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Katie Labgold	Date

Severe Maternal Morbidity and Health Equity:

Impactful Racial Disparities Research Relying on Population-Based Surveillance Data

By

Katie Labgold
Doctor of Philosophy

Epidemiology

_____

Michael R. Kramer, PhD, MS
Advisor

_____

Carolyn Drews-Botsch, PhD, MPH
Committee Member

_____

Anne Dunlop, MD, MPH
Committee Member

_____

Penelope P. Howards, PhD, MS
Committee Member

Accepted:

_____

Kimberly Jacob Arriola, PhD, MPH

Dean of the James T. Laney School of Graduate Studies

_____

Date

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By

Katie Labgold
MPH, University of Virginia, 2017
BA, University of Virginia, 2015

Advisor: Michael R. Kramer, PhD, MS

An abstract of
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James T. Laney School of Graduate Studies of Emory University
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Abstract

Severe Maternal Morbidity and Health Equity:

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By Katie Labgold

In the United States (US), there are racial disparities in adverse maternal health outcomes, known as severe maternal morbidity (SMM). Gaps in our understanding of the epidemiology of SMM may be contributing to persisting disparities. This dissertation seeks to advance maternal health equity by conducting rigorous epidemiologic research on SMM racial disparities using population-based surveillance data. We used Georgia 2006-2019 hospital discharge records linked with birth and fetal death certificates among Non-Hispanic (NH) Black and NH White women, ages 15-49 years.

In **aim 1**, we investigated how the choice of SMM case definition alters conclusions about the magnitude of the Black-White racial disparity in SMM incidence. Results suggested that the magnitude of the relative Black-White disparity was greatest when the case definition required a longer length of hospital stay (LOS) (rate ratio: 2.0). Conclusions on the absolute scale varied across all case definition modifications (rate difference: 31.2-96.4 events per 10,000 hospitalizations). After reviewing the peer-reviewed literature and considering conceptual challenges in SMM measurement, we recommend an SMM case definition including postpartum hospitalizations, excluding the blood transfusion indicator, and including any LOS.

In **aim 2**, we estimated the proportion of the Black-White disparity in SMM risk operating through hypertensive disorders of pregnancy (HDP). We estimated that NH Black women experienced an excess risk of 55.7 SMM events per 10,000 hospitalizations compared to NH White women. After blocking the pathways through HDP, the excess risk among NH Black women decreased to 41.1 SMM events (proportion eliminated: 26%).

In **aim 3**, we estimated the joint effect of neighborhood relative income inequality and racial segregation on SMM incidence. Results indicated that neighborhood racialized income inequality produced greater than expected SMM risk based on income inequality and racial segregation alone (interaction contrast: 26.4).

Our findings contribute to racial disparities research by identifying a conceptually strong SMM case definition. Further, these findings add to our understanding of the epidemiology of SMM incidence and Black-White disparities at both the individual and neighborhood level in the unique context of the southern US. Sustained research on structural and proximal modifiable determinants of SMM incidence and Black-White disparities is needed.

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Chapter 1: Introduction to investigating Black-White racial disparities in severe maternal morbidity risk

Overview of severe maternal morbidity

Severe maternal morbidity (SMM) is a group of adverse maternal health outcomes related to pregnancy.[1] Often described as maternal mortality 'near misses,' SMM is regularly conceptualized as a step on the continuum of severity from a healthy pregnancy, a pregnancy with morbidity, severe morbidity, and in the worst scenarios, death.[2] As such, the focus on SMM originally arose from an interest in preventing maternal mortality events.

SMM is a rare outcome, estimated to occur in roughly 0.3-1.5% of pregnancies.[3,4] Although SMM events are rare, the United States (US) SMM incidence has increased between 24-45% in the past decade, and there are persistent racial and geographic disparities.[4] Studies have shown that non-Hispanic (NH) Black women are at 1.2 to >3 times increased risk for SMM compared to NH White women.[4–7] Further, the southern US has one of the highest SMM risks.[4] Racial disparities in SMM incidence, specifically the excess risk among NH Black women compared to NH White women, are hypothesized to be largely preventable.[3] In response to the large disparities in SMM and the overall growing burden, reducing the SMM incidence has been identified as a national priority; SMM metrics have been incorporated in the Healthy People 2020 and Title V Maternal and Child Health Block Grant measures.[8,9]

Although the relationship of SMM to maternal mortality has been a primary driver of the prevention of SMM, there are short- and long-term health consequences that warrant independent interest.[1,10] Limited peer-reviewed literature exists for the outcomes following an SMM event as a composite indicator[11–13]; however, studies focusing on specific SMM indicators (e.g., acute myocardial infarction[14,15] and acute respiratory distress syndrome (ARDS)[16,17]) have indicated both short- and long-term physical, emotional, and mental health outcomes following the adverse pregnancy event. Additionally, women openly sharing their personal experiences of near-miss pregnancies have added to the growing public awareness of SMM as a set of critical

and preventable diseases. In a powerful collection of stories gathered by NPR and ProPublica, hundreds of women detailed the emotional, mental, and physical impacts occurring after an SMM event.[18] These included depression, anxiety, persistent pain during the postpartum period, mobility issues, complications in later pregnancies, and the need for long-term rehabilitation and additional surgeries.[18]

Health equity assumptions for investigating racial disparities in SMM risk

Thoughtful disparities research requires the explicit acknowledgment of the assumptions guiding the operationalization of research questions and covariates, selection of methods, and interpretation of findings. Health equity research goes beyond the objectives of investigating overall incidence by seeking to capture and understand the underlying processes that produce inequitable differences by marginalized groups. Thus, we cannot assume that the measures and methods used to study the total population risk of SMM best serve the objective of investigating Black-White racial disparities in SMM incidence. A health equity lens thus centers the consideration of what processes produce worse maternal health outcomes among Black women. We define a health disparity as a preventable difference in a health outcome that is harmful to historically marginalized populations and therefore is unjust.[19] We focus specifically on the dimension of maternal race, given the persistence of racial disparities in SMM, maternal mortality, and other maternal health outcomes.[5,20,21] This is particularly relevant in the southern US, given the ways in which social and structural factors have uniquely shaped the lived experiences of NH Black vs. NH White women.[22–24] Three primary goals are underlying our objectives of health equity research on racial disparities:

Modifiability[25]: To eliminate the disparity in SMM between racial groups, we must identify determinants of the disparity that can be modified. This may be through direct intervention on the exposure or intervention on intermediates on the causal pathway between the exposure and SMM. In health equity research, the meaning of maternal race is derived from

how structural racism shapes the lived experiences of communities differentially by race in the US. As such, several mechanisms may produce Black-White racial disparities. One mechanism is a difference in the prevalence of the risk factor between racial groups.[26,27] Specifically, a greater probability of exposure to the risk factor in one racial group produces a greater proportion of the population with the outcome in that racial group, and thus unequal health outcomes.[26,27] A second mechanism is that the relationship of the risk factor and the outcome is stronger for NH Black vs. NH White women because of the inequitable impact of structural processes (e.g., structural racism) on NH Black women, which produces racial disparities.[26,27]

To highlight these two mechanisms, consider the risk factor of prenatal care in the context of SMM racial disparities. If we identify a difference in the proportion of NH Black women and NH White women receiving quality prenatal care, then differential exposure to prenatal care might suggest that structural racism differentially allocated access to care. If this access is improved, racial disparities in SMM risk would be reduced. However, an observed statistical interaction of race and prenatal care may suggest that structural racism and inadequate prenatal care together produce potentially greater than expected harm for NH Black women compared to White women. This may be due to the deleterious impacts of other racialized experiences (e.g., concentrated poverty, inequitable education) that may work synergistically to produce excess risk among NH Black women. Considering these two potential mechanisms has important implications for clarifying the mediators evaluated in SMM racial disparities research with the goal of identifying opportunities for public health intervention.

Balancing population health perspectives[25]: Decisions about interventions to reduce disparities should be achieved considering the largest disparity, the total population burden, and the size of population subgroups. As such, the goal of balancing population health perspectives guides our public health conclusions in several ways, including identifying acceptable mechanisms for reducing disparities and, therefore, opportunities for public health intervention.

For example, a small racial disparity may be observed if there is a high SMM rate among both Black and White women. But equally poor health among the more privileged group is inconsistent with improving health equity. Thus, although the disparity is low, further investigation of these localities is warranted given a high population burden.

Interpretability[25]: The choice in measures (e.g., disparity measures: ratio or difference between racial groups) and the methods used for racial disparities research should be the most appropriate to achieve the stated objective. However, for study findings to be impactful, measure and method complexity should be balanced with the ease of implementation and communication to stakeholders. If study findings cannot be communicated effectively, then we cannot meaningfully engage stakeholders in developing interventions to advance health equity in maternal health outcomes. We preference the use of rate difference measures, given our objectives of communicating the public health impact. Further, we present results from simpler analytic methods when results do not meaningfully change from the application of more complex analytic tools.

These three goals guide how we conceptualize and discuss the investigation of health equity specific to Black-White disparities in SMM risk. Further, they frame our approach to reviewing prior research and identifying research gaps for future investigation.

The role of administrative population-based surveillance data in addressing SMM racial disparities

Public health surveillance plays a vital role in addressing racial disparities by systematically documenting ethnoracial differences in health outcomes over time and across places.[28,29] Population-based surveillance data on racial disparities enables the description of populations' health status, the investigation of modifiable determinants of the disparity, and ultimately has the potential to inform public health decision-making and resource distribution.[28,29] Currently, there is no standardized surveillance system for tracking SMM events in the US.[30] Thus, the primary data source for surveillance and etiologic research on

Black-White disparities in SMM risk is preexisting hospital discharge billing records.[30] Hospital discharge records are often linked with vital statistics birth and fetal death records when available.

Identifying 'SMM' events

A key attribute of a quality public health surveillance system is a well-defined case definition for identifying the outcome.[31] In the absence of a national surveillance system, state health departments and researchers have identified SMM in hospital discharge records using the Centers for Disease Control and Prevention (CDC)/Alliance for Innovation in Maternal Health (AIM) indicator list of adverse maternal health outcomes consistent with a potential SMM event (**Table 1.1**; **Appendix Table A1**).[32,33]

Table 1.1. CDC indicator list for identifying SMM using hospital discharge record diagnosis and procedure codes.

	SMM Indicator	Code Type
1.	Acute myocardial infarction	DX
2.	Aneurysm	DX
3.	Acute renal failure	DX
4.	Adult respiratory distress syndrome	DX
5.	Amniotic fluid embolism	DX
6.	Cardiac arrest/ventricular fibrillation	DX
7.	Conversion of cardiac rhythm	PR
8.	Disseminated intravascular coagulation	DX
9.	Eclampsia	DX
10.	Heart failure/arrest during surgery or procedure	DX
11.	Puerperal cerebrovascular disorders	DX
12.	Pulmonary edema / Acute heart failure	DX
13.	Severe anesthesia complications	DX
14.	Sepsis	DX
15.	Shock	DX
16.	Sickle cell disease with crisis	DX
17.	Air and thrombotic embolism	DX
18.	Blood products transfusion	PR
19.	Hysterectomy	PR
20.	Temporary tracheostomy	PR
21.	Ventilation	PR

Abbreviations: DX: Diagnosis; PR: Procedure

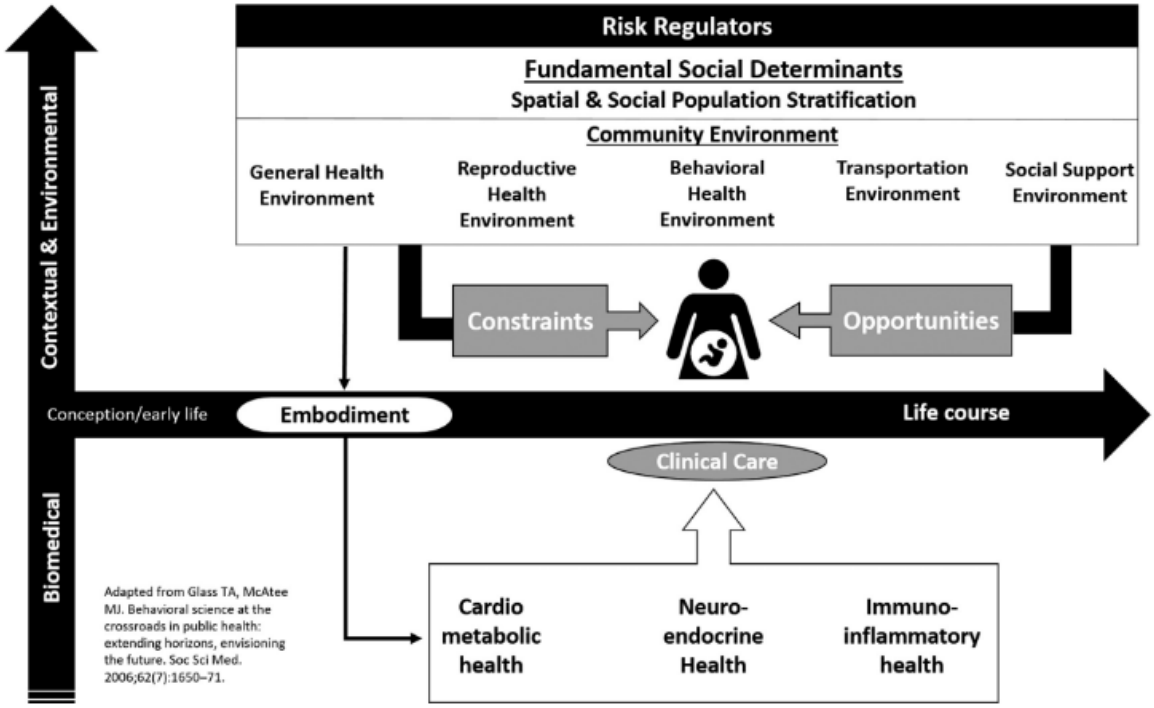
Although most studies rely on the CDC indicator list to identify SMM outcomes, there is no consensus on an SMM case definition. Specifically, there is no guidance on how to apply the CDC indicator list in hospital discharge records (e.g., the time period to consider or how to incorporate information on the severity of events). This has led to differences in the application of the CDC list for identifying SMM cases across epidemiology studies.[1,3,4,34–36] Three of the most common modifications are excluding potential SMM cases identified only by a blood transfusion ICD-CM code during labor and delivery, including de novo postpartum SMM events, and excluding cases meeting the definition with shorter length of stay (LOS).[1,3,4,34–36] Each modification potentially alters the number of SMM events identified while the population at risk (i.e., pregnancies) remains the same.

Conceptually, the goal of these modifications is to improve the consistency and accuracy of SMM identification in surveillance. Yet practically, these definition modifications have limited our ability to track and investigate racial disparities in SMM incidence across studies.[37] To date, no study has evaluated how the choice of case definition changes our understanding of the direction and magnitude of racial disparities in SMM incidence. If there are differences in how each case definition identifies SMM for NH Black versus NH White women, then conclusions about the disparity may change. Differences in disparity estimates under varying SMM case definitions can impede our ability to improve health equity in maternal health outcomes. Fundamentally, our ability to advance health equity in maternal health outcomes through the investigation of the differential burden and drivers of the disparity is hindered if we do not have valid and reliable estimates of the disparity at geographic levels that matter most for the production of the disparity. This may be a contributor to differential prevention and the persistence of disparities across populations.

Epidemiology of SMM and Black-White racial disparities in SMM risk

Risk factors for SMM and Black-White disparities in SMM risk are predominately characterized at three levels: (1) individual, (2) hospital, and (3) non-health system contextual levels (most commonly, the residential neighborhood). The relationship of multi-level environments and individuals can be conceptualized through a framework developed by Kramer et al. (2019) advocating for the inclusion of community-level determinants in maternal mortality reviews (**Figure 1.1**).[22] Given the relationship between maternal mortality and SMM, this model helps conceptualize how multifactorial determinants produce racial disparities in SMM.

Figure 1.1. Conceptual model for community determinants of maternal mortality, from Kramer et al., Am J Obstet Gynecol, 2019. [22]

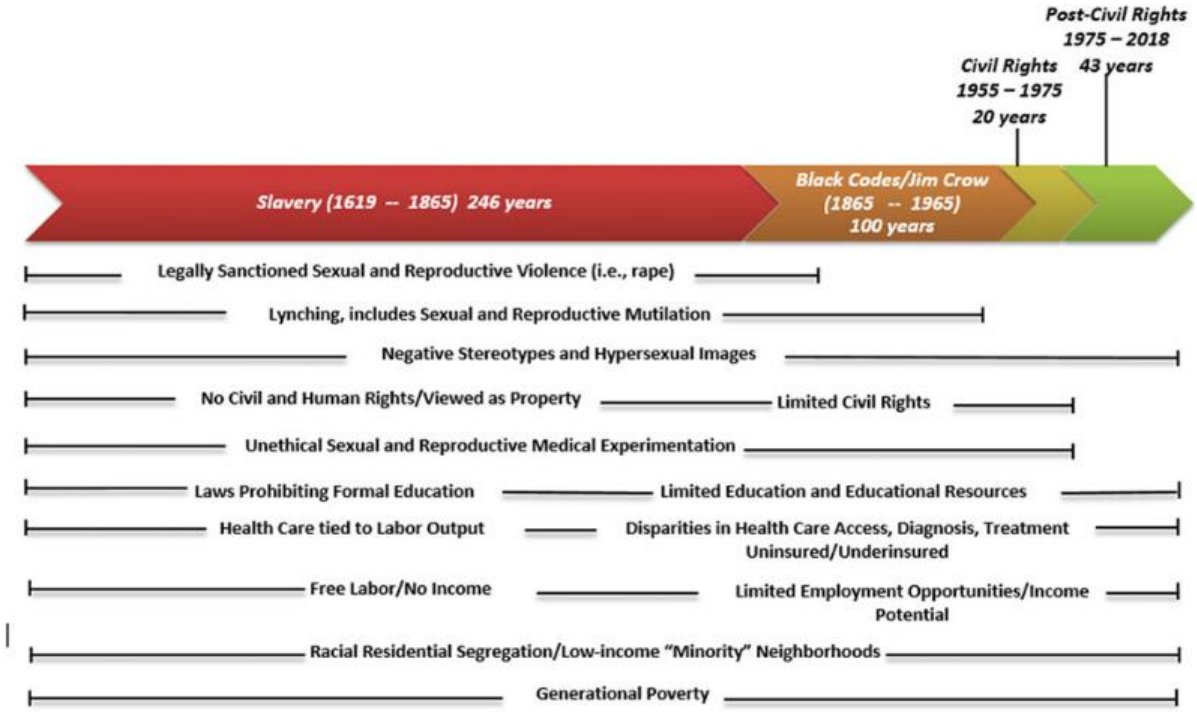


As described in **Figure 1.1**, women are situated in a community environment shaped by social and spatial population stratification processes, often referred to as structural determinants of health.[22,24,38] Structural determinants of health include structural racism, classism, and sexism.[24,38] Structural classism is the "The institutional [...] practices and beliefs that assign differential value to people according to their socioeconomic class; an economic system that creates excessive inequality and causes basic human needs to go unmet."[39] Structural racism is the "differential access to society's goods, services, and opportunities by race" perpetuated by institutions through policies, practices, and social norms.[40,41] As such, structural classism and racism are fundamental drivers of spatial and social stratification, which maintains class, racial, and racialized class hierarchies through the unequal distribution of power and resources.[42] This unequal distribution of power and resources, in turn, influences which community environments a woman is exposed to and further what opportunities she has access to.

In the US, structural classism and racism are fundamental determinants of health overall and of Black-White racial disparities in health outcomes.[24,38,42–46] The association has been documented for numerous perinatal, maternal, and chronic health outcomes.[24,38,42–46] The social stratification produced by structural classism and racism processes is observed across aspects of American life; it is operationalized as epidemiologic exposures of racial and economic residential segregation, access to quality employment, housing, healthcare, education, and equal treatment in the criminal justice system.[47] These social determinants of health are spatially patterned, and thus emphasize the idea that 'place' and the spatial context of communities in which women live likely play a vital role in the distribution of SMM incidence.[21,48]

Recognizing how history has shaped current social stratification can inform our understanding of the epidemiology of SMM Black-White racial disparities and thus our public health actions. Consider the timeline presented by Prather et al. (2018) (**Figure 1.2**).[23]

Figure 1.2. A timeline of key historical and contemporary racial and social experiences of Africans and their American descendants in the United States, from Prather et al. Health Equity, 2018.[23]



In **figure 1.2**, Prather et al. document how structural racism and classism processes produced historically unequal access to resources that continue to be observed today.[23] These mechanisms include racial segregation, generational poverty, limited educational resources, and differential access to healthcare, diagnosis, and treatment. Thus, some of the fundamental causes of Black-White disparities in SMM risk may not be prevented since they have already occurred. However, recognition of these historical determinants can be used to identify present-day structural or more proximal individual-level causes to remediate the inequitable exposures that have shaped the structure of today's society.

When investigating racial disparities in SMM incidence, this framework motivates the examination of structural and social determinants of health. In practice, it may guide the potential causes and intermediates that should be tracked and considered for intervention on the path from upstream causes of SMM (e.g., structural racism and classism) to individual SMM risk.[21,48] Further, this framework guides the identification and operationalization of measures we incorporate into etiologic and surveillance research to inform public health action (e.g., identifying metrics of structural racism). Finally, it clarifies the interpretation of disparity measures in surveillance (i.e., race as a social construct encapsulating historical and present-day racism at multiple levels). Through the lens of these conceptual frameworks, we review the current epidemiology of SMM and Black-White disparities in SMM risk, beginning with individual-level risk factors.

