques the use of race-based fetal growth standards, arguing that they may perpetuate disparities rather than address them.
- **Importance to Project:** It provides critical insights into how racialized medical practices exacerbate disparities, informing my analysis of systemic biases in healthcare technologies.

Conclusion

The technical project focuses on designing a gel phantom model to mimic two distinct intrauterine fetal heartbeats. We will then use this model to collect sound wave signals from the separate fetal heart rate generators, pre-process them into frequency-series data, and filter them into the normal range for heartbeat sound wave frequency using a band filter in MATLAB. We will implement the triangulation algorithm to differentiate the fetal positions and heart rates based on the time difference of signal arrival from different sensors. To validate the performance of the novel design, we will test heart generators at a fixed distance in the gel phantom and compare the error rate in heartbeat measurements with the standard clinical Doppler Ultrasound (DUS) device.

In addition to the technical construction of the gel phantom and implementation of signal processing algorithms, the STS research project aims to understand why minority and low-income groups have worse pregnancy outcomes, as shown by the increased maternal and fetal mortality among minority groups. The outcome of this STS research will be a research paper that utilizes Actor-Network Theory and Critical Race Theory to detail the reasons for the role of DUS in the disparities in pregnancy care. This paper will serve as a guide for those looking to understand and correct this disparity.

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