Individual-level risk factors

Based on **Figure 1.1**, we conceptualize that individual-level risk factors are mediators of the effect of structural racism on SMM. Several individual-level risk factors are associated with increased SMM risk in unadjusted and adjusted analyses (e.g., adjusting for other sociodemographic, clinical, and hospital-level risk factors). These include socioeconomic characteristics such as teen pregnancy and advanced maternal age (aOR: 1.3-2.0)[4,34,49,50] and

Medicaid insurance payor (aOR: 1.0-1.4).[4,34,49,50] Individual-level pre-existing health characteristics[5] have also been considered, including pre-existing and pregnancy-related hypertension (unadjusted OR: 1.5-3.5)[49–51], diabetes mellitus (unadjusted OR: 1.3)[49–51], asthma (unadjusted OR: 1.2)[49,51], cardiac disease (aOR: 2->10)[49,50,52,53], tobacco use (unadjusted OR: 1.1)[50], and obesity (aOR: 0.99-1.3).[49–51,54] A final common set of individual-level risk factors are clinical characteristics during the prior and current pregnancies[52] such as no receipt of prenatal care (aOR: 1.5)[7] and delivery by cesarean section (aOR: 2.7-4.7).[34,49]

Despite the investigation of risk factors with overall SMM incidence, there has been limited investigation of whether these risk factors are important drivers of the Black-White disparity in SMM risk.[7,55] Hypertensive disorders of pregnancy (HDP) have been hypothesized to be a potentially important driver of racial disparities in SMM because of the increased risk of SMM overall and the higher prevalence of HDP among NH Black women.[21,56] Under the conceptual framework presented in **Figure 1.1**, individual-level risk factors such as HDP may be potential opportunities to intervene on the pathway from contextual-level factors (e.g., racism) to individual SMM risk. This includes both prevention of HDP by addressing social determinants of health and clinical treatment of HDP.

A number of studies have reported conclusions that individual-level factors, often considered in aggregate, do not fully explain the increased risk of SMM among Black women compared to White women.[7,49,57] For example, Leonard et al. (2019) reported that the association of race and SMM (unadjusted OR: 1.9; 95% CI: 1.9, 2.0) was not fully attenuated after adjustment for individual-level attributes, including pre-existing and pregnancy-related comorbidities, cesarean delivery, and maternal sociodemographic characteristics (aOR: 1.4; 95% CI: 1.4, 1.5).[7] These results are consistent with other studies using similar methods. However, there may be bias in the estimated remaining disparity given the choice of statistical methods. Developments in causal mediation analyses techniques allow for the investigation of the degree

to which potential risk factors operating as intermediates may explain the Black-White disparity in SMM risk.[58,59] However, specific causal decomposition models are needed to account for the fact that racism is likely also a cause of confounders of the mediator-outcome association.[58,59] Failure to use causal decomposition models (i.e., use of regression-based methods as applied in prior research) are expected to overestimate the proportion of the Black-White disparity eliminated by removal of the mediator.[58]

Area-level determinants of Black-White disparities

Contextual risk factors at the hospital-level

To date, the majority of research investigating the association of contextual risk factors and SMM racial disparities have focused on hospital-level attributes. Hospital-level risk factors of interest have included the proportion of racial and ethnic minorities and payor mix in the delivery hospital.[50,60–62] This interest stems from a growing recognition that health practices at hospitals, including a provider's implicit bias, likely play a role in producing racial disparities in SMM incidence.[60,63,64]

Several studies have indicated both within- and between-hospital differences in SMM Black-White disparities. In a study of US deliveries, Howell et al. (2016) investigated the association between the proportion of Black deliveries and risk of SMM.[61] Operationalization of the exposure was categorical into high- (top 5th percentile of hospitals), medium- (5-25th percentile), and low-Black serving hospitals (26-100th percentile) after ranking hospitals by the proportion of Black deliveries from highest to lowest. The authors found that 74% of Black deliveries occurred in 25% of hospitals (high- and medium-Black serving). These hospitals had higher rates of SMM among both Black and White women after risk-adjustment for individual- and hospital-level characteristics. Additionally, the largest relative disparity was noted between Black and White women at low-Black serving hospitals (RR: 1.4) compared to medium-Black serving (RR: 1.2) and high-Black serving (RR: 1.1) hospitals.[61] Overall, this study provided

evidence that Black and White women both did worse in lower quality of care settings, while the disparities were greatest in higher quality of care settings.[61] This finding has important implications for considering the processes producing Black-White racial disparities in SMM risk (e.g., resource deprivation vs. differential treatment).

Additional hospital characteristics have been studied and are commonly incorporated into risk-adjustment strategies for evaluating SMM racial disparities between hospitals.[61,63] These characteristics include teaching status (aOR: 1.2-1.3)[50,61,63,65], low delivery volume (aOR: 1.4) [61,63], smaller hospital bed size (aOR: 0.88)[50,61], lower maternal levels of care (aOR: 0.33-0.82)[63,66,67], urban location (aOR: 1.0-1.1)[50,61,65], and southern or western US geographic region (aOR: 1.1-1.4).[50,61,68] As with individual-level factors, some researchers have concluded that hospital-level factors may not fully explain the increased risk of SMM among Black women (albeit with expected residual bias and similar limitations regarding the adjustment of potential individual- and hospital-level covariates on the causal pathway).[60,69,70] Simulation studies by Howell et al. (2016) estimated that 48% of the absolute Black-White disparity in New York City was explained by hospital-level characteristics after controlling for patient-level factors.[60] Guglielminotti et al. (2019) estimated that 23% of the variation in SMM incidence in New York state was explained by patient-level factors and 55% explained by hospital-level factors.[69] They found no meaningful proportion of the variation was explained at the county level, leaving an estimated 22% of the variation in SMM outcomes unexplained.[69]

Given the growing literature on hospital-level risk factors to SMM racial disparities, the hospital has been promoted as a primary place for reducing SMM disparities (e.g., implementation of educational and safety measures).[21,71] Although incorporating hospital-level characteristics into research on Black-White disparities in SMM incidence is important for the reasons identified above, investigation solely at the hospital level is likely incomplete. Hospitals are just one level in a multilevel environment that produces and reproduces adverse maternal

health outcomes (**Figure 1.1**).[22] Failing to investigate the community contexts in which women live and hospitals exist may miss fundamental drivers of SMM incidence overall and Black-White disparities in SMM incidence.[22]

Contextual risk factors beyond the hospital-level

As discussed previously, structural determinants of health refer to the processes that produce inequitable resources, and thus inequitable health outcomes across populations (e.g., structural racism and classism).[24,38,46,72] A review by Wang et al. (2020) identified that only a handful of studies had documented structural determinants at the neighborhood level.[46,72,73] Further, only one study has explicitly focused on contextual risk factors in the southeastern US.[74]

Poverty is well accepted as a fundamental determinant of health and a direct consequence of classism.[75] Although relatively infrequent, one of the more common contextual social determinants of health measures in surveillance and etiologic research is the proportion of individuals living below the federal poverty line in a women's geographic unit of residence (e.g., zip code, census tract).[73,76,77] A study by Howland et al. (2019) in New York City investigated the association of neighborhood poverty and SMM incidence.[78] The authors reported that after accounting for clustering by the delivery hospital and adjusting for individual-level risk factors, women living in a higher poverty community district (30-44% living below the federal poverty line) did not have meaningfully increased odds of SMM compared to women living in a lower poverty district (<15% population federal poverty line) (aOR: 1.04, 95% CI: 0.97-1.11).[78] Several potential explanations may clarify the null finding, including a 'true' null association of poverty and SMM. An alternative explanation is failed construct validity from a lack of meaningful exposure operationalization (e.g., the definition of high as >30%). A third explanation for this finding is that the causal pathway from poverty to

SMM incidence was blocked almost completely by adjustment for downstream risk factors of neighborhood poverty (e.g., hospital and individual-level characteristics).

In the US, it is informative to contextualize poverty as a racialized measure given the historical inequity in the distribution of wealth across racial groups.[23,79] In essence, this captures how the processes of structural classism and racism shape the environments by which NH Black and NH White women are inequitably exposed to, and the health-promoting resources that are differentially available.[24,79,80] One, if not the most commonly used measure of racialized poverty and affluence in the public health literature, is the index concentration of extremes (ICE).[81,82] Created by Massey, for the study of economic polarization (extreme concentrations of wealth and poverty), ICE was expanded by Krieger et al. for use in public health research to three common variations: ICE for income (Massey), ICE for race, and ICE for race and income.[77,83] ICE for race and income ranges from -1 to 1, and is calculated as the number of NH White persons with an income in the 80th percentile minus the number of NH Black persons with an income in the 20th percentile divided by the total population.[84] A score of -1 indicates that all individuals in that place are of NH Black race and ethnicity and in the lowest economic quintile (most extreme deprivation). On the opposite end of the scale, a score of +1 indicates that all individuals in that locality are of NH White race and ethnicity and in the highest economic quintile (most extreme privilege). ICE measures have been argued as advantageous for public health surveillance of health equity due to the availability of data for public use, the utility of the measure at multiple geographic levels (e.g., census tract and county), and the simplicity of the construct presentation as a single measure.[76,77,84–87]

Racialized income inequality (operationalized as ICE for race and income) has been studied as a potential determinant of racial disparities in SMM-related health outcomes such as maternal mortality[88], infant mortality,[76,81,86,89] preterm birth[76,86], and cardiovascular health (e.g., diabetes and hypertension).[85] Adjusted odds ratios have ranged from 1.2 to 2.9 for the least

privileged quintiles in reference to the most privileged categories (again, with similarly noted limitations of adjusting for individual-level risk factors hypothesized to be on the causal pathway from neighborhood racialized income inequality to SMM risk).[76,81,86,89] To date, only two studies have incorporated ICE for race and income measures in the study of SMM. Janevic et al. (2020) studied ICE measures at the zip code level in New York City using linked birth certificates and hospital discharge records during 2012-2014 inclusive.[90] The authors reported that unadjusted analyses of women living in zip codes with the lowest quintile of ICE for race and income scores compared to the highest quintile resulted in a risk difference of 1.7 cases per 100 deliveries (95% CI: 1.4, 1.9).[90] A second analysis in South Carolina 2012-2019 identified that a high-risk spatial cluster of SMM incidence included more disadvantaged populations than individuals not included in the cluster.[74] The authors reported the odds of an SMM event (including blood transfusion) living in a high-risk cluster were 1.1 to 1.2 times higher for individuals living in the least (OR: 1.1, 95% CI: 0.93, 1.2) or middle privileged tertiles (OR: 1.2, 95% CI: 1.0, 1.3) of ICE for race and income compared to the most privileged tertile.[74]

Research on racialized income inequality using ICE for race and income has advanced our understanding of structural determinants of SMM risk. Yet, there are challenges in interpreting and operationalizing ICE measures that may hinder the public health implications of this work. Scores at the extremes are more clearly interpretable but rarely occur. A more common scenario is a range of scores around 0, which likely produces an epidemiologic causal effect identification consistency violation because numerous racialized income inequality scenarios can produce similar ICE values with different potential outcomes.[91] A second conceptual and logistical challenge is there is no clear guidance on how to best operationalize ICE scores. Thus, there has been notable variation in the inclusion of ICE scores in statistical models, ranging from continuous to categorical (e.g., terciles and quintiles).[76,84,85,88] Another consistency violation may be a threat to inference in prior epidemiologic studies of ICE for race and income because the range of scores (which likely reflect different racialized economic

scenarios) are arbitrarily combined across operationalizations (e.g., the highest quintile ranging from scores 0.0-0.5 vs. 0.4-0.6). These two consistency violations from non-extreme scores and exposure operationalization create a challenge for effectively translating findings into public health decision-making.

Exploring alternate racialized income inequality measures and their components (i.e., income inequality and racial segregation) may advance the investigation of SMM incidence overall and Black-White disparities in SMM incidence. Racially and ethnically concentrated areas of poverty (RECAP) and affluence (RECAA) is one alternate set of measures that may have utility for capturing the construct of racialized income inequality. RECAP areas are traditionally defined as neighborhoods where most residents are people of color, and ≥40% live below the Federal poverty line.[92] RECAA areas are often defined as neighborhoods where ≥80% of the residents are NH White race and ethnicity, and the median household income is ≥$125,000 (roughly 200% of the 2016 national median household income).[93] Similar to ICE, the RECAA measure recognizes that segregation not only contributes to concentrated areas of disadvantage in neighborhoods composed predominately of individuals of color, but concentrated areas of advantage in predominately NH White neighborhoods.[93–96]

RECAA and RECAP measures have flexibility in their categorization, allowing them to be adapted as relative measures specific to the study region (e.g., state) rather than a US-based definition.[92,93,97] These measures have been termed racially and ethnically concentrated areas of relative poverty (RECArP) and affluence (RECArA).[97] The use of relative rather than absolute measures provides advantages for state-specific surveillance and etiologic studies by accounting for the within-state aspects of racialized poverty and affluence that may be producing inequitable maternal health outcomes across racial groups.[97] To our knowledge, no studies have used RECArA and RECArP definitions to investigate the joint effects of income inequality and racial segregation on adverse maternal health outcomes. In general, there is a need for

additional research on structural determinants of SMM risk. Advancing our understanding of the association of structural racism/classism and SMM incidence, specifically in the unique context of the southeastern US, may aid in identifying at-risk populations and interventions to advance maternal health equity.

Opportunities for advancing our understanding of the Black-White disparity in SMM risk

Many opportunities exist to improve the investigation of racial disparities in SMM relying on population-based surveillance data. In this dissertation, we focus on the following opportunities:

1. The need for guidance in SMM case definition selection for estimating Black-White racial disparities in SMM incidence. This includes investigating how the choice of SMM case definition alters our conclusions about the direction and magnitude of SMM incidence and the Black-White racial disparity.
2. The need for an improved understanding of potentially modifiable individual-level factors on the pathway of structural racism to excess risk among NH Black Women. This includes an investigation of comorbidities such as HDP.
3. The need for additional research on the relationship of structural determinants of health (i.e., structural classism and racism) and SMM.

Specific dissertation aims

This dissertation seeks to advance maternal health equity by conducting rigorous epidemiologic research on SMM racial disparities using population-based surveillance data. This dissertation will investigate the following aims:

Aim 1. To investigate how conclusions about the magnitude of SMM incidence and the Black-White racial disparity in SMM incidence vary under common SMM case definitions.

Aim 2. To estimate the proportion of the Black-White racial disparity in SMM risk explained through pathways including HDP.

Aim 3. To estimate the joint effect of relative income inequality and racial segregation on SMM risk.

Dissertation structure

Chapter 2 describes the data sources and study population used in all three dissertation aims. Chapters 3-5 present the specific background, methods, results, and conclusions for each aim. Finally, Chapter 6 summarizes the main findings of this dissertation research in the context of public health importance and future research. Appendices detailing specific conceptual and methodologic decisions, sensitivity analyses, and additional descriptive tables for each aim are included at the end of this dissertation.

Chapter 2: Study population and data sources

Study population

All three specific aims are retrospective cohort studies. Our target population is all pregnant individuals of non-Hispanic (NH) Black and NH White race/ethnicity who are Georgia residents ages 15-49 years. Our study cohort was defined as NH Black and NH White Georgia residents ages 15-49 who had any delivery hospitalization record in a Georgia hospital between January 1, 2006 and December 31, 2019. We identified pregnancies using the CDC/AIM recommended ICD-9/10-CM hospital discharge birth denominator codes for the study of SMM (v6-27-2020) (**Appendix Table A2**).[33]

We do not have complete information on our hypothetical target population; thus, we conceptualize the relationship of our primary data source to the target population as follows. As stated above, a hospitalization record is needed to identify potential SMM events. Our study population excludes individuals in our target population who had a live birth or fetal death outside of a hospital and were not transferred to a hospital. This includes births at home or in birth centers and fetal deaths not resulting in hospitalization. We expect there to be few individuals born outside the hospital. However, we might hypothesize that individuals having a home birth are at lower risk of an SMM event. High-risk pregnancies would be planned for a hospital birth, and planned home birth pregnancies that have an emergency event during delivery would be transferred to a hospital.[98] In essence, we may be modestly underestimating the denominator for delivery hospitalizations, spuriously inflating the SMM rate. However, this is expected to be small (<1%) based on vital statistics birth certificate records. We also hypothesize that lower-risk pregnancies may be more likely to be individuals of NH White race and ethnicity. In vital statistics birth certificate data, 0.7% of NH White live births were outside of the hospital, compared to 0.4% of NH Black live births. We would expect this to bias

disparity estimates toward the null by overestimating the number of NH White cases per the total number of deliveries.

Additionally, our study population fails to capture births among Georgia residents occurring outside of the state. Births occurring outside of the state are expected to be differential by place (e.g., residence near the Alabama-Georgia border, where the nearest maternal hospital may be in Alabama). These deliveries would not be captured in Georgia hospital discharge records or vital statistics, and may be differential by maternal race given the spatial variation in racial composition throughout Georgia.

Georgia hospital discharge records

Georgia hospital discharge records are the primary data source for this study, given that we require ICD-CM codes to identify SMM events. From January 1, 2006 to December 31, 2019, hospital discharge records contained data on over 1.4 million pregnancies among NH Black and White women in Georgia. Hospital readmissions were linkable with the delivery hospitalization by a unique maternal longitudinal ID. Georgia hospital discharge records provided information on individual-level maternal demographic and diagnosis information and hospital-level characteristics: maternal race, maternal ethnicity, maternal age, marital status, insurance payor, up to ten diagnosis and six procedure codes for identifying delivery hospitalizations, SMM events and maternal comorbidities (e.g., hypertensive disorders during pregnancy), maternal geocoded location of residence at aggregated at multiple geographic units (census block group, census tract, county), hospital length of stay (days), and urbanicity of the maternal county of residence.

Georgia vital statistics records: birth and fetal death certificates

Hospital discharge records were linked with Georgia birth and fetal death certificates through the hospital discharge maternal longitudinal ID and record ID. This allowed for the

incorporation of additional individual-level covariates: gestational age (weeks), maternal education, multiple gestation, and delivery type.

Hospital discharge and vital statistics record linkage

Given the available data, we evaluated whether there were differences in the race-stratified distribution of SMM, maternal characteristics, and delivery characteristics between the complete hospital discharge record dataset and the hospital discharge records without linkage to a vital statistics record (**Table 2.1**). This comparison was designed to investigate whether conclusions drawn from the linked dataset might differ from using the complete hospital discharge record.

Table 2.1. Describing select characteristics of deliveries in the complete hospital discharge dataset and hospital discharge records with no linkage, NH Black and NH White women, ages 15-49 years, Georgia 2006-2019.

	NH Black		NH White	
Characteristic	Complete Hospital Discharge Records	Hospital Discharge Records with No Linkage	Complete Hospital Discharge Records	Hospital Discharge Records with No Linkage
N (Column %)	N = 623,402	N = 57,226 (9%)	N = 820,769	N = 69,332 (9%)
SMM21				
SMM (delivery)	12,546 (2.2%)	1,521 (2.7%)	9,585 (1.3%)	1,021 (1.5%)
SMM (delivery or postpartum)	14,943 (2.6%)	1,792 (3.1%)	11,201 (1.5%)	1,191 (1.7%)
No SMM	608,459 (97.4%)	55,434 (96.9%)	809,568 (98.5%)	68,141 (98.3%)
SMM20 (No Blood Transfusion)				
SMM (delivery)	4,913 (0.87%)	684 (1.2%)	4,120 (0.55%)	418 (0.60%)
SMM (delivery or postpartum)	7,321 (1.3%)	956 (1.7%)	5,740 (0.76%)	588 (0.85%)
No SMM	616,081 (98.7%)	56,270 (98.3%)	815,029 (99.2%)	68,744 (99.2%)
Marital status				
Married	157,773 (25%)	24,983 (44%)	518,773 (63%)	40,797 (59%)
Unmarried	411,765 (66%)	27,915 (49%)	236,704 (29%)	22,625 (33%)
Missing	53,864 (9%)	4,328 (8%)	65,292 (8%)	5,910 (9%)
Insurance Payor				
Medicaid	410,748 (66%)	33,778 (59%)	307,618 (37%)	34,994 (50%)
Self-Pay	14,067 (2%)	2,310 (4%)	11,462 (1%)	1,896 (3%)
Private	171,570 (28%)	18,436 (32%)	451,977 (55%)	28,799 (42%)
Other Payors	25,178 (4%)	2,490 (4%)	46,810 (6%)	3,363 (5%)
Missing	1,839 (<1%)	212 (<1%)	2,902 (<1%)	280 (<1%)
Maternal age category (years)				
15-19	73,429 (12%)	4,720 (8%)	60,307 (7%)	6,417 (9%)
20-24	188,175 (30%)	14,086 (25%)	185,126 (23%)	18,356 (26%)
25-29	167,665 (27%)	15,680 (27%)	238,475 (29%)	18,780 (27%)

Characteristic	NH Black		NH White	
	Complete Hospital Discharge Records	Hospital Discharge Records with No Linkage	Complete Hospital Discharge Records	Hospital Discharge Records with No Linkage
30-34	117,695 (19%)	12,988 (23%)	213,972 (26%)	15,436 (22%)
35-39	60,898 (10%)	7,572 (13%)	101,373 (12%)	8,226 (12%)
40-44	14,623 (2%)	2,044 (4%)	20,318 (2%)	2,002 (3%)
45-49	917 (<1%)	136 (<1%)	1,198 (<1%)	115 (<1%)
County of residence				
Rural	102,701 (16%)	6,888 (12%)	214,565 (26%)	17,743 (26%)
Urban	520,701 (84%)	50,338 (88%)	606,204 (74%)	51,589 (74%)
Year				
2006	46,824 (8%)	4,723 (8%)	63,882 (8%)	5,026 (7%)
2007	48,545 (8%)	5,423 (9%)	71,384 (9%)	8,231 (12%)
2008	48,419 (8%)	4,808 (8%)	70,297 (9%)	7,944 (11%)
2009	46,696 (7%)	4,277 (7%)	62,546 (8%)	5,105 (7%)
2010	44,422 (7%)	3,911 (7%)	60,119 (7%)	4,801 (7%)
2011	44,095 (7%)	3,849 (7%)	59,323 (7%)	4,647 (7%)
2012	42,572 (7%)	3,726 (7%)	56,816 (7%)	4,403 (6%)
2013	43,273 (7%)	3,822 (7%)	55,878 (7%)	4,501 (6%)
2014	43,372 (7%)	3,821 (7%)	55,839 (7%)	4,542 (7%)
2015	42,591 (7%)	3,727 (7%)	55,575 (7%)	4,464 (6%)
2016	43,599 (7%)	3,936 (7%)	55,200 (7%)	4,399 (6%)
2017	43,835 (7%)	3,893 (7%)	52,955 (6%)	3,912 (6%)
2018	42,538 (7%)	3,652 (6%)	50,751 (6%)	3,783 (5%)
2019	42,621 (7%)	3,658 (6%)	50,204 (6%)	3,574 (5%)

Hospital discharge data subset to our study population of interest included 1,444,172 delivery hospitalizations, of which 126,558 (9%) could not be linked with a vital statistics birth or fetal death record. The percentage of unlinked hospital discharge records did not vary by maternal race and ethnicity. Yet there were differences in the race-specific distribution of selected covariates between deliveries in the complete study population and deliveries in the unlinked dataset. Among NH Black deliveries, there was a meaningful difference (>5%) in the distribution of marital status, insurance payor, and maternal age between deliveries in the complete and unlinked hospital discharge records. Specifically, compared to deliveries in the complete study population, deliveries that were not linkable were more likely to be among women who were unmarried (44% vs. 25%), and less likely to be among women who were Medicaid-insured (59% vs. 66%) and ages 24 years or younger (33% vs. 42%). Among NH White deliveries, there was a greater proportion of deliveries with Medicaid as their insurance payor in the unlinked dataset compared to the complete hospital discharge dataset.

Of smaller magnitude, there was a higher prevalence of SMM indicators for both SMM including (SMM21) and excluding blood transfusion (SMM20) at both the delivery and postpartum hospitalizations for women in the excluded hospital discharge records compared to the complete data source (**Table 1.1**; **Appendix Table A1**).[32,33] Although the difference is <1%, this change is potentially meaningful given the rare prevalence of SMM.

Our comparison of the complete and unlinked hospital discharge records suggested that the use of the complete dataset is preferred over the linked dataset for the surveillance of SMM disparities. As such, we imputed missing observations when interested in covariates from the vital statistics record that were not linkable. However, one limitation of using the complete dataset with imputed covariate values is the threat of differential missingness of hospital discharge records with no vital statistics linkage, which would violate most imputation assumptions (i.e., covariates missing at random).

Identification of maternal race and ethnicity

Given that the hospital discharge record was the primary data source for identifying the study population, we defined maternal race and ethnicity using hospital discharge maternal sociodemographic information. Maternal race and ethnicity are coded as separate variables. We included women with recorded "White" and "Black or African-American" race. Maternal ethnicity is coded as "Hispanic," "Not Hispanic," or "Unknown." We restricted to "Not Hispanic" and "Unknown" ethnicity, under the assumption that "Unknown" ethnicity were individuals who were of non-Hispanic ethnicity and had no ethnicity information recorded (n = 357,454; 24%). To explore the validity of this assumption, we compared the identified deliveries to the reported race and ethnicity in vital statistics records for deliveries with successful linkage and no missing race/ethnicity information. Some researchers have suggested that vital statistics race and ethnicity is the gold standard measure for maternal ethnoracial information. However, the primary study for which this claim is asserted comes from an analysis conducted over 20 years ago in California, which has a higher proportion of Hispanic identifying individuals.[99] Still, if we consider vital statistics as the gold-standard measure, of the 560,766 women who were coded as Black in the hospital discharge record, 532,510 were coded as Black in the vital statistics record (PPV: 95%). For NH White women, the PPV was 96% (715,926/747,742). The equivalent estimate for non-Hispanic ethnicity was 96% (1,250,261/1,297,646). The high estimated PPV improved our confidence in the use of hospital discharge race and ethnicity information.

Data security and confidentiality

The use of hospital discharge records and vital statistics records were provided by the Georgia Department of Public Health (GDPH) to Katie Labgold for this dissertation work as part of a doctoral internship. All analyses using identifiable data were conducted using the GDPH-owned, password-protected laptop. All presented data was aggregated to ensure confidentiality.

Ethics

The Emory IRB granted this dissertation research expedited approval with no annual review under the practice of public health surveillance (IRB ID: STUDY00002040).

Area-level data

The American Community Survey (ACS) is a publicly available yearly survey administered through the Census Bureau.[100] We obtained population-based sociodemographic factors for 2006-2019 at the census tract and census block group levels. Variables of interest included: the proportion of individuals with a household income below the poverty line, median household income, and the proportion of racial and ethnic groups. Census tract-level urbanicity was obtained from the US Department of Agriculture (USDA) 2010 rural-urban commuting areas codes (2019 revision).[101] Area-based data was linked to the hospital discharge dataset using the maternal residence geographic unit of interest (e.g., residential block group for block-group level variables). Study-specific details of data preparation and variable operationalization are provided in the methods and appendices of each aim.

Chapter 3: Purpose-built measures: identifying a primary case definition of severe maternal morbidity (SMM) for racial disparities surveillance and research

Abstract

Severe maternal morbidity (SMM) is an increasingly important public health concern with notable racial disparities. Yet, the surveillance of population patterns and disparities in SMM is impeded by inconsistent case definitions. In addition to a standard list of outcomes identifiable through hospital discharge codes, authors define cases by including/excluding blood transfusions, including/excluding postpartum hospitalizations, or restricting to an exceptionally long length of stay. There has been no investigation of how SMM case definition selection affects conclusions in surveillance studies describing racial disparities. Evaluation specific to tracking disparities is essential for ensuring that the case definition captures, rather than masks or exaggerates, underlying processes that produce inequitable risk for marginalized groups. Using 2006-2019 Georgia hospital discharge records, we investigated how conclusions about the SMM incidence and SMM Black-White disparity varied by case definition. Our results demonstrate that public health conclusions vary by the case definition and the scale of the disparity measure (absolute vs. relative). A clear rationale for case definition selection is needed, given these conclusions guide public health decision-making. We present a rationale for preferring the case definition including postpartum hospitalizations and excluding blood transfusion when investigating racial disparities in SMM incidence using hospital discharge data.

Introduction

Severe maternal morbidity (SMM) is a group of adverse maternal health outcomes related to pregnancy.[1] Often described as maternal mortality "near misses," SMM is conceptualized as a step on the continuum from a healthy pregnancy, to a pregnancy complicated by a morbidity, severe morbidity, and in the worst scenarios, death.[2] While vague, this conceptual definition of SMM attempts to capture the consensus that SMM are life-threatening events related to pregnancy that could have resulted in maternal death.[2]

SMM is often used as an indicator for tracking maternal health.[102] Because there is no standardized surveillance system for SMM events, SMM surveillance has primarily been conducted on a state-specific and study-by-study basis.[37] This has limited our ability to consistently track SMM outcomes and disparities over time and across places. Thus, variations in the methodologic approach for identifying an SMM event may contribute to discrepancies between study conclusions which inform decision-making—ultimately resulting in differential prevention and the persistence of disparities across places.

Common SMM case definitions

Hospital discharge records are the primary data source for identifying SMM events.[30] The US Centers for Disease Control and Prevention (CDC) recommends a list of 21 diverse outcomes plausibly tied to pregnancy, labor, and delivery for the identification of SMM in hospital discharge records.[32] SMM outcomes cover a range of severe events, including disseminated intravascular coagulation, acute renal failure, hysterectomy, sepsis, and receipt of blood transfusion (**Appendix Table A1**).[32,33] However, there is no universally standard case definition for applying this list in SMM surveillance overall, nor specific to monitoring racial disparities in SMM. As such, several case definition modifications to the CDC list have been commonly applied in SMM etiologic studies and are regularly recommended in SMM surveillance:

1. Excluding blood transfusion: The CDC list includes an indicator for receipt of blood transfusion. Blood transfusion is the most prevalent SMM international classification of disease clinical modification (ICD-CM) code; It is the sole case-defining indicator in ~70-80% of potential SMM cases when using the complete CDC list.[4,35] Clinical consensus is that transfusion of four or more units of blood is sufficient to define an SMM case.[1,103] However, the ICD-CM coding schema provides no information on the number of units administered. Many 'SMM' events likely received only 1-2 units and, thus were not truly severe.[1,103] Because of this limitation, it is common to present SMM estimates both with and without the blood transfusion indicator.[1,103–105] Exclusion of blood transfusion removes potential SMM events for which blood transfusion ICD-CM procedure codes were the only SMM indicator.

2. Including postpartum SMM: Many clinicians have argued that SMM events can occur not only at delivery but also during the postpartum period.[10,30,106] However, most studies only incorporate potential SMM events based on ICD-CM codes during the delivery hospitalization.[10,30,34] This is often due to challenges in accessing and/or linking delivery hospitalization records to hospital discharge records during the postpartum period.[10,30,34] Linkage across sequential hospitalizations is more feasible when longitudinal maternal IDs are available; however other methods could facilitate linkage (e.g., probabilistic matching or machine learning).[107] This modification includes potential SMM events during the delivery hospitalization and hospitalizations through 42 days postpartum.

3. Excluding hospitalization length of stays (LOS) <90th percentile: As with the blood transfusion indicator, ICD-CM codes for other SMM indicators do not contain information on outcome severity that would allow for us to distinguish SMM from

less severe pregnancy-related morbidity. Some studies have noted that because SMM events are those that are the most severe, women would remain in the hospital for an extended LOS.[10,35] Thus, data-driven LOS thresholds have been applied to identify SMM events. A common threshold considers potential SMM events as women identified from the CDC list that have a LOS greater than or equal to the study-specific 90th percentile.[10,35] This is further stratified by delivery type, given differences in LOS for vaginal and cesarean births.[10,35] This modification excludes potential SMM events identified by the CDC indicator list that have a shorter length of stay.

To date, only one study has explicitly focused on quantitatively comparing select SMM case definition modifications in the same population.[108] The authors only evaluated the exclusion of blood transfusion and LOS <90th percentile during the delivery hospitalization.[108] However, there was limited contextualization of the consequences of each definition for public health practice and no evaluation of whether differing case definitions changed conclusions about racial disparities in SMM.

Case definition variation and surveilling racial disparities in SMM risk

The choice of a case definition is important because a poor choice may mask or exaggerate underlying racial disparities in SMM. For example, exclusion of postpartum hospitalizations may underestimate Black-White racial disparities in SMM risk if a greater proportion of NH Black women have chronic disease risk factors that further increase the risk of postpartum cardiovascular SMM. Investigating the magnitude of the absolute and relative Black-White racial disparity under different case definitions can aid in evaluating the degree to which bias may affect study conclusions. Specifically, different case definitions estimate the number of SMM events differently across racial groups, then we will expect a difference in the absolute racial disparity between case definitions. Yet, even if there is bias in the identification on an

absolute scale, the relative measure of the disparity could be a reliable estimate if the proportion of the SMM events identified by the case definition for NH Black and NH White women is the same (e.g., a scenario of perfect specificity and non-differential sensitivity).[109]

Differences in the conclusions about the presence or magnitude of racial disparities by case definition have implications for allocating resources, comparing SMM incidence and disparities over time and across populations, and identifying causes of SMM in etiologic research relying on surveillance data. Although concerns about the influence of case definition variation on the surveillance of racial disparities in SMM have been highlighted as challenges to preventing and mediating disparities, they have not yet been investigated.[110] Thus, we evaluate how conclusions about the magnitude of SMM incidence and the Black-White racial disparity in SMM change across five distinct SMM case definitions.

Characterizing SMM incidence and Black-White racial disparities in SMM under alternate case definitions

Approach

Study Population & Data Sources

Our cohort was defined as NH Black and NH White Georgia residents ages 15-49 who had any delivery hospitalization record in a Georgia hospital between January 1, 2006 and December 31, 2019. Hospital discharge records were used to identify pregnancies and SMM, and maternal race and ethnicity. Pregnancies were identified using the CDC/Alliance for Innovation on Maternal Health (AIM)-recommended ICD-9/10-CM birth denominator codes for the study of SMM (**Appendix Table A2**).[33] Delivery hospitalizations included both live births or fetal deaths, but excluded molar and ectopic pregnancies and induced terminations (**Appendix Table A2**).[33] Subsequent hospitalizations within 42 days postpartum were linked with delivery hospitalization records using a unique maternal longitudinal identifier.

Identification of SMM

Pregnancies were evaluated for having an 'SMM' event or not based on alternate case definitions. All case definitions relied on the CDC/AIM v6-27-2020 list of SMM-defining ICD-CM codes identifying severe outcomes plausibly tied to pregnancy, labor, and delivery (**Appendix Table A1**).[32,111] We considered five SMM case definitions operationalized from a unique combination of the blood transfusion, postpartum, and LOS modifications (**Table 3.1**).[32,33] The 90th percentile LOS threshold was identified as a LOS greater than three days for a vaginal birth and five days for a cesarean birth. For completeness, we provide the results for definition modifications not included in **Table 3.1** in the **Aim 1 Appendix**.

Table 3.1. Five case definitions based on three modifications to the CDC definition for identifying SMM.

Case Definition Key	Excluding Blood Transfusion (BT)	Including Postpartum (PP)	Excluding LOS <90th percentile
#1) No modifications			
#2) Exclude BT	X		
#3) Excluding BT & Include PP	X	X	
#4) Excluding BT & LOS < 90th percentile	X		X
#5) All modifications	X	X	X

Estimating SMM incidence and Black-White racial disparities under alternate SMM case definitions

Our cohort is defined by pregnancies, not individuals. Thus, a single individual can have multiple SMM events over different pregnancies. Our interest is in describing SMM incidence, but we use the terminology SMM rate (events per the total number of deliveries) to be consistent with SMM surveillance practices.

For each case definition, we calculated the SMM rate and the race-specific rate per 10,000 delivery hospitalizations, the absolute and relative Black-White disparity (rate difference

(RD) and rate ratio (RR)), and accompanying 95% confidence intervals. To build intuition about differences in the processes identifying SMM under each case definition, we investigated whether the number and proportion of SMM events attributable to each SMM indicator varied by maternal race and case definition.

Findings

The 2006-2019 Georgia rate of SMM cases per 10,000 delivery hospitalizations varied by case definition and maternal race/ethnicity. The overall rate of SMM ranged from 45.8 events (95% CI: 44.7, 46.9) per 10,000 hospitalizations for the least inclusive definition (#4 excluding BT and LOS <90th percentile) to 170.8 events (168.7, 173.0) per 10,000 hospitalizations for the most inclusive definition investigated (#1 no modifications) (**Table 3.2**). For NH Black women, the rate during this period ranged between a low of 63.5 (95% CI: 61.5, 65.5) for definition #4 to a high of 225.6 events per 10,000 hospitalizations (95% CI: 222.0, 229.3) for definition #1 (**Table 3.2**). For NH White women, the rates ranged between a low of 32.3 (95% CI: 31.1, 33.5) in definition #4 to a high of 129.2 events per 10,000 hospitalizations (95% CI: 126.8, 131.7) in definition #1 (**Table 3.2**).

Table 3.2. Overall and race-specific SMM rates, absolute and relative Black-White racial disparity estimates, and 95% confidence intervals, Georgia NH Black and NH White women, ages 15-49, 2006-2019.

Case Definition	Overall Rate*	NH Black Rate*	NH White Rate*	Black-White Rate Difference*†	Black-White Rate Ratio†
#1: No modifications	170.8 (168.7, 173.0)	225.6 (222.0, 229.3)	129.2 (126.8, 131.7)	96.4 (92.0, 100.9)	1.8 (1.8, 1.8)
#2: Excluding BT	70.2 (68.8, 71.5)	89.8 (87.4, 92.1)	55.3 (53.7, 56.9)	34.5 (31.7, 37.3)	1.6 (1.6, 1.7)
#3: Excluding BT & Including PP	101.1 (99.5, 102.8)	132.8 (129.9, 135.6)	77.1 (75.2, 79.0)	55.7 (52.3, 59.1)	1.7 (1.7, 1.8)
#4: Excluding BT & LOS	45.8 (44.7, 46.9)	63.5 (61.5, 65.5)	32.3 (31.1, 33.5)	31.2 (28.9, 33.5)	2.0 (2.0, 2.0)
#5: All modifications	55.1 (53.9, 56.3)	76.9 (74.7, 79.1)	38.5 (37.2, 39.9)	38.4 (35.8, 40.9)	2.0 (1.9, 2.0)

Abbreviations: BT = Blood transfusion; PP = Postpartum; RD = Rate Difference, RR = Rate Ratio
**Rate and RD per 10,000 deliveries*
†RD = (NH Black Rate) – (NH White Rate); RR = (NH Black Rate)/(NH White Rate)

The largest changes were observed when excluding the blood transfusion indicator, followed by the inclusion of postpartum hospitalizations (**Table 3.2**). Case definition #3 had an estimated RD roughly half that of case definition #1. Whereas, case definitions #2, 4, and 5 had similar estimates of the absolute disparity that were roughly a third of case definition #1 (RD: 34.5, 31.2, and 38.4) (**Table 3.2**). On the multiplicative scale, the magnitude of the estimated RR was smallest for case definition #2 excluding blood transfusion (RR: 1.6, 95% CI: 1.6, 1.7), with similar RR's for case definitions #1 (no modifications) (RR: 1.8, 95% CI: 1.8, 1.8) and #3 (exclusion of BT and inclusion of PP) (RR: 1.7, 95% CI: 1.7,1.8) (**Table 3.2**). The estimated RR had the greatest magnitude when excluding LOS <90th percentile (RR: 2.0).

The top five indicators of SMM varied by whether the LOS restriction was included as part of the case definition (**Aim 1 Appendix**). Within a case definition, the top five indicators of SMM were the same for NH Black and NH White women within a case definition (**Aim 1 Appendix)**. Still, the rank order varied by race. For case definition #1, the top five indicators included blood transfusion, disseminated intravascular coagulation, acute renal failure, ARDs, and hysterectomy. Exclusion of blood transfusion from the case definition moved pulmonary embolism into the top five indicators for definitions #2-3. When blood transfusion was excluded and the case definition required a longer hospital length of stay (definitions #4-5), sepsis rather than pulmonary embolism was the fifth most common indicator for both NH Black and NH White women. Further, the proportion of each indicator among all SMM events varied by both race and case definition (**Aim 1 Appendix**). For example, in definition #1, disseminated intravascular coagulation was indicated in 14% of NH Black and 19% of NH White SMM cases versus 35% of NH Black and 45% of NH White SMM cases in case definition #2 (Black-White prevalence ratio: 0.74 and 0.78, respectively).

Discussion

The choice of SMM case definition alters our conclusions about the magnitude of the estimated SMM incidence, as well as relative and absolute Black-White racial disparities. The 2006-2019 SMM rates and absolute disparity estimates were dependent on the total number of cases, which varied widely between case definitions based on the degree of modification inclusivity (**Table 3.2**). Unsurprisingly, this was most influenced by the exclusion of the blood transfusion indicator, given its indication in ~70% of the potential SMM events in our study population when using case definition #1 (**Aim 1 Appendix**). Alternatively, the magnitude of the estimated Black-White relative disparity between case definitions appeared to be largely driven by the exclusion of hospital LOS <90th percentile (**Table 3.2**). Thus, the relative relationship of who was and was not captured under the LOS modification for NH Black and NH White groups varied by case definition.

The direction of estimates was the same across definitions, indicating that there is an excess risk among NH Black women compared to NH White women. Yet, differences in the estimated magnitude across case definitions have important public health consequences that often are unstated. Estimates of the race-specific risk and the Black-White disparity inform the distribution of resources and our understanding of the excess burden. Thus, we may make decisions to prioritize SMM over other maternal and child health outcomes based on the estimated magnitude of the problem. Further, reliable estimates are needed to track progress for improving SMM outcomes and disparities over time and across populations, as well as identify drivers of the racial disparities. Fundamentally, if we do not have valid and reliable estimates of the disparity, then our ability to advance health equity in maternal health outcomes is hindered.

The race-specific and case-definition differences in the rank order and the proportion of SMM indicators are also consistent with a hypothesis that modifications are likely targeting

different attributes of an SMM event (**Aim 1 Appendix**). This may ultimately be an issue that the conceptual SMM definition is still not well enough defined with respect to the choice of indicators, the at-risk periods, and the disease severity. More practically, limitations of identifying SMM events in hospital discharge records are likely producing misclassification errors that may outweigh improved conceptual validity achieved by implementing certain case definition modifications. Establishing consensus on the gold standard definition of SMM – one that clarifies the adverse outcomes, risk periods, and severity thresholds – is essential so that we can investigate how well each measure is identified in the pre-existing administrative records we have available to us. In the meantime, we need guidance on the choice of definition for use in SMM racial disparities surveillance and etiologic research based on our current understanding of the strengths and limitations of each definition's application in hospital discharge records. Beyond that, we should strive to better capture SMM events through the implementation of a specific surveillance system for SMM and racial disparities in SMM.

Selecting a case definition for tracking and investigating racial disparities in SMM incidence

An optimal case definition cannot likely be selected solely through quantitative analysis (e.g., validity assessment) given the differences in the operationalization of the conceptual SMM definition (no agreed-upon gold-standard measure). There have been few validation studies on the modifications of blood transfusion and LOS, but the case definitions and populations evaluated (e.g., delivery hospitalization only) have varied.[112,113] Until consensus is achieved on a more specific operationalization of the conceptual SMM definition and the surveillance systems for SMM case ascertainment are improved, we can still advance the surveillance and research of SMM racial disparities through transparency in case definition selection. None of the available case definitions are likely perfect. We use the CDC standardized criteria for evaluating quality surveillance systems as a framework for describing the strengths and limitations of each case definition's applicability in hospital discharge records.[31] Strengths and limitations were based

on available evidence and plausible assumptions in the absence of peer-reviewed literature.[31] Attributes of quality surveillance systems include:

1. Simplicity & Accessibility: Ease of implementing the modification.
2. Data quality: Accuracy of hospital discharge records in identifying SMM indicators and populations at risk.
3. Sensitivity: Proportion of true SMM cases captured by the case definition in hospital discharge records.
4. PPV: Proportion of SMM cases identified in hospital discharge records that are true SMM events.
5. Representativeness: Extent to which the system accurately describes the occurrence of the disease in the target population (e.g., by racial group).
6. Timeliness: Reporting speed under the modification.
7. Flexibility: Adaptability of modification to changes.
8. Stability: Whether the modification identifies SMM events well over time and across places.
9. Usefulness: Utility of the modification in meeting the surveillance objectives.

Of the three case definition modifications, the gold-standard measure of what is and is not an SMM event is best defined for the blood transfusion indicator (i.e., receipt of four or more blood transfusion units). Validation studies for the identification of blood transfusion in hospital discharge data suggest that ICD-CM codes are relatively accurate for identifying receipt of any blood transfusion based on blood bank records.[114] However, the utility of this indicator for SMM surveillance relying on hospital discharge records is lacking (**Table 3.3**). Because defining a delivery as a *severe* morbidity requires transfusion of four or more units, the inclusion of blood transfusion affects specificity, PPV, and possibly stability (to the extent transfusion of 1-3 units varies over time and space).[1,103] For example, compared with the gold

standard of four or more transfusion units, the PPV of the blood transfusion indicator (yes/no) has been found to be poor (44%) without information on the number of units transfused.[115] The greatest limitation of excluding the blood transfusion indicator is that we would expect reduced sensitivity, such that some true SMM events will be missed. Taken together, the strengths of exclusion outweigh the limitations, suggesting that SMM surveillance and research relying on hospital discharge records should use an SMM case definition excluding the blood transfusion indicator.

Table 3.3. Strengths and limitations of three SMM case definition modifications under CDC quality attributes of surveillance systems.[31]

Attribute	Strengths and Limitations of SMM Case Definition Modifications		
	Exclusion of Blood Transfusion	**Inclusion of Postpartum Hospitalizations**	**Exclusion of Length of Stay < 90th Percentile**
Simplicity & Acceptability: *Ease of implementing the modification.*	Strength Inclusion/exclusion of blood transfusion indicator is standard practice with CDC ICD-CM indicators.[32]	Situational Strength/Limitation Inclusion of postpartum (PP) events requires data linkage. Simplicity of PP inclusion varies by data source and resource availability.[10,30,34]	Strength Simple calculation and implementation of 90th percentile threshold.[10]
Data quality: *Accuracy of hospital discharge records in identifying SMM indicators/population.*	Strength Blood transfusion ICD-CM codes as an indicator of any receipt of blood transfusion (documented in blood bank records) has moderate/good sensitivity (65-91%) overall.[114]	Expected Strength No studies available, but ICD-CM codes expected to have reasonable documentation in delivery and postpartum hospitalization records.	Expected Strength LOS information is available and expected to be accurate.
Sensitivity: *The proportion of true SMM cases captured by the surveillance system.*	Expected Limitation Gold-Standard Measure: Receipt of 4+ blood transfusion units. Exclusion of blood transfusion is expected to increase the number of false negatives, given BT only cases represent a large proportion of potential SMM events.[112]	Expected Strength Gold-standard measure: Unclear (conceptual agreement SMM can occur during PP). No validation studies available. Expect same or improved sensitivity because capturing more potential SMM cases.	Expected Limitation Gold-standard measure: Unclear (conceptual agreement SMM is a severe event).[10,113] Sensitivity may be reduced from the exclusion of potential 'true' SMM events under a more inclusive definition.[113]

Attribute	Strengths and Limitations of SMM Case Definition Modifications		
	Exclusion of Blood Transfusion	**Inclusion of Postpartum Hospitalizations**	**Exclusion of Length of Stay < 90th Percentile**
Positive predictive value: *The proportion of SMM cases identified by the surveillance system that are true SMM events*	Strength Gold-Standard Measure: Receipt of 4+ blood transfusion units Validation studies of blood transfusion ICD-CM code indicate poor/moderate PPV given 4 units of blood are needed to meet SMM clinical criteria (PPV: 44%).[112–114]	Not enough information Gold-standard measure: Unclear (conceptual agreement SMM can occur during PP). No validation studies available. Unclear scenario for the PPV.	Limitation Gold-standard measure: Unclear (conceptual agreement SMM is a severe event).[10,113] LOS is not specific to the maternal health outcome, thus PPV is likely reduced by the practice of extending maternal stay if the infant has extended stay. Studies have indicated poor/moderate PPV (38-67%).[112,113]
Representativeness *The extent to which the system accurately describes the occurrence of the disease in the population (e.g., by racial group).*	Not enough information	Expected Strength Exclusion of postpartum events may miss potential SMM events that are more likely to occur in certain populations (e.g., NH Black women).[36]	Expected Limitation Exclusion of shorter LOS may differentially select to potential SMM events based on maternal race or hospital payment. E.g.) if Black women receive less timely and quality care, they may be more likely to be discharged early; Individuals with insurance payor caps may have shorter length of stays compared to those without payor caps, which is distinct from health outcome needs.
Timeliness: *Reporting speed.*	Not relevant No expected difference in timeliness of reporting.	Not relevant No expected difference in timeliness of reporting.	Not relevant No expected difference in timeliness of reporting.

Attribute	Strengths and Limitations of SMM Case Definition Modifications		
	Exclusion of Blood Transfusion	**Inclusion of Postpartum Hospitalizations**	**Exclusion of Length of Stay < 90th Percentile**
Flexibility: *Adaptability to changes.*	Not relevant Inclusion/exclusion of blood transfusion relies on ICD-Codes; both are adaptable to changes.	Not relevant Inclusion/exclusion of postpartum hospitalizations relies on ICD-Codes; both are adaptable to changes.	Not relevant Inclusion/exclusion of maternal LOS relies on hospital discharge record; both are adaptable to changes.
Stability: *Whether the modification identifies SMM events well over time and across places.*	Strength Sensitivity of blood transfusion hospital discharge codes compared to medical record review may vary between hospitals (47-80%).[114] Further, there have been changes in the implementation of blood transfusion codes over time (e.g., ICD-10-CM added many different BT codes) and across hospitals in the identification of SMM.[116]	Not enough information.	Expected Limitation There may be variation in LOS across hospitals not specific to SMM events. Further, it is unclear how hospital factors for an increased LOS have changed over time.
Usefulness *Utility in meeting surveillance objective.*	Strength Administrative records do not indicate the number of blood transfusion units received.[104] Blood transfusion ICD-CM codes do not consistently meet the conceptual definition of SMM event.	Strength Information is available in hospital discharge record for identification. Inclusion of potential postpartum SMM events is consistent with a construct that severe pregnancy outcomes may occur or be identified after the delivery hospitalization.[106]	Limitation Longer LOS is theoretically consistent with the conceptual definition of a severe adverse pregnancy outcome.[10] But, LOS is not specific to maternal health outcome which limits usefulness in SMM surveillance relying on hospital discharge data.

Often not explicitly defined are the at-risk periods that constitute an SMM event. The ways in which we discuss the strengths and limitations of the postpartum modification relies on whether we agree that SMM events can or cannot occur during the postpartum period (and if so, how long of a period after pregnancy can SMM events occur?). If we accept that SMM events can occur during the postpartum period, then we should seek to identify SMM events in the postpartum period insomuch as we are able to feasibly and accurately identify them in the hospital discharge records. Thus, under the attribute of usefulness, the clinical consensus of the postpartum period being an at-risk period for SMM events and the availability of methods to link subsequent hospitalizations suggests that postpartum hospitalizations should be included (**Table 3.3**).[106] The inclusion of potential postpartum SMM events is further supported by considering attributes of data quality, sensitivity, and representativeness. Simplicity and acceptability are potential limitations of this modification since data linkage of postpartum and delivery hospitalizations is a commonly cited challenge.[10,30,34] A fully identifiable linkage key is available in Georgia, so we can more feasibly link potential postpartum SMM events. Yet this may not be true for other localities. Consideration of this logistical challenge should acknowledge that a greater proportion of postpartum SMM events have been documented to occur among NH Black women.[36] Thus, we may induce selection bias by limiting the investigation to delivery-only events if SMM events during the postpartum period are "true" *de novo* SMM events that are caused by racial differences in life course health trajectories.

Even if we conceptually do not consider the postpartum period to be an at-risk period for SMM events, there is a potential for SMM misclassification errors that may bias estimates from delivery-only events. Considering the attributes of representativeness and identification accuracy, SMM events that occurred during the delivery hospitalization may not be captured until the postpartum period. This could produce differential misclassification by race if Black women are less likely to receive adequate and timely care.[20,117] Weighing the available evidence

and plausible assumptions, the strengths of including the postpartum period outweigh the limitations. Thus, we recommend a case definition that includes SMM events in the postpartum period, especially when record linkage is logistically feasible. However, we note that the inclusion of postpartum SMM was not the greatest driver of differences in conclusions by case definition, particularly when considering the relative disparity in the SMM incidence (**Table 3.2**). Thus, if logistical barriers to linkage are insurmountable, our results suggest that only select parameter estimates of the Black-White disparity would be meaningfully obscured.

Finally, we consider the modification of identifying SMM events with long LOS. Like blood transfusion, ICD-CM codes do not indicate the severity of the morbidity. Thus conceptually, restriction to a longer LOS may aid in identifying SMM events if we accept the idea that *severe* morbidity compared to morbidity would result in longer hospital stays. Although restricting to a longer LOS theoretically improves the measurement of SMM by identifying more severe events, the utility of this modification when applied in hospital discharge records may be lacking given accuracy, stability, and representativeness limitations (**Table 3.3**). For example, conversations with state health department staff suggested that maternal LOS may not be specific to adverse maternal outcomes; rather, LOS may be more reflective of adverse neonatal outcomes leading to a longer maternal LOS. Questionable identification accuracy is consistent with limited validation studies of the postpartum LOS modification for identifying SMM events (PPV: 38-67%).[113] Further concerns about the stability and the representativeness of this modification presented limitations that may obscure the ability to appropriately capture the SMM construct. For example, it is plausible that if Black women receive less timely and quality care, they may be more likely to be discharged early. In contrast, White women with less severe morbidity may remain in the hospital as part of routine follow-up. Overall, the limitations of the LOS modification appear to outweigh the strengths of potentially improved measurement. Thus, we recommend no restriction of hospital LOS for the tracking and investigation of racial disparities in SMM risk.

Ultimately, this informal review of the literature and plausible assumptions about the processes of identifying an SMM event in hospital discharge data best support the conclusion that definition #3 – the CDC indicator list excluding blood transfusion, including postpartum hospitalizations, and any LOS – is conceptually the most reliable definition for estimating racial disparities in SMM risk.

This analysis and associated commentary can help inform future surveillance and etiologic research on SMM racial disparities in several ways. On a conceptual level, we demonstrate one approach to clarifying and communicating the peer-reviewed evidence and assumptions that motivate the choice of a case definition given competing choices. More concretely, we provide a rationale specific to the identification of SMM relying on hospital discharge records. Further, we explicitly considered how case definitions might operate differently for identifying NH Black and White women, thus impacting our estimates of the racial disparity. This is important given that exploration of the variation in overall SMM rate estimates across case definitions may miss important processes that differentially identify SMM events between racial groups.

Our results provide context for research already completed and the implications of definition choice for comparing future studies using different case definitions. If the goal is to understand the relative disparity, case definitions #1 and #2 provide similar estimates as definition #3 (**Table 3.2**). However, if the interest is in the absolute disparity (RD), all other case definitions would produce substantively different results.

Limitations

A key limitation is the lack of agreement on the SMM gold-standard definition to evaluate each case definition, particularly for the postpartum and LOS modifications. This limited the availability of peer-reviewed literature to explicitly evaluate identification inaccuracies, as well as other key attributes of quality surveillance systems. Relatedly, our study

could not directly investigate measurement errors in the assessment of SMM events as drivers of the case definition differences. Prior studies have suggested that the accuracy of identification of SMM events may be differential by the delivery hospital.[104,114,118] The racial distribution of patients in hospitals is non-random.[60,61] Thus, differential measurement errors by the delivery hospital may further bias comparisons of SMM definitions if the misclassification error is also differential by the case definition. More research, including validation studies of SMM identification stratified by race/ethnicity, is needed to investigate this potential misclassification bias once a clearer consensus on a more specific SMM conceptual definition is achieved. As such, we had to make assumptions about processes that may obscure comparisons of NH Black and White SMM risk in evaluating the strengths and limitations of each case definition for use specific to investigating racial disparities in SMM risk. Lastly, we could not feasibly evaluate the full range of case definition modifications observed in the literature. We selected the three modifications investigated above because they were commonly implemented in SMM surveillance and etiologic studies. However, this list of modifications is not exhaustive; other modifications are the inclusion of the antepartum period, severity restriction through ICU admission, and alternate operationalizations of the postpartum period (e.g., 90 days).

Conclusions

Despite the noted limitations, this study highlights how different SMM case definitions impact public health conclusions about the magnitude of SMM incidence and racial disparities in SMM. It is standard practice to present multiple definitions in SMM studies (most commonly the inclusion and exclusion of blood transfusion). However, the differences in SMM incidence and disparities by definition motivate the selection of a primary case definition to inform public health action. Until a consensus definition is reached and the surveillance systems for SMM identification are improved, transparency in articulating the choice of SMM case definition is critical when surveilling disparities in SMM using hospital discharge records. We concluded that the SMM case definition including postpartum hospitalizations and excluding blood

transfusion was best supported by available evidence and plausible assumptions for quality surveillance and research of SMM and racial disparities in SMM risk.

Chapter 4: Decomposing the Black-White racial disparity in severe maternal morbidity (SMM) risk: the role of hypertensive disorders of pregnancy

Abstract

Objective: To estimate the proportion of the Non-Hispanic (NH) Black-White racial disparity in SMM risk explained through pathways including hypertensive disorders of pregnancy (HDP) using causal decomposition models.

Methods: Using 2006-2019 Georgia hospital discharge records linked with vital statistics, we investigated the role of HDP by decomposing the absolute racial disparity in SMM incidence (excluding blood transfusion and including postpartum hospitalizations) using G-estimation of structural nested mean models.

Results: NH Black women experienced an excess 55.7 SMM events (95% CI: 52.2, 59.0) per 10,000 delivery hospitalizations compared to NH White women. Given our assumptions, the absolute disparity remaining after blocking the pathways through HDP was 41.1 SMM events per 10,000 deliveries (95% CI: 37.8, 44.4), explaining 26% of the disparity.

Conclusion: Our results suggest that intervening on the pathway of HDP is likely an effective opportunity for reducing Black-White disparities. This involves intervention on both clinical and social determinants of health risk factors to reduce the prevalence of HDP and moderate the racialized experiences producing excess risk among NH Black women through HDP. Yet, interventions targeting pathways beyond HDP will also be necessary to reduce the excess risk among NH Black women, given the large majority of the disparity remains unexplained.

Introduction

In the United States (US), Non-Hispanic (NH) Black women have an increased risk of adverse maternal outcomes related to pregnancy, delivery, and the postpartum period known as severe maternal morbidity (SMM) (RR: 1.2-2.6).[4–6,61] The excess SMM risk among NH Black women compared to NH White is hypothesized to be largely preventable.[3] Yet, racial disparities in SMM risk have persisted over time and across places.[20,21]

Individual-level comorbidities, such as hypertensive disorders of pregnancy (HDP), are a known cause of SMM and maternal mortality.[119–121] HDP is estimated to occur in 6-10% of US pregnancies.[122–124] HDP rates are highest among NH Black women and women living in the southern US, compared to NH White women and women living in other US regions.[122–124] As such, HDP has been hypothesized to be a potentially important driver of racial disparities in SMM.[21,56] This has led to several proposed strategies targeting HDP as a critical opportunity for reducing disparities (e.g., enhanced models of prenatal care, patient safety bundles).[21,56,71] However, to date, no studies have explicitly estimated the proportion of the Black-White racial disparity that operates through the pathway of HDP. Thus, we do not understand how effective targeting HDP would be for reducing Black-White disparities. Equally important, we do not know how much of the disparity would remain unexplained, requiring alternative or additional strategies.

Maternal race in SMM research is often used as a proxy for investigating how racism produces inequitable excess risk (i.e., preventable and thus plausibly avoidable) among NH Black women compared to NH White.[125] The incidence and control of HDP are socially structured through historical and present-day processes that differentially determine the availability of knowledge and resources by race (e.g., access to quality primary care and healthy food options).[22,125] Conceptualizing risk factors such as HDP as intermediates on the causal pathway from racism to SMM motivates the application of causal mediation analysis for

decomposing disparities.[59] When investigating racial disparities, decomposition models can be used to estimate the residual magnitude of the disparity (known as the controlled direct effect (CDE)) that does not operate through the evaluated mediator pathway.[59] Thus, using effect decomposition methods in SMM racial disparities research can inform the degree to which control of HDP would reduce the Black-White disparity.[59] Despite its potential value for advancing maternal health equity, to our knowledge no studies have employed causal mediation methods to explicitly investigate the role of individual-level or hospital-level factors in mediating the SMM racial disparity. This study aims to estimate the proportion of the Black-White racial disparity in SMM risk explained through pathways including HDP using causal decomposition models.

Methods

Study Population

We defined our study cohort as NH Black and NH White Georgia residents ages 15-49 who had any delivery hospitalization record in a Georgia hospital for deliveries between January 1, 2006 and December 31, 2019. We identified pregnancies using the US Centers for Disease Control and Prevention (CDC)/Alliance for Innovation in Maternal Health (AIM)-recommended ICD-9/10-CM hospital discharge birth denominator codes for the study of SMM (**Appendix Table A2)**.[33] Pregnancies could have resulted in a live birth or fetal death, but molar and ectopic pregnancies and induced terminations were excluded.[33] Pregnancies, not individuals, define our cohort. Thus, a single individual can have multiple SMM events over different pregnancies.

Identifying SMM

SMM events were identified using the CDC/AIM v6-27-2020 list of SMM-defining ICD-CM (**Appendix Table A1**).[32,111] We used an SMM case definition excluding the blood

transfusion indicator and including postpartum hospitalizations through 42-days postpartum based on a set of criteria for evaluating the quality of surveillance systems (**Chapter 3**).[31]

Decomposition Analysis

Causal Effect Definition and Assumptions

We applied causal decomposition analysis methods to decompose the absolute NH Black-White racial disparity (risk difference (RD)). The RD was selected to measure the excess burden, which has advantages in applied epidemiology for interpretability and quantifying the potential public health impact.[25] Our interest is in estimating SMM incidence. Still, we use the terminology SMM rate per 10,000 deliveries (events per the total number of deliveries) when presenting estimates to be consistent with the terminology used in prior studies.

Our goal was to estimate the proportion of the disparity that does not operate through the evaluated mediator pathway (HDP), specifically, the CDE.[126,127] If validly estimated, the CDE is interpretable as the excess risk among NH Black women remaining if the mediator was set to the referent value (no HDP) (**eq. 4.1**):[58,59]

(4.1) $$CDE(HDP = No) =$$

$$E[SMM(HDP = No)|RACE = NH\ Black] - E[SMM(HDP = No)|RACE = NH\ White]$$

Our conceptualization of the relationship of race, HDP, and SMM is based on the assumptions that (1) the excess SMM risk among NH Black compared to NH White women is preventable and (2) that the NH Black-White risk difference is driven by structural racism. Structural racism shapes the opportunities and constraints to accessing health information, healthy environments, stress, and healthcare services including pre-conceptional primary care and perinatal/postpartum care.[22] Thus, in our study, the operationalized exposure of race captures the consequences of racism and a host of lived experiences that differ by race. Note that the

proxy of race is imperfect; thus, we cannot identify the effect of racism from other lived experiences captured by race (i.e., racialized sociocultural factors).[128]

Decomposition analyses require careful consideration of four (at times, exceptionally strong) assumptions: (1) No exposure-outcome confounding, (2) No mediator-outcome confounding, (3) No exposure-mediator confounding, and (4) No mediator-outcome confounding affected by the exposure (**Aim 2 Appendix**).[126,127] Valid estimation of the CDE only requires assumptions #1 and #2 to be met.[58] However, assumption #4 guides the choice of decomposition methods because confounding adjustment using standard regression methods blocks a path from racism to SMM that does not operate through HDP (**Aim 2 Appendix**).[58] Assumptions for causal decomposition analysis are in addition to the standard assumptions needed for estimating a causal effect.[58] These include the stable unit treatment value assumption (SUTVA: no interference), consistency (no variations in the potential outcome under the same treatment), positivity (non-zero probability of exposure and covariate for all outcome strata), no measurement error, and correctly specified models.[58,91,129]

Exposure and Mediator

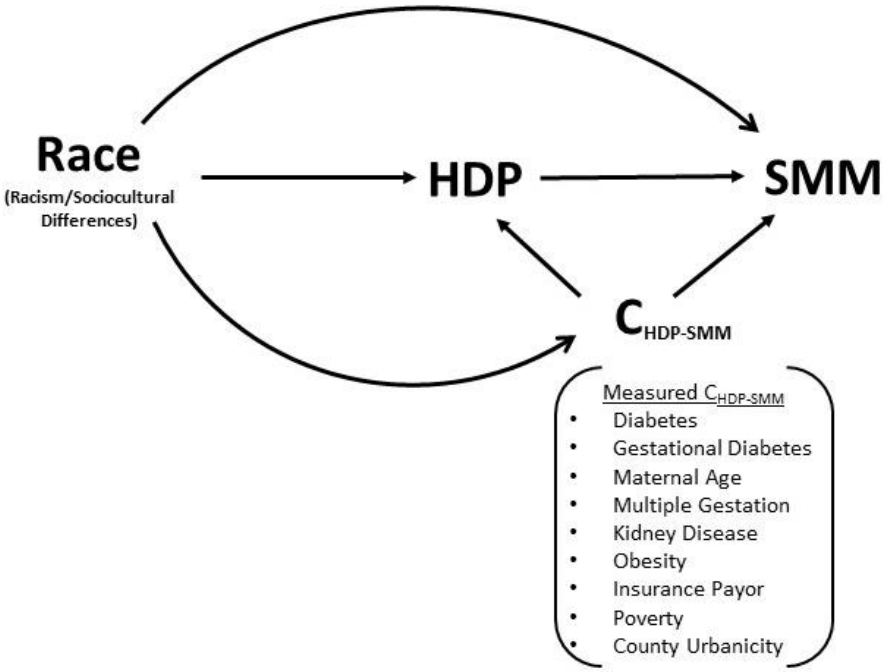
Race was coded as NH Black and NH White based on information from the hospital discharge record. If race was available and no ethnicity information was available, individuals were coded as non-Hispanic (**Chapter 2**). HDP (mediator) was identified in hospital discharge records based on ICD-9/10-CM codes for chronic hypertension, gestational hypertension, and preeclampsia (**Aim 2 Appendix**).

Covariates

Models were adjusted for measured HDP-SMM (mediator-outcome) confounders based on our hypothesized directed acyclic graph (DAG) (**Figure 4.1**). Adjusted covariates included maternal age, diabetes mellitus, gestational diabetes mellitus, obesity, multiple gestation, kidney disease, insurance payor, census tract proportion of the population living below the federal

poverty line, and county-level urbanicity.[73,124,130,131] The operationalization of these variables is described in the **Aim 2 Appendix**.

Figure 4.1. Hypothesized relationship of race (racism, sociocultural factors), HDP, SMM, and HDP-SMM (mediator-outcome) confounders.



When the exposure is race (racism), we do not conceptualize assumption #1 as a threat to validity, given no arrow is hypothesized to cause race (**Figure 4.2**). We hypothesized that all measured mediator-outcome confounders were descendants of the exposure, violating assumption #4. We further hypothesized that there were mediator-outcome confounders that were unmeasured, unavailable, or poorly measured in our dataset (e.g., substance use, prenatal care receipt, health behaviors, and other unknown factors) (**Figure 4.2**).

We conducted multiple imputation of covariates with missing values using additive regression, bootstrapping, and predictive mean matching, which assumes covariates are missing at random.[132] These included imputation of multiple gestation (n=127,808, 8.8%), insurance

payor (n=4,741, 0.3%), and census tract poverty (n=88, 0.001%). We described patterns of missingness by maternal race and SMM status and compared the results using imputed data to complete case analyses in the **Aim 2 Appendix**.

G-estimation of structural nested mean models

G-estimation of a structural nested mean model was selected over other generalized methods (e.g., inverse probability-weighted marginal structural models and structural transformation) because these models are doubly robust, allowing for consistent estimation of the CDE with either correct mediator or outcome model specification.[59,126] We first estimated the magnitude of the total Black-White disparity (i.e., the total effect of racism on SMM). G-estimation of a structural nested mean model to estimate the CDE is a two-step process (**Aim 2 Appendix**). In step one, we first transformed the SMM outcome to remove the effect of HDP (setting HDP=No). In step two, we estimated the effect of race on the transformed SMM outcome (i.e., the effect of racism on SMM not through HDP). The standard error of the CDE was used to calculate conservative 95% confidence intervals. We calculated the proportion of the disparity eliminated by the complete prevention of HDP as the total effect minus the CDE, divided by the total effect.

Hypothesizing about the processes producing Black-White racial disparities in SMM risk through HDP

If HDP is an essential driver of the Black-White disparity, we are interested in hypothesizing about the processes producing this disparity. Two hypothesized scenarios are whether the race-specific differences in SMM risk are driven by differences in the prevalence of the mediator (e.g., a greater proportion of NH Black women have uncontrolled HDP) or a difference in the strength of association of HDP and SMM for NH Black vs. NH White women (e.g., the interaction of maternal race and the HDP). We compared the prevalence difference of HDP by maternal race (i.e., the prevalence of HDP among NH Black minus the prevalence

among NH White women). Further, we compared the estimated SMM risk by maternal race and HDP status under a common referent (NH White women with no HDP).

Results

Between 2006-2019, the SMM rate was 132.8 per 10,000 hospitalizations among NH Black women and 77.1 per 10,000 among NH White women (**Table 4.1**). Compared to NH White women, a greater proportion of NH Black women were ages 24 or younger (42% vs. 30%), Medicaid insured (66% vs. 38%), and living in an urban county (84% vs. 74%). The median proportion of individuals living below the federal poverty line was higher and more variable for NH Black women's residential census tracts (17.2%, interquartile range (IQR): 16.8) compared to NH White women's tracts (9.3%, IQR: 10.7).

Table 4.1. Maternal sociodemographic and clinical characteristics stratified by maternal race and ethnicity from the imputed dataset, Georgia, 2006-2019.

N (column %)	**NH Black**	**NH White**
	N = 623,402	N = 820,769
SMM Rate per 10,000 Deliveries	132.8	77.1
HDP		
Any HDP	77,515 (12%)	76,308 (9%)
Chronic Hypertension	28,782 (5%)	17,977 (2%)
Gestational Hypertension	20,501 (3%)	28,859 (4%)
Preeclampsia (mild or severe)	29,901 (5%)	30,984 (4%)
No HDP	545,887 (88%)	744,461 (91%)
Maternal Age		
15-19 years	73,429 (12%)	60,307 (7%)
20-24 years	188,175 (30%)	185,126 (23%)
25-29 years	167,665 (27%)	238,475 (29%)
30-34 years	117,695 (19%)	213,972 (26%)
35-39 years	60,898 (10%)	101,373 (12%)
40-44 years	14,623 (2%)	20,318 (2%)
45-49 years	917 (<1%)	1,198 (<1%)
Insurance Payor		
Private	172,130 (28%)	453,596 (55%)
Medicaid	411,901 (66%)	30,8678 (38%)
Self-Pay	14,109 (2%)	11,514 (1%)
Other	25,262 (4%)	46,981 (6%)
Multiple Gestation		
Single	610,756 (98%)	806,019 (98%)
Multiple	12,646 (2%)	14,750 (2%)
Gestational Diabetes Mellitus		
Yes	20,585 (3%)	29,476 (4%)
No	602,817 (97%)	791,293 (96%)
Pre-existing Diabetes Mellitus		
Yes	5,789 (1%)	5,496 (1%)
No	617,613 (99%)	815,273 (99%)
Renal Disease		
Yes	1,337 (<1%)	1,756 (<1%)
No	622,065 (99%)	819,013 (99%)
Obesity		
Underweight/Healthy	584,717 (94%)	789,230 (96%)
Overweight/Obesity	38,685 (6%)	31,539 (4%)
County Urbanicity		
Urban	520,701 (84%)	606,204 (74%)
Rural	102,701 (16%)	214,565 (26%)
Percentage of Individuals Living Below the Poverty Line in Residential Census Tract		
Median (IQR)	17.2 (16.8)	9.3 (10.7)

Abbreviations: HDP = Hypertensive disorders of pregnancy; IQR = interquartile range, NH = Non-Hispanic; SMM = Severe maternal morbidity

Overall, NH Black women experienced an excess 55.7 SMM events (95% CI: 52.2, 59.0) per 10,000 delivery hospitalizations compared to NH White women (i.e., the total effect) (**Table 4.2**). The absolute disparity remaining after blocking the pathways through HDP was 41.1 SMM events per 10,000 deliveries (95% CI: 37.8, 44.4), explaining 26% of the disparity. The proportion eliminated was slightly higher in the complete case analysis (30%) (**Aim 2 Appendix**).

Table 4.2. The total effect, estimated CDE, and proportion of the disparity eliminated for the effect of race and SMM through the mediator HDP.

	Total Effect* (95% CI)	**CDE* (95% CI)**	**Proportion Eliminated**
HDP	55.7 (52.2, 59.0)	41.1 (37.8, 44.4)	26%

*Total effect and CDE represent the excess risk among NH Black women (Black-White Rate Difference per 10,000 hospitalizations)

In **Table 4.3**, we estimated that the prevalence of HDP among NH Black women (12.4%) was 3.1% higher than the prevalence of HDP among NH White women (9.3%). Further, there was evidence of statistical interaction of maternal race and HDP on the additive scale. Specifically, the risk of SMM among NH Black women with HDP was greater than expected based on the estimated risks for NH Black women with no HDP, NH White women with HDP, and NH White women without HDP (interaction contrast: 100.6 (84.2, 116.9).

Table 4.3. Additive statistical interaction of maternal race and HDP status on SMM risk, and proportion of race-specific deliveries with HDP.

	Maternal Race						
	NH White			**NH Black**			RD per 10,000 hospitalizations for maternal race in strata of HDP status
HDP Status	N SMM/ Deliveries	Proportion of Race-Specific Deliveries	RD per 10,000 hospitalizations (95% CI)	N SMM/ Deliveries	Proportion of Race-Specific Deliveries	RD per 10,000 hospitalizations (95% CI)	
No HDP	4,838/744,461	90.7%	0.0	5,681/545,887	87.6%	33.6 (30.2, 37.1)	33.6 (30.2, 37.1)
HDP	1,490/76,308	9.3%	114.1 (104.5, 124.0)	2,596/77,515	12.4%	238.8 (226.2, 251.4)	124.7 (109.1, 140.4)
RD per 10,000 hospitalizations for HDP in strata of maternal race			114.1 (104.5, 124.0)			205.2 (192.5, 217.8))	
Interaction contrast: 91.1 (75.1, 107.1)							

RDs adjusted for insurance payor, maternal age, multiple gestation, pre-existing diabetes mellitus, gestational diabetes mellitus, renal disease, obesity, and proportion of residential census tract living below the federal poverty line.

Abbreviations: HDP = hypertensive disorders of pregnancy; NH = non-Hispanic; RD = rate difference; SMM = severe maternal morbidity;

Discussion

Hypertensive disorders are a known cause of SMM overall, and our results suggest that HDP likely plays a vital, yet incomplete, role in mediating Black-White racial disparities in SMM risk.[119,120] Given assumptions hold, we estimated that if HDP were to be completely eliminated, we would expect 26% of the disparity to be eliminated, indicating that HDP is an important pathway of excess risk among NH Black women (**Table 4.2**). These results are not surprising, given that cardiometabolic risk factors are a leading cause of SMM and maternal mortality.[71,119,121]

Our results suggested that both differences in the prevalence of the mediator in each racial group and the interaction of race (racism) and HDP may be important mechanisms of the excess SMM risk among NH Black women through HDP (**Table 4.3**). These findings are consistent with the hypothesis that reducing the prevalence of HDP overall would reduce some of the Black-White racial disparity in SMM risk. However, a focus on reducing the prevalence overall would be insufficient for remediating the disparity without further consideration of how differences in contextual- and individual-level experiences among Black women produce elevated SMM risk through HDP compared to NH White women.

The finding that the association of HDP on SMM risk was stronger for NH Black women compared to NH White women is consistent with our conceptualization that the inequitable excess risk among NH Black women operating through HDP may be driven by structural racism.[22,24] Structural racism thus produces differential access to healthcare systems such as quality primary care, prenatal care, and postpartum care, and neighborhood factors such as safety and the availability of healthy food options, green space, and educational opportunities.[22,133,134] For example, among HDP indicators, the greatest Black-White prevalence difference was observed for chronic hypertension (**Table 4.1**). Considering this estimate in the context of results from mediation analyses and our interaction assessment may suggest that

failed periconceptional and life course primary care, as well as differential access to healthy environments, are contributing to the excess risk among Black women. Such that a greater proportion of NH Black women were entering into pregnancy with chronic cardiometabolic disease, putting them at an increased risk of SMM. This is especially true if pre-existing HDP was not properly managed as a result of structural constraints.

Improving our understanding of the pathways of structural racism to SMM through HDP allows us to identify clinical and social determinants of health opportunities to reduce Black-White disparities in SMM risk. Although HDP is a meaningful opportunity for intervention, our results elucidate that focusing solely on HDP would result in almost three-quarters of the Black-White disparity remaining (**Table 4.2**). Thus, other pathways must be investigated and subsequently intervened upon to achieve health equity in maternal health outcomes.

Our study further adds to the literature by employing causal mediation analysis methods to decompose the Black-White racial disparity in SMM risk. We estimated the CDE using conventional multivariable regression methods (i.e. the difference method) to exemplify how the use of statistical adjustment and counterfactual regression methods in estimating the CDE if there were a violation of assumption #4.[58,59] Analyses suggested that we would have overestimated the importance of HDP (CDE = 38.2 (95% CI: 35.9, 41.7), proportion explained: 31%) if using conventional regression methods rather than g-estimation of a structural nested mean model (**Aim 2 Appendix**). Ultimately, this may be contributing to the persistence of disparities by overemphasizing the proportion of the disparity that is potentially modifiable through the investigated risk factors.

It is essential to reiterate that the validity of the CDE estimate in any mediation analysis, and thus, the stated conclusions, depend on strong assumptions that are challenging to directly evaluate and likely not completely met. These assumptions include complete control of mediator-outcome confounders, correct model specification, consistency, positivity, SUTVA,

and no measurement error.[58] Yet, if assumptions of the sensitivity analyses also hold, our assessment of unmeasured mediator-outcome confounders suggests that the difference in CDE estimate and the total effect would likely not be explained fully by unmeasured mediator-outcome confounding.

Beyond unmeasured confounding, the identification of SMM is likely threatened by misclassification errors, which may further be differential by race.[104,112,114,118] We used a conceptually strong case definition for SMM; however, we could not explicitly investigate the impact of misclassification bias given a lack of validation information (**Chapter 3**). We relied on individual-level maternal race as a proxy for accumulated experiences resulting from structural racism. However, we cannot identify the effect of structural racism from other attributes conflated in the social meaning of maternal race (e.g., sociocultural differences/individual-level experiences of racism). Thus, the total and CDE estimates of racism on SMM may be confounded by other contextual- and individual-level experiences conflated in the social meaning of race. Further, the operationalization of the mediator incorporated three HDP outcomes. Although they have similar public health interventions, pregnancy-related and pre-existing HDP have different clinical intervention opportunities.[135] This is important to consider in conceptualizing opportunities for the elimination/control of HDP in aggregate, rather than individual disease categories.[91] Lastly, the implementation of the proportion of the disparity eliminated by HDP modeled a scenario in which HDP is completely prevented. A more realistic conceptualization might evaluate a scenario where HDP is controlled. However, we are unable to distinguish controlled from uncontrolled HDP in administrative hospital discharge records. As such, we would expect that 26% of the disparity would be eliminated under the complete prevention of HDP occurrence, and <26% under the complete control of HDP. Beyond the estimation of the proportion eliminated, the recognition of the disparity pathways operating through HDP provides insight into upstream opportunities for prevention, which are known to be associated with hypertensive and other cardiometabolic disorders.[134] Ultimately,

epidemiologic bias in estimating direct effects from mediation analyses of the NH Black-White racial disparity may be inevitable. Thus, transparency of assumptions through DAGs and the inclusion of sensitivity analyses when feasible are essential when implementing these models to improve their potential public health impact.

Conclusions

Despite these limitations, this study provided evidence that intervening on the pathway of HDP is likely an effective opportunity for reducing Black-White disparities. This involves intervention on both clinical and social determinants of health factors to reduce the prevalence of HDP and moderate the racialized exposures producing excess risk among NH Black women through HDP. Yet, interventions targeting pathways beyond HDP will also be necessary to reduce the excess risk among NH Black women, given the large majority of the disparity remains unexplained. Future studies should employ causal mediation models such as g-estimation of structural nested mean models to investigate potential drivers of the remaining Black-White disparity in SMM risk.

Chapter 5: Estimating the joint effect of neighborhood relative income inequality and racial segregation on severe maternal morbidity (SMM) risk in Georgia

Abstract

Objective: This study aimed to estimate the joint effect of neighborhood relative income inequality and racial segregation on SMM.

Methods: Using 2010-2019 Georgia hospital discharge records, we estimated the joint effect of census tract-level relative income inequality and racial segregation in the total population on the additive scale using a generalized linear model and an interaction term for the two exposures. Income inequality was categorized into three groups as relative concentrated poverty, affluence, or mixed-income. Racial segregation was dichotomously categorized as relative concentrated NH White or persons of color (POC).

Results: Under the common referent of women living in relatively mixed-income and relatively concentrated NH White neighborhoods, there were 14.4 fewer SMM cases per 10,000 hospitalizations (95% CI: -20.8, -7.9; 95% CI: -29.8, 0.9) among women living in concentrated affluent neighborhoods, regardless of neighborhood racial composition. Women living in POC neighborhoods with mixed-income and concentrated poverty had 24.3 and 32.8 excess SMM cases per 10,000 hospitalizations, respectively. We estimated an interaction contrast of the extreme categories of racialized income inequality of 26.4 (95% CI: 7.6, 43.8), providing evidence of positive interdependence on the additive scale.

Discussion: Our results suggest that processes of structural classism and racism operating through neighborhood relative income inequality and racial segregation in combination (i.e., racialized income inequality) produces greater SMM risk than expected from relative income inequality and racial segregation alone. Continued research on structural determinants of SMM incidence and Black-White disparities in SMM incidence, especially in the southern US, is critical for advancing maternal health equity.

Introduction

In the United States (US), there are racial and geographic disparities in adverse maternal health outcomes, known as severe maternal morbidity (SMM).[3–5,37] Black women and women living in the southern US experience a higher risk of SMM than White women (RR: 1.2-2.6) and the western/midwestern US regions (RR: 1.1-1.4).[3–5,37] Applying a health equity framework to investigating SMM incidence recognizes that women live, and thus are exposed to, community-level environments shaped by social and spatial population stratification processes.[22,24,38] These structural determinants of health include the processes of structural classism, racism, and sexism.[22,24,38]

Income inequality is a fundamental social determinant of health and a consequence of structural classism.[38] The harms of concentrated poverty on health have been highlighted as early as 1840 in recounts by Flora Tristan, who described the toxic workplace and housing environments accompanying poorer health among factory workers and city residents.[136,137] Inequitable distributions of wealth, and thus power and resources, influence the community environments women are exposed to over their life course and during pregnancy. On the alternate ends of the economic spectrum, concentrated affluence affords women living in these communities with health-related advantages such as access to quality employment, housing, healthcare, and education opportunities.[22] Women living in communities with concentrated poverty are often deprived of these basic conditions.[22]

In the US, the distribution of poverty and wealth is socially and spatially structured through other structural determinants of health, including sexism and racism.[23,24,79,87] Structural racism has been a core institutional process shaping social and spatial stratification since the inception of the US.[23,24] Beginning with slavery, structural racism has continued to shape the racialized class structure of the US through Jim Crow policies, redlining, and mass incarceration.[23,24] In this way, the racially inequitable distribution of wealth and power has systematically restricted

Black women's access to health-promoting privileges.[23,24] This is particularly relevant in the southeastern US, given the entrenched reproductive injustices stemming from a well-documented history of social, political, and economic oppression of communities of color and low-income persons in this region.[138]

As a result of this systematic disinvestment, communities with concentrated poverty and persons of color (POC) have vastly different neighborhood characteristics that may increase the risk of adverse maternal health outcomes, including SMM.[139,140] Yet to date, only three studies have investigated the relationship of racialized income inequality with SMM and maternal mortality, and only one of these studies was in the southeastern US.[72,74,88,90] All three studies used the same measure of racialized income inequality – the Index of Concentration of Extremes (ICE) for race and income.[74,88,90] These studies have consistently estimated that women living in predominately NH Black communities with concentrated poverty had an increased risk of SMM[90] and maternal mortality[88] compared to women living in predominately NH White neighborhoods with concentrated affluence.

The ICE for race and income measure spotlights the two extremes of the racialized aspects of income inequality, specifically concentrated poverty among predominately NH Black communities and concentrated affluence among predominately NH White communities.[81,84] However, considering the additional combinations of racialized income inequality (e.g., concentrated poverty in NH White communities and concentrated affluence in communities of color) may provide new insight into the production of SMM risk for the total population and Black-White disparities in SMM risk. Further, alternative measures of racial segregation and income inequality to ICE for race and income that capture relative (i.e., geographic-specific) thresholds of racialized poverty and affluence, rather than absolute US-based thresholds, may be informative for advancing our understanding of how structural determinants increase SMM risk in high-risk geographic locations.[97] Thus, the objective of this study was to estimate the

joint effect of relative income inequality and racial segregation on SMM. We further explored whether the effect and probability of each neighborhood exposure varied by individual-level maternal race and ethnicity.

Methods

Study Population and Data Sources

Our cohort was defined as pregnancies among NH Black and NH White Georgia residents ages 15-49 with any delivery hospitalization record in a Georgia hospital between January 1, 2010, and December 31, 2019. Hospital discharge records provided SMM international classification of disease (ICD)-9/10-clinical modification (CM) diagnosis and procedure codes, maternal race and ethnicity, and census tract of residence at the time of delivery. Pregnancies were identified using the Centers for Disease Control and Prevention (CDC)/Alliance for Innovation in Maternal Health (AIM) recommended ICD-9/10-CM hospital discharge birth denominator codes for the study of SMM (**Appendix Table A2**).[32,33] Delivery hospitalizations included live births and fetal deaths, but excluded molar and ectopic pregnancies and induced terminations (**Appendix Table A2**).[32,33]

Outcome

SMM events were identified using the CDC/AIM list of SMM-defining ICD-9/10-CM codes defining a diverse set of severe outcomes plausibly tied to pregnancy, labor, and delivery documented at the delivery hospitalization or within 42 days postpartum (**Appendix Table A1**).[32,33] Examples of SMM indicators include disseminated intravascular coagulation, hysterectomy, and acute renal failure. We excluded the blood transfusion only indicator given the low positive predictive value of this indicator for identifying an SMM event.[1,103–105]

Exposure

The exposures of interest are relative income inequality and relative racial segregation, for which we are interested in estimating the joint effect (relative racialized income inequality).

Hospital discharge records were linked with publicly-available census tract-level data from the American Community Survey (ACS) to obtain the proportion of racial/ethnic populations, median household income, and the proportion of individuals with a household income below the federal poverty line (**Aim 3 Appendix**).[141]

We conceptualized relative income inequality and racially segregated neighborhoods based on measures described by Shelton (2018) at the census tract level.[97] These measures were expanded from measures used by the US Department of Housing and Urban Development (HUD) and Goetz, Damiano, and Williams (2019) to describe racially concentrated poverty and affluence relative to the study area (e.g., Georgia) and study year, rather than an absolute US-based threshold.[92,93,97] Relative racial segregation was operationalized dichotomously as:

- Relatively concentrated NH White neighborhood: Census tract with a proportion of NH White race and ethnicity residents that was greater than or equal to the state average.[97] For example, the state average was 56% in 2010 and 53% in 2019.[100]
- Relatively concentrated POC neighborhood: Census tract with a greater proportion of individuals of Black, Hispanic, Asian, mixed, or other non-White race and ethnicity than the state average (44% and 47% in 2010 and 2019, respectively).[100]

Relative income inequality was operationalized as a three-level covariate:

- Relatively concentrated affluence neighborhood: Census tract with less than 10% of the population living below the federal poverty level and a median household income greater than or equal to 150% of the state median household income.[97] This equated to $75,976 in 2010 and $90,040 in 2019.[100]
- Relatively concentrated poverty neighborhood: Census tract with greater than or equal to 20% of the population living below the federal poverty level and a median household

income less than or equal to 80% of the state median household income.[97] This equated to $40,521 in 2010 and $48,021 in 2019.[100]

- Relatively mixed-income neighborhood: Census tract not in the two other extreme concentrated income inequality categories. This category included census tracts with median household incomes between 81 and 149% of the Georgia median household income. Further, it included neighborhoods with a median household income greater than or equal to 150% of the Georgia median household income with a moderate or high proportion of individuals living below the federal poverty level (greater than or equal to 10%) and neighborhoods with a median household income less than or equal to 80% of the Georgia median household income with low or moderate proportions of individuals living below the federal poverty level (<20%).

We conducted sensitivity analyses using alternate exposure definition operationalizations (**Aim 3 Appendix**).[92,93]

Covariates

Census tract urbanicity was obtained from the US Department of Agriculture rural and urban commuting areas dataset.[101] We defined census tract urbanicity as urban core/suburban and large/small town rural.[101,142] Race and ethnicity was defined as NH Black and NH White using the indicated maternal race and ethnicity in the maternal delivery hospitalization record. Women who had information on race but not ethnicity were coded as non-Hispanic (**Chapter 2**).

Analysis

We first estimated the joint effect of census tract-level relative income inequality and racial segregation in the total population on the additive scale using a generalized linear model with a binomial distribution and identity link, and an interaction term for the two exposure variables. Our interest is in describing SMM incidence, but we use the terminology 'SMM rate'

(events per the total number of deliveries) to be consistent with other SMM research. We did not adjust for maternal sociodemographic characteristics or characteristics of the delivery hospitalization since these covariates were conceptualized as on the causal pathway from racialized income inequality and SMM.

Three sets of risk difference comparisons were estimated. We can conceptualize the joint effects as a six-level categorical variable describing the relative racial composition and income inequality of the neighborhood (e.g., relative concentrated poverty in a relatively concentrated POC community). Thus, in assessing the interaction of relative income inequality and racial segregation, we used the relative mixed-income in a relatively concentrated NH White neighborhood category as the common referent to highlight the extreme consequences of structural racism and classism processes (i.e., concentrated poverty in communities of color and concentrated affluence in predominately NH White communities).[143] Further, we compared the SMM risk within strata of relative income inequality (i.e., neighborhoods with concentrated POC compared to concentrated NH White neighborhoods) and within strata of relative racial segregation (i.e., concentrated affluent and impoverished neighborhoods compared to mixed-income neighborhoods).

We calculated the interaction contrast (IC) on the additive scale to investigate whether there was evidence of positive or negative interdependence for the extreme contrasts (eq. 1):

$$(eq.1)\ IC = Risk(Poverty, POC) - Risk(Poverty, White) - Risk(Affluence, POC) + Risk(Affluence, White)$$

If there is no epidemiologic bias, then an IC = 0 would indicate no evidence of additive statistical interaction. An IC > 0 indicates evidence of greater than expected risk than what we would expect in the absence of additive interaction, while an IC < 0 indicates lower than expected risk.

We conducted a number of modeling sensitivity analyses. First, we adjusted for census tract urbanicity, given that urbanicity may be conceptualized as a confounder of the racialized income inequality and SMM association. Next, we evaluated the use of generalized estimating equation (GEE) models with an exchangeable correlation structure to account for potential violations of statistical dependence due to clustering of individuals within a census tract (**Aim 3 Appendix)**.[144] Lastly, we included year-specific spatial filtering eigenvectors to assess potential violations of statistical dependence due to spatial autocorrelation of census tracts (**Aim 3 Appendix)**.[145]

We described the proportion of maternal race-specific deliveries, race-specific SMM rates, and the Black-White rate difference estimates within strata of racialized income inequality. This sub-analysis was motivated by an interest in whether racialized experiences captured by the individual-level maternal race variable (e.g., embodied individual- and structural-level experiences of racism, sociocultural factors) differed by racially and economically stratified socio-contextual environments (e.g., proxies of structural racism and classism processes). Further, we sought to hypothesize about the role of racialized income inequality in the production of Black-White disparities in SMM risk. Specifically, whether Black-White disparities in SMM risk may be operating through a difference in how racialized income inequality affects NH Black vs. White women or by differences in the probability of exposure to more privileged or deprived neighborhood environments.

Results

The majority of deliveries occurred in mixed-income neighborhoods, as well as relative concentrated POC neighborhoods with concentrated poverty (**Table 5.1**). The proportion of deliveries at older ages (30+ years) increased with increasing neighborhood affluence for both concentrated NH White and concentrated POC neighborhoods. Concentrated affluence neighborhoods had a greater proportion of deliveries among women with a private insurance

payor, which further differed by neighborhood racial composition (concentrated NH White: 76%; concentrated POC: 68%). The proportion of women with a year of college education or more predominately differed by relative neighborhood income inequality with 74-78% in concentrated affluent areas, compared to 54-56% and 35-40% in mixed-income and concentrated poverty neighborhoods, respectively. A slight majority of women living in relative concentrated poverty, predominately NH White neighborhoods resided in rural census tracts (59%). Alternatively, the large majority of women living in all other racialized income inequality strata resided in urban census tracts (78-100%). There were no meaningful differences across exposure strata for maternal clinical characteristics, specifically pre-existing hypertension or diabetes and delivery type.

Table 5.1. Characteristics of 2010-2019 Georgia delivery hospitalizations stratified by residential census tract relative racialized income inequality category for NH Black and White women ages 15-49 years.

	Residential Census Tract Relative Racialized Income Inequality Strata					
Income Inequality	Relative Concentrated Affluence		Relative Mixed-Income		Relative Concentrated Poverty	
Racial Segregation	Relative Concentrated NH White	Relative Concentrated POC	Relative Concentrated NH White	Relative Concentrated POC	Relative Concentrated NH White	Relative Concentrated POC
Characteristics N Deliveries (column %)	N = 98,426	N = 13,600	N = 340,282	N = 226,924	N = 73,011	N = 233,210
Maternal Race and Ethnicity						
NH Black	12,660 (13%)	5,567 (41%)	64,222 (19%)	152,009 (67%)	19,979 (27%)	178,380 (76%)
NH White	85,766 (87%)	8,033 (59%)	276,060 (81%)	74,915 (33%)	53,032 (73%)	54,830 (24%)
Maternal Age, years						
15-19	2,149 (2%)	337 (2%)	23,788 (7%)	15,397 (7%)	8,374 (11%)	26,660 (11%)
20-24	8,638 (9%)	1,441 (11%)	82,109 (24%)	53,387 (24%)	24,539 (34%)	77,118 (33%)
25-29	22,498 (23%)	3,107 (23%)	103,651 (30%)	64,333 (28%)	21,728 (30%)	67,425 (29%)
30-34	38,129 (39%)	4,972 (37%)	85,336 (25%)	56,573 (25%)	12,568 (17%)	40,699 (17%)
35-39	21,789 (22%)	2,970 (22%)	37,231 (11%)	29,741 (13%)	4,804 (7%)	17,340 (7%)
40-44	4,889 (5%)	707 (5%)	7,743 (2%)	7,003 (3%)	956 (1%)	3,753 (2%)
45-49	334 (<1%)	66 (<1%)	424 (<1%)	490 (<1%)	42 (<1%)	215 (<1%)
Marital Status						
Married	77,500 (79%)	9,706 (71%)	187,595 (55%)	95,393 (42%)	28,262 (39%)	51,545 (22%)
Unmarried	16,021 (16%)	3,417 (25%)	117,810 (35%)	116,052 (51%)	35,613 (49%)	154,779 (66%)
Missing	4,905 (5%)	477 (4%)	34,877 (10%)	15,479 (7%)	9,136 (13%)	26,886 (12%)
Insurance Payor						
Private	7,4828 (76%)	9,284 (68%)	172,345 (51%)	88,759 (39%)	23,398 (32%)	49,377 (21%)
Public	16,762 (17%)	3,289 (24%)	140,233 (41%)	117,390 (52%)	44,723 (61%)	168,385 (72%)
Self-Pay	1,943 (2%)	510 (4%)	4,426 (1%)	6,373 (3%)	755 (1%)	4,516 (2%)
Other	4,758 (5%)	497 (4%)	22,673 (7%)	14,073 (6%)	4,042 (6%)	10,484 (4%)
Missing	135 (<1%)	20 (<1%)	605 (<1%)	329 (<1%)	93 (<1%)	448 (<1%)

	Residential Census Tract Relative Racialized Income Inequality Strata					
Income Inequality	Relative Concentrated Affluence		Relative Mixed-Income		Relative Concentrated Poverty	
Racial Segregation	Relative Concentrated NH White	Relative Concentrated POC	Relative Concentrated NH White	Relative Concentrated POC	Relative Concentrated NH White	Relative Concentrated POC
Maternal Education						
Less than 9th grade	203 (<1%)	22 (<1%)	2,744 (1%)	1,671 (1%)	1,235 (2%)	3,696 (2%)
9th through 11th grade	1,749 (2%)	235 (2%)	28,745 (8%)	16,062 (7%)	10,745 (15%)	38,205 (16%)
High school diploma or GED (12)	10,461 (11%)	1,643 (12%)	87,757 (26%)	60,433 (27%)	25,379 (35%)	86,136 (37%)
Some college or more	76,324 (78%)	10,087 (74%)	188,876 (56%)	121,805 (54%)	29,023 (40%)	82,043 (35%)
Missing	9,689 (10%)	1,613 (12%)	32,160 (9%)	26,953 (12%)	6,629 (9%)	23,130 (10%)
Pre-pregnancy hypertension						
No	89,157 (91%)	12,072 (89%)	304,675 (90%)	198,495 (87%)	65,158 (89%)	203,525 (87%)
Yes	1,174 (1%)	207 (2%)	5,668 (2%)	4,490 (2%)	1,691 (2%)	5,786 (2%)
Missing	8,095 (8%)	1,321 (10%)	29,939 (9%)	23,939 (11%)	6,162 (8%)	23,899 (10%)
Pre-pregnancy gestational diabetes						
No	89,809 (91%)	12,196 (90%)	307,842 (90%)	200,997 (89%)	66,144 (91%)	207,120 (89%)
Yes	522 (1%)	83 (1%)	2,501 (1%)	1,988 (1%)	705 (1%)	2,191 (1%)
Missing	8,095 (8%)	1,321 (10%)	29,939 (9%)	23,939 (11%)	6,162 (8%)	23,899 (10%)
Delivery Type						
C-section	32,178 (33%)	4,550 (33%)	106,437 (31%)	70,830 (31%)	23,936 (33%)	73,275 (31%)
Vaginal	59,189 (60%)	7,846 (58%)	206,949 (61%)	134,046 (59%)	43,127 (59%)	140,253 (60%)
Missing	7,059 (7%)	1,204 (9%)	26,896 (8%)	22,048 (10%)	5,948 (8%)	19,682 (8%)
Census Tract Urbanicity						
Urban Core/Suburban	98,336 (99%)	13,600 (100%)	277,930 (82%)	221,647 (98%)	30,036 (41%)	182,528 (78%)
Rural	90 (<1%)	0	62,352 (18%)	5,277 (2%)	42,975 (59%)	50,674 (22%)

Compared with the common referent of women living in a relative mixed-income, concentrated NH White neighborhood, there were 14.4 fewer SMM cases per 10,000 hospitalizations (95% CI: -20.8, -7.9; 95% CI: -29.8, 0.9) among women living in both concentrated affluent NH White and concentrated affluent POC neighborhoods (**Table 5.2**). Women living in concentrated poverty, NH White neighborhoods had a negligible excess of SMM cases per 10,000 (RD: 6.3, 95% CI: -1.4, 14.4) compared to the common referent. Women living in relative mixed-income and concentrated poverty POC neighborhoods had 24.3 excess SMM cases (95% CI: 18.8, 29.8) and 32.8 excess SMM cases (95% CI: 27.2, 38.4) per 10,000 hospitalizations, respectively. Sensitivity analyses using different exposure operationalizations and model specifications did not change conclusions about the magnitude of the joint effect (**Aim 3 Appendix**).

Table 5.2. Additive statistical interaction of census tract-level relative income inequality and racial segregation on SMM risk, NH Black and NH White women, ages 15-49 years, Georgia 2010-2019.

Relative Income Inequality	**Relative Racial Segregation**						RD (95%) for relative concentrated POC within strata of income inequality
	Relative Concentrated NH White			**Relative Concentrated POC**			
	N SMM/ Deliveries	SMM Rate per 10,000 (95% CI)	RD per 10,000 (95% CI)	N SMM/ Deliveries	SMM Rate per 10,000 (95% CI)	RD per 10,000 (95% CI)	
Relative Concentrated Affluence	781/98,426	79.3 (73.8, 84.9)	-14.4 (-20.8, -7.9)	108/13,600	79.4 (64.5, 94.3)	-14.4 (-29.6, 0.9)	0.1 (-15.9, 16.0)
Relative Mixed-Income	3,191/340,282	93.8 (90.5, 97.0)	0.0	2,680/226,924	118.1 (113.7, 122.5)	24.3 (18.8, 29.8)	24.3 (18.8, 29.8)
Relative Concentrated Poverty	731/73,011	100.1 (92.9, 107.4)	6.3 (-1.4, 14.4)	2,952/233,210	126.6 (122.0, 131.1)	32.8 (27.2, 38.4)	26.5 (17.9, 35.0)
RD (95% CI) for relative concentrated affluent income inequality within strata of racial segregation			-14.4 (-20.8, -7.9)			-38.7 (-54.3, -23.1)	
RD (95% CI) for relative concentrated poverty income inequality within strata of racial segregation			6.3 (-1.4, 14.4)			8.5 (2.1, 14.8)	
Measure of interaction on the additive scale (extremes):			26.4 (7.6, 43.8)				

Abbreviations: CI = confidence interval; NH = non-Hispanic; POC = persons of color; RD = rate difference; SMM = severe maternal morbidity

Within the strata of relative racial segregation, the SMM rates for mixed-income and relatively concentrated poverty neighborhoods were similar and notably higher than the SMM rates in relatively concentrated affluent neighborhoods (**Table 5.2**). Within strata of concentrated NH White neighborhoods, women living in affluent neighborhoods had 14.4 fewer SMM cases per 10,000 deliveries (95% CI: -20.8, -7.9) compared to mixed-income neighborhoods, while the excess risk was negligible for women living in concentrated poverty neighborhoods (RD: 6.3, 95%: -1.4, 14.4). (**Table 5.2**). Within strata of concentrated POC neighborhoods, women residing in affluent areas had 38.7 fewer SMM cases per 10,000 deliveries (95% CI: -54.3, -23.1) compared to women residing in relative mixed-income POC neighborhoods. Women living in POC neighborhoods with concentrated poverty had a negligible excess SMM risk (RD: 8.5, 95% CI: 2.1, 14.8) under the same referent.

Within strata of concentrated affluence, women living in concentrated POC neighborhoods had no increased risk of SMM compared to women living in NH White concentrated neighborhoods (RD: 0.1, 95% CI: -15.9, 16.0) (**Table 5.2**). The magnitude of excess risk was greater within the mixed-income strata, with women living in POC neighborhoods having 24.3 excess cases per 10,000 deliveries (95% CI: 18.8, 29.8) compared to women living in predominately NH White neighborhoods. This estimate was similar to estimates within the strata of concentrated poverty (RD: 26.5, 95% CI: 17.9, 35.0).

We estimated an additive interaction contrast of the extreme categories of relative racialized income inequality of 26.4 (95% CI: 7.6, 43.8) (**Table 5.2**). This IC estimate suggests evidence of positive interdependence on the additive scale. Thus, the joint effect of relative racialized income inequality was greater than what would be expected based on the sum of the separate effects of relative income inequality and racial segregation.

The Georgia 2010-2019 RD for SMM among NH Black women compared to NH White women was 57.2 events per 10,000 deliveries (95% CI: 53.0, 61.4) (**Table 5.3**). When stratifying SMM events by individual-level maternal race, there were smaller magnitude

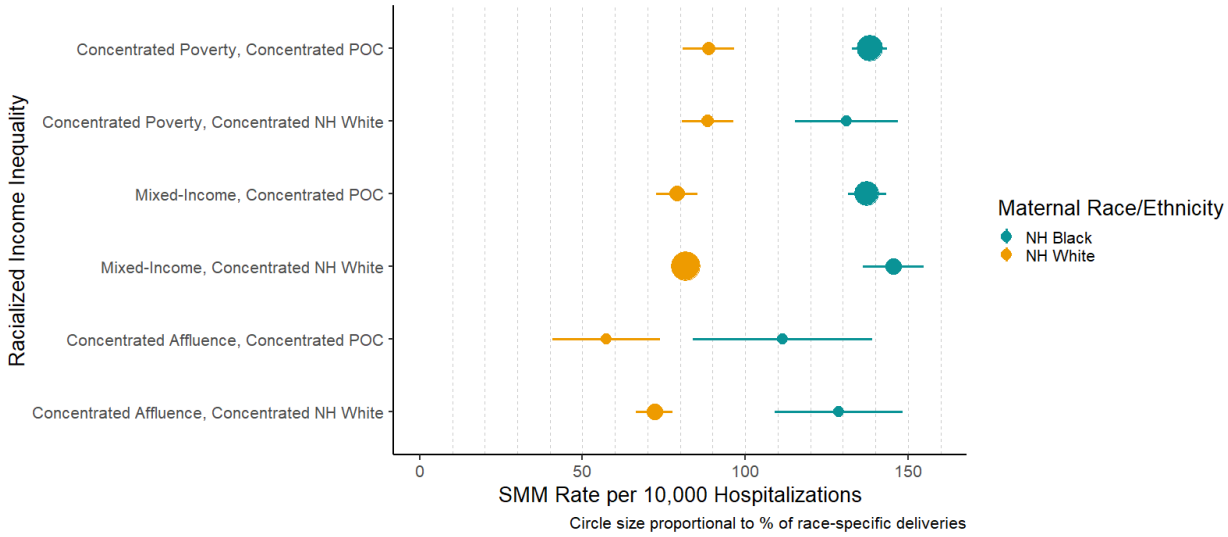
gradients in the individual-level maternal race-specific SMM rates and Black-White rate differences in SMM incidence between strata of racialized income inequality (**Table 5.3; Figure 5.1**). Further, estimates had less precision than the maternal-race-pooled rates (**Table 5.2 & 5.3**). For NH Black women, the SMM rates trended highest for women living in mixed-income (concentrated NH White: 145.4 per 10,000 deliveries, 95% CI: 136.2, 154.7; concentrated POC: 137.4 per 10,000 deliveries (95% CI: 131.5, 143.2)) and concentrated poverty POC neighborhoods (138.2, 95% CI: 132.8, 143.7). For NH Black women, the lowest magnitude of race-specific rate estimates was estimated for women living in affluent POC neighborhoods (111.4 per 10,000 deliveries, 95% CI: 83.8, 138.9). For NH White women, SMM rates trended highest for women living in concentrated poverty neighborhoods (88 per 10,000 deliveries, 95% CI: 81, 97) and lowest for women living in affluent neighborhoods (Concentrated NH White: 72.1 per 10,000 deliveries (95% CI: 66.4, 77.7); Concentrated POC: 57.3 per 10,000 deliveries (95% CI: 40.8, 73.8).

Table 5.3. Race-specific SMM rates & Black-White rate difference estimates within relative income inequality and racial segregation strata.

Exposure Strata		NH Black Women			NH White Women			Black-White Rate Difference per 10,000
		N SMM/ Deliveries	SMM Rate per 10,000	% Deliveries	N SMM/ Deliveries	SMM Rate per 10,000	% Deliveries	
Georgia		5,975/ 432,817	138.0 (134.6, 141.5)		4,468/ 552,636	80.8 (78.5, 83.2)		57.2 (53.0, 61.4)
Relative Income Inequality	**Racial Segregation**							
Concentrated Affluence	Concentrated NH White	163/ 12,660	128.8 (109.1, 148.4)	3%	618/ 85,766	72.1 (66.4, 77.7)	16%	56.7 (37.1, 78.0)
Concentrated Affluence	Concentrated POC	62/ 5,567	111.4 (83.8, 138.9)	1%	46/ 8,033	57.3 (40.8, 73.8)	1%	54.1 (23.0, 87.7)
Mixed Income	Concentrated NH White	934/ 64,222	145.4 (136.2, 154.7)	15%	2,257/ 276,060	81.8 (78.4, 85.1)	50%	63.7 (54.0, 73.7)
Mixed Income	Concentrated POC	2,088/ 152,009	137.4 (131.5, 143.2)	35%	592/ 74,915	79.0 (72.7, 85.4)	14%	58.3 (49.7, 66.9)
Concentrated Poverty	Concentrated NH White	262/ 19,979	131.1 (115.4, 146.9)	5%	469/ 53,032	88.4 (80.5, 96.4)	10%	42.7 (25.5, 60.8)
Concentrated Poverty	Concentrated POC	2,466/ 178,380	138.2 (132.8, 143.7)	41%	486/ 54,830	88.6 (80.8, 96.5)	10%	49.6 (39.9, 59.0)

Abbreviations: CI = confidence interval; NH = non-Hispanic; POC = persons of color; RD = rate difference; SMM = severe maternal morbidity

Figure 5.1. NH Black and NH White race-specific SMM rates per 10,000 by relative income inequality and racial segregation strata, scaled by the race-specific proportion of women residing in neighborhood.



The proportion of deliveries among women living in each neighborhood differed by individual-level maternal race (**Table 5.3; Figure 5.1**). NH Black women had a notably higher probability of living in relatively concentrated poverty neighborhoods, while NH White women had a higher probability of living in relatively concentrated affluent neighborhoods.

Discussion

Structural determinants of health, including racism and classism, have socially and spatially structured the opportunities and privileges available to some women at the price of exclusion for others. Our study provides evidence that women living in relatively concentrated communities of color with concentrated poverty – communities marked by systematic economic, political, and social disinvestment - had an increased risk of SMM compared to women living in relatively concentrated NH White mixed-income communities. At the same time, women living in affluent communities had a lower risk of SMM compared to women living in mixed-income NH White neighborhoods, highlighting the economic privileges of improved maternal health outcomes. Further, evidence of additive positive interdependence emphasized the superadditive effect of income inequality and racial segregation, which highlights the

inequitable distribution of conferred harms and advantages through processes of structural classism and racism in combination.

Consistent with prior SMM studies, Black women in Georgia from 2010-2019 had an increased risk of SMM compared to NH White women. Individual-level racially stratified estimates had reduced precision of the estimated racialized income inequality joint effect. Yet, a gradient of SMM risk remained; Within strata of individual-level maternal race, SMM rates trended lower for NH White and NH Black women residing in concentrated affluent communities and higher for NH White and Black women living in mixed-income and concentrated poverty neighborhoods.

There was a notable difference in the exposure distribution by individual-level maternal race. NH Black women had a greater probability of exposure to racialized concentrated poverty neighborhoods (41% vs. 10%), while NH White women had a greater probability of exposure to racialized affluent neighborhoods (16% vs. 3%). Despite the small magnitude of SMM race-specific risk differences across racialized income inequality strata, the large number of women that are differentially distributed by race across neighborhood racialized economic extremes has the potential for meaningful public health impact. Ultimately, the results are consistent with our conceptual framework that opportunities and disadvantages in community environments shaped by structural processes of racism and classism further shape SMM risk.

These findings are also consistent with prior research using ICE for race and income, which compares the more extreme ends of socioeconomic and racial polarization (e.g., the highest quintile of concentrated NH Black poverty and highest quintile of concentrated NH White affluence). Dyer et al. (2021) estimated that Louisiana women living in the highest tertile of ICE scores (concentrated poverty in concentrated Black neighborhoods) had 1.7 (95% CI: 1.0, 2.9) times risk of maternal mortality compared to women living in the lowest tertile of ICE (concentrated predominately White, affluent neighborhoods).[88] Similar to our study, the

authors did not detect the presence of significant statistical interaction of racialized income inequality and maternal mortality risk by individual-level maternal race.[88] Still, they noted that Black women had a higher probability of exposure to racialized concentrated poverty neighborhoods.[88] Specific to SMM, Janevic et al. (2020) estimated that in NYC, women living in the highest quintile of concentrated NH Black communities in poverty had an excess risk of 170 SMM events (95% CI: 140, 190), compared to women living in neighborhoods of concentrated NH White affluence.[90] The excess risk among concentrated racial and economic extremes was substantially larger than what was observed in our study (RD: 47.3 SMM per 10,000). This may be due to several study differences, including variation in the study population (e.g., the inclusion of additional ethnoracial groups), contextual factors (i.e., US South entire state vs. northern city), racialized income inequality measurement (e.g., use of ICE), choice of exposure referent (e.g., concentrated poverty vs. mixed/middle income), and alternate SMM case definitions (e.g., inclusion/exclusion of postpartum hospitalizations).[90]

Our work further expands upon this prior research by using a definition relative to the study area, as well as the investigation of the other relative income inequality and racial segregation categories (i.e., concentrated NH White poverty and affluence in communities of color). Notably, the SMM risk in the pooled analysis was similarly low among women living in affluent POC and NH White neighborhoods, highlighting the community-level benefits of concentrated affluence on decreased SMM risk. Yet, only 1% of births among NH Black women occurred in affluent POC neighborhoods and 3% of births among NH Black women in affluent NH White neighborhoods, highlighting the differential social stratification of exposure to potential health-promoting privileges for NH Black compared to NH White women.

There are a number of implications of this work. Investigating the statistical interaction of relative income inequality and racial segregation advanced our understanding of how different structural determinants may produce excess SMM risk for some women and decreased

risk for others. This is particularly important in the unique context of the state of Georgia, which has a long history of structural racism, substantial geographic and socioeconomic variation among NH Black women, and income inequality among NH White women. Additional implications of this work include identifying specific neighborhood targets characterized by increased SMM risk for further investigation and intervention. The finding that both NH Black and NH White women living in a racially concentrated area of relative poverty had higher SMM race-specific rates is not surprising, given that concentrated poverty places are often characterized by limited financial and political resources that harm health for all.[93,94,97] The recognition that NH Black and NH White women are unequally exposed to disadvantaged and privileged environments further aids in the health equity implication of targeting these localities.

Several limitations should be considered. The validity of the estimated joint effect relies on strong assumptions that are unlikely to be fully met and difficult to evaluate. These include no unmeasured confounding, correct model specification, positivity, consistency, and no measurement error. We explored the sensitivity of RD estimates under varying exposure definitions, which did not meaningfully change conclusions about the presence of positive interdependence (**Aim 3 Appendix**). However, violation of the consistency assumption – particularly, whether the exposure definition for mixed-income neighborhoods is well-defined enough to result in a consistent potential outcome under a counterfactual framework – cannot be empirically tested. We used a conceptually strong case definition of SMM (**Chapter 3**). However, there are still misclassification errors in the identification of SMM that may further be differential by place and race.[112,113] Lastly, our ability to investigate race-specific risks and Black-White disparities between racialized income inequality strata was limited by substantial estimate imprecision due to SMM being a rare outcome. Despite the use of 10 years of data, our study was not sufficiently powered to detect individual-level maternal race differences as part of a three-way interaction with relative income inequality and racial segregation.

Despite these limitations, this study adds to the small but growing literature on structural determinants of SMM in a specific high-risk geographic locality in the US South. Our results suggest that processes of structural classism and racism operating through relative income inequality and racial segregation in combination (i.e., racialized income inequality) produces greater SMM risk than we would expect from relative income inequality and racial segregation alone. Future research should seek to investigate other measures of racialized income inequality to continue contextualizing the processes of racism and classism operating through spatial and social stratification of social determinants of health. This includes investigating other attributes of structural racism and classism processes (e.g., mass incarceration), as well as resiliency in these communities to better understand the excess SMM risk among NH Black women and women living in the southern US. Ultimately, sustained research on structural determinants of SMM incidence and Black-White disparities in SMM incidence is critical for advancing maternal health equity.

Chapter 6: Conclusions

Summary of findings and recommendations

Despite the longstanding awareness of racial and geographic inequality in maternal health outcomes, actions to eliminate the excess SMM risk among NH Black women and women living in the southern US have been insufficient. The studies comprising this dissertation sought to advance maternal health equity by conducting rigorous epidemiologic research on SMM racial disparities using population-based surveillance data. We first identified a case definition for use in SMM racial disparities research (**Chapter 3**). We then added to our understanding of the epidemiology of Black-White racial disparities in SMM risk at the individual level by investigating the proportion of the absolute disparity mediated through hypertensive disorders of pregnancy (HDP) (**Chapter 4**). In the final aim, we advanced our understanding of the epidemiology of SMM risk and Black-White disparities at the area level by estimating the joint effect of relative income inequality and racial segregation (**Chapter 5**).

Specifically, in aim 1, we investigated how the choice of SMM case definition changes conclusions about the magnitude of the Black-White racial disparity in SMM incidence. We described the magnitude of the disparity using five SMM case definitions, which were uniquely defined from a combination of three modifications. These modifications were the exclusion of the blood transfusion indicator, the inclusion of postpartum hospitalizations, and the exclusion of hospitalization length of stay less than the 90th percentile. Results suggested that the length-of-stay modification was the largest source of differences in conclusions about the magnitude of the Black-White racial disparity on the relative scale. Conclusions on the absolute scale varied across all modifications. The results of this study emphasize the importance of transparency in definition selection since conclusions about the magnitude of the disparity varied by case definition choice. Given this finding, we described the strengths and limitations of each case definition under a framework of CDC-defined attributes of quality surveillance systems. A critical contribution of this aim is the recommendation to use the case definition that includes

postpartum hospitalizations and excludes the blood transfusion indicator in surveillance and etiologic research of SMM racial disparities. This recommendation was based on empirical evidence and guided by theory-driven perspectives of surveillance goals with a health equity lens.

The second aim of this dissertation sought to estimate the proportion of the Black-White disparity in SMM risk operating through HDP. We estimated that NH Black women experienced an excess risk of 55.7 SMM events per 10,000 delivery hospitalizations compared to NH White women. After blocking the pathways through HDP, the excess risk among NH Black women decreased to 41.1 SMM events. If mediation analysis and causal effect assumptions hold, the estimated CDE in comparison to the total effect suggested that 26% of the Black-White disparity would be eliminated if HDP was completely prevented. The complete elimination of HDP is an unlikely scenario. Still, this estimate highlights that intervening on HDP directly – and more broadly, the paths in which HDP operates – may be an effective opportunity to reduce Black-White racial disparities in SMM risk (e.g., intervention on both clinical and social determinants of health). Hypertension has well-documented associations with social determinants of health that are socially structured by racism and classism, such as access to quality primary healthcare, healthy food environments, safer neighborhoods, and quality education. Thus, the results of our analysis may allow us to identify opportunities to prevent HDP and thus improve maternal health equity based on what we have learned from existing literature on the epidemiology of pregnancy-related cardiometabolic risk factors. Importantly, our results also indicate that roughly three quarters of the disparity remains unexplained through pathways not mediated by HDP. This finding emphasizes the need for additional research on potential mediators of the Black-White racial disparity in SMM risk beyond HDP.

In aim 3, we estimated the joint effect of relative income inequality and racial segregation on SMM incidence. Aim 3 findings indicated that processes of structural classism

and racism operating through relative income inequality and racial segregation in combination (i.e., racialized income inequality) produces greater SMM risk than what we would expect from relative income inequality and racial segregation alone. We further highlighted that NH Black women had a higher probability of exposure to systematically disadvantaged neighborhoods (i.e., concentrated poverty, POC communities). In comparison, NH White women had a higher probability of exposure to neighborhoods with greater privilege (i.e., concentrated affluence, NH white communities). Thus, targeting social determinants of health in communities with greater disadvantage could have meaningful impacts for reducing SMM risk overall, and potentially Black-White racial disparities in SMM risk. However, given the imprecision of estimates, additional research is needed to support conclusions about the relationship of neighborhood racialized income inequality and Black-White racial disparities in SMM risk. Ultimately, the results of this study add to the limited literature on structural determinants of maternal health, specifically relative racialized income inequality and SMM risk. We further present evidence of this association in a high-risk population; in particular, the southern US, a region marked by a history of structural racism, substantial geographic and socioeconomic variation among Black women, and income inequality among NH White women.

Strengths and limitations

A common strength across all aims is the richness of data sources over several years. We used over ten years of individual-level data for all Georgia hospital discharge records with a pregnancy or delivery diagnosis/procedure code, providing comprehensive coverage of SMM outcomes for NH Black and White women. Further, we linked hospital discharge records with Georgia birth and fetal death certificates, incorporating additional maternal sociodemographic and delivery characteristics. Given access to both data sources, we described the study population by comparing the complete and unlinked hospital discharge records (**Chapter 2**). This comparison improved our confidence in estimates using the complete data source by

contextualizing potential epidemiologic biases that would result from the exclusion of unlinked records.

An additional strength was the use of advanced epidemiologic and statistical theory and methods to address the identified research gaps and provide recommendations for improved epidemiologic research on Black-White racial disparities in SMM risk. In aim 2, these included causal mediation analysis for decomposition of the Black-White racial disparity in SMM incidence. In aim 3, the use of generalized estimating equations (GEE) and eigenvector spatial filtering (ESF) methods allowed for evaluating the statistical dependence of SMM outcomes within and between neighborhoods that may violate statistical modeling assumptions.

Limitations were discussed specific to each aim in the relevant chapter. However, two limitations were consistent across aims that merit further discussion. The potential misclassification of SMM in hospital discharge billing records remains a significant threat to validity that will continue to be challenging to investigate and remediate until a consensus case definition is achieved and we have a more suitable data system for surveillance. In the absence of validation studies across the range of SMM case definitions, or any validation studies stratified by race, we could not meaningfully evaluate the influence of misclassification errors in this dissertation using quantitative bias analysis methods. Additionally, many (and at times, very strong) assumptions are needed to validly estimate the effects in this dissertation. For example, the decomposition models used in aim 2 rely on the validity of assumptions specific to mediation analyses, in addition to standard assumptions required for estimating a causal effect. For both aims 2 and 3, there are consistency violations in decomposing the effect of race (a proxy for the embodiment of the effects of structural racism) and neighborhood racialized income inequality (a proxy for structural racism and classism processes measured as neighborhood racial composition, median household income, and the proportion of individuals living below the federal poverty line). Although imperfect alone, the use of race and racial

segregation measures are critical for capturing structural determinants of health under the goal of advancing maternal health equity. We sought to transparently discuss our assumptions and the potential consequences of assumption violations. However, the conceptualization of "race" and the measurement of structural determinants of health remains a challenge in causal effect estimation of SMM racial disparities.

Future directions

We identified new areas for future research in addressing the aims of this dissertation. Consensus must be achieved in the operationalization of the SMM case definition. With clarity on what constitutes an SMM event, quantitative validation studies can be conducted for SMM measurement given currently available data sources (i.e., hospital discharge records). Further, validation studies tied to specific SMM case definitions are needed to evaluate these potential misclassification biases, particularly those stratified by race and hospital. Until consensus is reached and validation studies are conducted, additional exploration of how conclusions are altered by case definition choice is warranted to contextualize surveillance and etiologic studies of SMM Black-White disparities. This may include investigating differences in conclusions by case definition about disparities over time. The results of aim 1 further emphasize that the ideal scenario is establishing an improved SMM surveillance system that better captures an agreed-upon operationalized SMM case definition. This would allow for more explicit identification of severe maternal morbidity events distinguishable from maternal morbidity.

If our assumptions hold, we estimated in aim 2 that at least 75% of the disparity remains unexplained through pathways not involving HDP. Thus, further investigation of potentially modifiable factors downstream from structural racism is warranted. The investigation of more proximal factors may include other individual-level comorbidities (e.g., diabetes mellitus) or specific healthcare access or intervention programs (e.g., expanded prenatal care, home-blood pressure monitoring). Area-level social determinants of health should also be investigated

directly to better understand the pathways by which intervention would reduce the excess risk of HDP and SMM among NH Black women. These might include the role of OBGYN and food deserts, quality housing, or neighborhood exposure to violence. Future health equity investigations of SMM applying decomposition models should consider using more direct measures of structural racism as the exposure, beyond individual-level race as a proxy measure for racism.

Future directions from aim 3 include investigating mediators of the relative racialized income inequality and SMM association. An additional focus should be on evaluating whether drivers of SMM risk are the same for localities with historically consistent racially concentrated poverty/affluence categorization and localities with changing categorization (e.g., through gentrification) given the changing spatial processes in these communities over time. Lastly, relative income inequality and racial segregation are just two measured consequences of structural racism and classism. Thus, additional research on other attributes of racialized income inequality can improve our understanding of the relationship of these structural determinants of health and SMM risk. These next steps will dive deeper into the relevance of relative racialized income inequality as an indicator for structural racism and classism in SMM surveillance and etiologic research.

Appendices

Identifying SMM in Hospital Discharge Data

Table A1. SMM Indicator ICD-9-CM and ICD-10-CM diagnosis and procedure codes, CDC/Alliance for Innovation in Maternal Health (AIM) v6-27-2020.[32,111]

Outcome	ICD-9-CM	ICD-10-CM
Acute myocardial infarction	410.xx	I21.xx, I22.x
Acute renal failure	584.5-584.9, 669.3x	N17.x, O90.4
Adult respiratory distress syndrome	518.5x, 518.81 518.82 518.84, 799.1	J80, J95.1, J95.2, J95.3, J95.82x, J96.0x, J96.2x R09.2
Air and Thrombotic Embolism	415.1x, 673.0x, 673.2x, 673.3x, 673.8x	I26.x, O88.0x, O88.2x, O88.3x, O88.8x
Amniotic fluid embolism	673.1x	O88.1x
Aneurysm	441.xx	I71.xx, I79.0
Blood products transfusion	99.0x	30230H0, 30230K0, 30230L0, 30230M0, 30230N0, 30230P0, 30230R0, 30230T0, 30230H1, 30230K1, 30230L1, 30230M1, 30230N1, 30230P1, 30230R1, 30230T1, 30233H0, 30233K0, 30233L0, 30233M0, 30233N0, 30233P0, 30233R0, 30233T0, 30233H1, 30233K1, 30233L1, 30233M1, 30233N1, 30233P1, 30233R1, 30233T1, 30240H0, 30240K0, 30240L0, 30240M0, 30240N0, 30240P0, 30240R0, 30240T0, 30240H1, 30240K1, 30240L1, 30240M1, 30240N1, 30240P1, 30240R1, 30240T1, 30243H0, 30243K0, 30243L0, 30243M0, 30243N0, 30243P0, 30243R0, 30243T0, 30243H1, 30243K1, 30243L1, 30243M1, 30243N1, 30243P1, 30243R1, 30243T1, 30250H0-30250T1, 30253H0-30253T1, 30260H0-30260T1, 30263H0-30263T1

Outcome	ICD-9-CM	ICD-10-CM
Cardiac arrest/ventricular fibrillation	427.41, 427.42, 427.5	I46.x, I49.0x
Conversion of cardiac rhythm	99.6x	5A2204Z, 5A12012
Cardiogenic shock	785.50, 785.51, 785.59	R57.x, T81.10XA, T81.11XA, T81.19XA
Disseminated intravascular coagulation	286.6, 286.9, 666.3x	D65, D68.8, D68.9, O72.3
Eclampsia	642.6x	O15. X
Heart failure/arrest during surgery or procedure	997.1	I97.12x, I97.13x, I97.710, I97.711
Hysterectomy	68.3x–68.9x	0UT90ZZ, 0UT94ZZ, 0UT97ZZ, 0UT98ZZ, 0UT9FZZ, 0UT90ZL
Puerperal cerebrovascular disorders	430.xx, 431.xx, 432.xx, 433.xx, 434. xx, 436.xx, 437.xx, 671.5x, 674.0x, 997.02	I60.xx- I68.xx, O22.51-O22.53, O873, I97.81x, I97.82x
Pulmonary oedema/acute heart failure	518.4, 428.0, 428.1, 428. 21, 428.23, 428.31, 428.33, 428.41, 428.43	J81.0, I50.1, I50.20, I50.21, I50.23, I50.30, I50.31, I50.33, I50.40, I50.41, I50.43, I50.9
Severe anesthesia complications	668.0x, 668.1x, 668.2x	O74.0, O74.1, O74.2, O74.3, O89.0x, O89.1, O89.2
Sepsis	038.xx, 995.91, 995.92, 670.2x	O85, O86.04, T80.211A, T81.4XXA, T81.44xx, R65.20, A40.x, A41.x, A32.7
Shock (excluding cardiogenic)	669.1x, 785.5x, 995.0, 995.4, 998.0x	O75.1, R57.x, R65.21, T78.2XXA, T88.2 XXA, T88.6XXA, T81.10XA, T81.11XA, T81.19XA
Sickle cell disease with crisis	282.42, 282.62, 282.64, 282.69	D57.0x, D57.21x, D57.41x, D57.81x
Temporary tracheostomy	31.1	0B110Z4, 0B110F4, 0B113Z4, 0B113F4, 0B114Z4, 0B114ZF4

Outcome	ICD-9-CM	ICD-10-CM
Ventilation	93.90, 96.01, 96.02, 96.03, 96.05	5A1935Z, 5A1945Z, 5A1955Z

Table A2. ICD-9-CM and ICD-10-CM diagnosis and procedure codes for identification of delivery hospitalizations, CDC/AIM v6-27-2020.

Categories	ICD-9-CM	ICD-10-CM
Include		
Delivery Diagnoses	V27, 650, 669.7, 669.71	Z37x, O75.82, O80, O82
Delivery DRGs	765, 766, 767, 768, 774, 775	765-768, 774-775, 783-788, 796-798, 805-807
Delivery Procedures	72.x, 73.22, 73.59, 73.6, 74.x	10D00Z0-10D00Z2, 10D07Z3-0D07Z8, 10E0XZZ
Exclude		
Diagnoses for Exclusion	630-639	O00.x, O01.x, O02.x, O03.x, O04.x, O07.x, O08.x
Procedures for Exclusion	69.01, 69.51, 74.91, 75.0	Any PR starting with '10A0'. 10A00ZZ, 10A03ZZ, 10A04ZZ, 10A07Z6, 10A07ZW, 10A07ZX, 10A07ZZ, 10A08ZZ

Aim 1 Appendix

SMM rate and Black-White disparity under alternate case definitions #6-8

Table A3. Three remaining SMM case definitions (#6-#8) based on the three modifications to the CDC SMM indicator list.

Case Definition Key	Excluding Blood Transfusion (BT)	Including Postpartum (PP)	Excluding LOS <90th percentile
#6) Include PP		X	
#7) Exclude LOS <90th percentile			X
#8) Include PP & exclude LOS <90th percentile		X	X

Table A4. The overall and race-specific SMM rates, the absolute and relative Black-White disparity estimates, and 95% confidence intervals for case definitions #6-8, Georgia NH Black and NH White women, ages 15-49, 2006-2019.

Case Definition	Overall Rate*	NH Black Rate*	NH White Rate*	Black-White Rate Difference*	Black-White Rate Ratio
#6) Include PP	201.7 (199.4, 204.0)	268.4 (264.4, 272.5)	151.0 (148.3, 153.6)	117.4 (112.7, 122.3)	1.8 (1.8, 1.8)
#7) Exclude LOS <90th%	146.4 (144.5, 148.4)	199.4 (195.9, 202.8)	106.2 (104.0, 108.4)	93.2 (89.0, 97.3)	1.9 (1.9, 1.9)
#8) Include PP & exclude LOS <90th%	155.7 (153.6, 157.7)	212.6 (209.0, 216.2)	112.4 (110.1, 114.7)	100.2 (95.9, 104.4)	1.9 (1.9, 1.9)

Abbreviations: BT = Blood transfusion; PP = Postpartum; RD = Rate Difference, RR = Rate Ratio
Rate and RD per 10,000 deliveries
***RD = (NH Black Rate) – (NH White Rate)*
***RR = (NH Black Rate)/(NH White Rate)*

SMM indicators race-stratified by case definition

Table A5. Race-stratified number of SMM cases and proportion of SMM cases by indicator for case definition #1, Georgia 2006-2019.

Case Definition #1) No Modifications						
	NH Black N = 14,067			NH White N = 10,605		
Rank	Indicator	Number	%	Indicator	Number	%
1	18. Blood products transfusion	9,909	70	18. Blood products transfusion	6,900	65
2	8. Disseminated intravascular coagulation	1,956	14	8. Disseminated intravascular coagulation	2,059	19
3	3. Acute renal failure	918	7	19. Hysterectomy	699	7
4	4. Adult respiratory distress syndrome	806	6	4. Adult respiratory distress syndrome	567	5
5	19. Hysterectomy	678	5	3. Acute renal failure	423	4
6	12. Pulmonary edema / Acute heart failure	524	4	12. Pulmonary edema / Acute heart failure	322	3
7	14. Sepsis	501	4	14. Sepsis	298	3
8	16. Sickle cell disease with crisis	373	3	9. Eclampsia	258	2
9	9. Eclampsia	364	3	15. Shock	246	2
10	15. Shock	331	2	11. Puerperal cerebrovascular disorders	186	2
11	17. Air and thrombotic embolism	212	2	17. Air and thrombotic embolism	145	1
12	11. Puerperal cerebrovascular disorders	198	1	21. Ventilation	99	1
13	21. Ventilation	162	1	13. Severe anesthesia complications	70	1
14	6. Cardiac arrest / ventricular fibrillation	96	1	10. Heart failure / arrest during surgery or procedure	54	1
15	13. Severe anesthesia complications	79	1	6. Cardiac arrest / ventricular fibrillation	40	<1
16	10. Heart failure / arrest during surgery or procedure	52	<1	7. Conversion of cardiac rhythm	34	<1
17	7. Conversion of cardiac rhythm	49	<1	5. Amniotic fluid embolism	29	<1
18	5. Amniotic fluid embolism	32	<1	20. Temporary tracheostomy	21	<1
19	20. Temporary tracheostomy	29	<1	1. Acute myocardial infarction	14	<1
20	1. Acute myocardial infarction	24	<1	2. Aneurysm	11	<1

Case Definition #1) No Modifications						
	NH Black N = 14,067			NH White N = 10,605		
Rank	Indicator	Number	%	Indicator	Number	%
21	2. Aneurysm	9	<1	16. Sickle cell disease with crisis	2	<1

Table A6. Race-stratified number of SMM cases and proportion of SMM cases by indicator for case definition #2, Georgia 2006-2019.

Case Definition #2) Exclude BT						
	NH Black N = 5,597			NH White N = 4,538		
Rank	Indicator	Number	%	Indicator	Number	%
1	8. Disseminated intravascular coagulation	1,956	35	8. Disseminated intravascular coagulation	2,059	45
2	3. Acute renal failure	918	16	19. Hysterectomy	699	15
3	4. Adult respiratory distress syndrome	806	14	4. Adult respiratory distress syndrome	567	12
4	19. Hysterectomy	678	12	3. Acute renal failure	423	9
5	12. Pulmonary edema / Acute heart failure	524	9	12. Pulmonary edema / Acute heart failure	322	7
6	14. Sepsis	501	9	14. Sepsis	298	7
7	16. Sickle cell disease with crisis	373	7	9. Eclampsia	258	6
8	9. Eclampsia	364	7	15. Shock	246	5
9	15. Shock	331	6	11. Puerperal cerebrovascular disorders	186	4
10	17. Air and thrombotic embolism	212	4	17. Air and thrombotic embolism	145	3
11	11. Puerperal cerebrovascular disorders	198	4	21. Ventilation	99	2
12	21. Ventilation	162	3	13. Severe anesthesia complications	70	2
13	6. Cardiac arrest / ventricular fibrillation	96	2	10. Heart failure / arrest during surgery or procedure	54	1
14	13. Severe anesthesia complications	79	1	6. Cardiac arrest / ventricular fibrillation	40	1
15	10. Heart failure / arrest during surgery or procedure	52	1	7. Conversion of cardiac rhythm	34	1
16	7. Conversion of cardiac rhythm	49	1	5. Amniotic fluid embolism	29	1
17	5. Amniotic fluid embolism	32	1	20. Temporary tracheostomy	21	<1
18	20. Temporary tracheostomy	29	1	1. Acute myocardial infarction	14	<1
19	1. Acute myocardial infarction	24	<1	2. Aneurysm	11	<1
20	2. Aneurysm	9	<1	16. Sickle cell disease with crisis	2	<1

Table A7. Race-stratified number of SMM cases and proportion of SMM cases by indicator for case definition #3, Georgia 2006-2019.

Case Definition #3) Excluding BT & Include PP						
	NH Black N = 8,277			NH White N = 6,328		
Rank	Indicator	Number	%	Indicator	Number	%
1	8. Disseminated intravascular coagulation	1,967	24	8. Disseminated intravascular coagulation	2,075	33
2	3. Acute renal failure	952	12	19. Hysterectomy	709	11
3	4. Adult respiratory distress syndrome	840	10	4. Adult respiratory distress syndrome	584	9
4	19. Hysterectomy	682	8	3. Acute renal failure	439	7
5	12. Pulmonary edema / Acute heart failure	562	7	12. Pulmonary edema / Acute heart failure	336	5
6	14. Sepsis	527	6	14. Sepsis	314	5
7	16. Sickle cell disease with crisis	391	5	9. Eclampsia	266	4
8	9. Eclampsia	389	5	15. Shock	254	4
9	15. Shock	340	4	11. Puerperal cerebrovascular disorders	197	3
10	17. Air and thrombotic embolism	246	3	17. Air and thrombotic embolism	156	2
11	11. Puerperal cerebrovascular disorders	242	3	21. Ventilation	101	2
12	21. Ventilation	170	2	13. Severe anesthesia complications	71	1
13	6. Cardiac arrest / ventricular fibrillation	102	1	10. Heart failure / arrest during surgery or procedure	54	1
14	13. Severe anesthesia complications	83	1	6. Cardiac arrest / ventricular fibrillation	44	1
15	7. Conversion of cardiac rhythm	54	1	7. Conversion of cardiac rhythm	36	1
16	10. Heart failure / arrest during surgery or procedure	53	1	5. Amniotic fluid embolism	29	<1
17	1. Acute myocardial infarction	36	<1	20. Temporary tracheostomy	24	<1
18	5. Amniotic fluid embolism	32	<1	1. Acute myocardial infarction	21	<1
19	20. Temporary tracheostomy	29	<1	2. Aneurysm	11	<1
20	2. Aneurysm	10	<1	16. Sickle cell disease with crisis	2	<1

Table A8. Race-stratified number of SMM cases and proportion of SMM cases by indicator for case definition #4, Georgia 2006-2019.

Definition #4) Excluding BT & LOS < 90th percentile						
	NH Black N = 3,959			NH White N = 2,652		
Rank	Indicator	Number	%	Indicator	Number	%
1	8. Disseminated intravascular coagulation	1,056	27	8. Disseminated intravascular coagulation	795	30
2	3. Acute renal failure	807	20	19. Hysterectomy	699	26
3	4. Adult respiratory distress syndrome	707	18	4. Adult respiratory distress syndrome	490	18
4	19. Hysterectomy	678	17	3. Acute renal failure	351	13
5	14. Sepsis	432	11	14. Sepsis	250	9
6	12. Pulmonary edema / Acute heart failure	373	9	12. Pulmonary edema / Acute heart failure	236	9
7	16. Sickle cell disease with crisis	323	8	15. Shock	214	8
8	15. Shock	296	7	9. Eclampsia	154	6
9	9. Eclampsia	247	6	21. Ventilation	99	4
10	21. Ventilation	162	4	17. Air and thrombotic embolism	86	3
11	17. Air and thrombotic embolism	155	4	11. Puerperal cerebrovascular disorders	75	3
12	11. Puerperal cerebrovascular disorders	133	3	7. Conversion of cardiac rhythm	34	1
13	6. Cardiac arrest / ventricular fibrillation	85	2	13. Severe anesthesia complications	31	1
14	7. Conversion of cardiac rhythm	49	1	5. Amniotic fluid embolism	25	1
15	13. Severe anesthesia complications	44	1	6. Cardiac arrest / ventricular fibrillation	25	1
16	10. Heart failure / arrest during surgery or procedure	31	1	20. Temporary tracheostomy	21	1
17	20. Temporary tracheostomy	29	1	10. Heart failure / arrest during surgery or procedure	19	1
18	5. Amniotic fluid embolism	24	1	1. Acute myocardial infarction	11	<1
19	1. Acute myocardial infarction	20	1	2. Aneurysm	5	<1
20	2. Aneurysm	7	<1	16. Sickle cell disease with crisis	2	<1

Table A9. Race-stratified number of SMM cases and proportion of SMM cases by indicator for case definition #5, Georgia 2006-2019.

Case Definition #5) All modifications						
	NH Black N = 4,795			NH White N = 3,163		
Rank	Indicator	Number	%	Indicator	Number	%
1	8. Disseminated intravascular coagulation	1,064	22	8. Disseminated intravascular coagulation	803	25
2	3. Acute renal failure	821	17	19. Hysterectomy	705	22
3	4. Adult respiratory distress syndrome	724	15	4. Adult respiratory distress syndrome	495	16
4	19. Hysterectomy	680	14	3. Acute renal failure	356	11
5	14. Sepsis	445	9	14. Sepsis	258	8
6	12. Pulmonary edema / Acute heart failure	389	8	12. Pulmonary edema / Acute heart failure	242	8
7	16. Sickle cell disease with crisis	331	7	15. Shock	218	7
8	15. Shock	301	6	9. Eclampsia	159	5
9	9. Eclampsia	261	5	21. Ventilation	99	3
10	17. Air and thrombotic embolism	167	3	17. Air and thrombotic embolism	90	3
11	21. Ventilation	164	3	11. Puerperal cerebrovascular disorders	78	2
12	11. Puerperal cerebrovascular disorders	149	3	7. Conversion of cardiac rhythm	35	1
13	6. Cardiac arrest / ventricular fibrillation	88	2	13. Severe anesthesia complications	32	1
14	7. Conversion of cardiac rhythm	51	1	6. Cardiac arrest / ventricular fibrillation	26	1
15	13. Severe anesthesia complications	45	1	5. Amniotic fluid embolism	25	1
16	10. Heart failure / arrest during surgery or procedure	31	1	20. Temporary tracheostomy	23	1
17	20. Temporary tracheostomy	29	1	10. Heart failure / arrest during surgery or procedure	19	1
18	5. Amniotic fluid embolism	24	1	1. Acute myocardial infarction	13	<1
19	1. Acute myocardial infarction	23	<1	2. Aneurysm	5	<1
20	2. Aneurysm	8	<1	16. Sickle cell disease with crisis	2	<1

Aim 2 Appendix

ICD-9/10-CM codes for HDP and Comorbidities

Table A10. ICD-9-CM and ICD-10-CM diagnosis and procedure codes for the identification of HDP and hypothesized mediator-outcome confounders.

Outcome	ICD-9-CM	ICD-10-CM
Chronic Hypertension	401-405.9, 642.0, 642.1, 642.2, 642.7	O10.0, O10.011, O10.012, O10.013, O10.019, O10.11, O10.111, O10.112, O10.113, O10.119, O10.12, O10.13, O10.2, O10.21, O10.211, O10.212, O10.213, O10.219, O10.22, O10.23, O10.3, O10.4, O10.9
Gestational Hypertension	642.3	O13.1, O13.2, O13.3, O13.4, O13.5, O13.9
Preeclampsia (Mild or Severe)	642.5, 642.4	O14.0, O14.00, O14.02, O14.03, O14.04, O14.05, O14.1, O14.10, O14.12, O14.13, O14.14, O14.15, O14.9, O14.90, O14.92, O14.93, O14.94, O14.9
Obesity/Overweight	V85.3, V85.30, V85.31, V85.32, V85.33, V85.34, V85.35, V85.36, V85.37, V85.38, V85.39, 278.01, V85.4, V85.40, V85.41, V85.42, V85.43, V85.44, V85.45, 278.0, 278.03, 278.00	E66.0, Z68.30, Z68.31, Z68.32, Z68.33, Z68.34, Z68.35, Z68.36, Z68.37, Z68.38, Z68.39 E66.01, E66.2, Z68.4, Z68.41, Z68.42, Z68.43, Z68.44, Z68.45, E66.09, E66.9
Chronic Renal Disease	581.x-583.x, 585.x, 587.x, 588.x, 646.2x	O26.83, I12, I13, N03- N05, N07, N08, N11.1, N11.8, N11.9, N18, N25.0, N25.1, N25.81, N25.89, N25.9, N26.9
Pre-existing Diabetes	250-250.9, 648.0	O24.0x, O24.01x, O24.11x, O24.12x, O24.13x, O24.31x, O24.82x
Gestational Diabetes	648.8	O24.41, O24.42, O24.43

Covariate Operationalization

Hospital Discharge Record

Race was coded dichotomously as NH Black and NH White based on information from the hospital discharge record. If race was available and no ethnicity information was available, individuals were coded as non-Hispanic (n = 357,454; 24%). HDP was coded dichotomously from ICD-9/10-CM codes in hospital discharge records for chronic hypertension, gestational hypertension, and preeclampsia (**Appendix Table A10).** Eclampsia was excluded because it is an indicator of SMM.

Maternal age was identified in the delivery hospital discharge record and coded as a continuous variable (years). Comorbidities, specifically diabetes mellitus, gestational diabetes mellitus, obesity, and kidney disease, were coded dichotomously from ICD-9/10-CM codes in delivery hospital discharge records (**Appendix Table A10**).

Insurance payor was coded as a four-level categorical variable: private payor, public payor, self-pay, and other in the hospital discharge record. County urbanicity was coded dichotomously as rural and urban based on the 2010 census measures available in the hospital discharge record.

Vital Statistics Birth and Fetal Death Records

Multiple gestation was coded dichotomously as single or multiple from the vital statistics record.

American Community Survey

The census tract proportion of the population living below the federal poverty line was calculated using 2006-2010, 2010-2015, and 2016-2019 five-year American Community Survey (ACS) estimates based on the variables “B17001_001” and “B17001_002”. The variable was operationalized as continuous in causal models.

Complete Case Analysis

Table A11. Patterns of missingness for multiple gestation, insurance payor, and neighborhood poverty by maternal race and SMM status.

	NH Black		NH White	
	Non SMM	**SMM**	**Non SMM**	**SMM**
N (column %)	N = 615,125	N = 8,277	N = 814,441	N = 6,328
Multiple gestation	57,031 (9%)	990 (12%)	69,186 (9%)	601 (9%)
Insurance Payor	1,812 (<1%)	27 (<1%)	2,879 (<1%)	23 (<1%)
Poverty	64 (<1%)	1 (<1%)	23 (<1%)	0 (0%)

Table A12. Estimated CDE and the proportion eliminated for the effect of race and SMM, through the mediator HDP, complete case analysis (n = 1,312,037).

	Total Effect* (95% CI)	**CDE* (95% CI)**	**Proportion Eliminated**
HDP	55.7 (52.2, 59.0)	38.7 (35.3, 42.1)	30%

*Total effect and CDE represent the excess risk among NH Black women (Black-White Rate Difference per 10,000 hospitalizations)

Decomposition Methods & Assumptions

Graphical representation of assumptions for decomposition analyses

Decomposition analyses require careful consideration of four (at times, exceptionally strong) assumptions (**Figure A1**):[126,127]

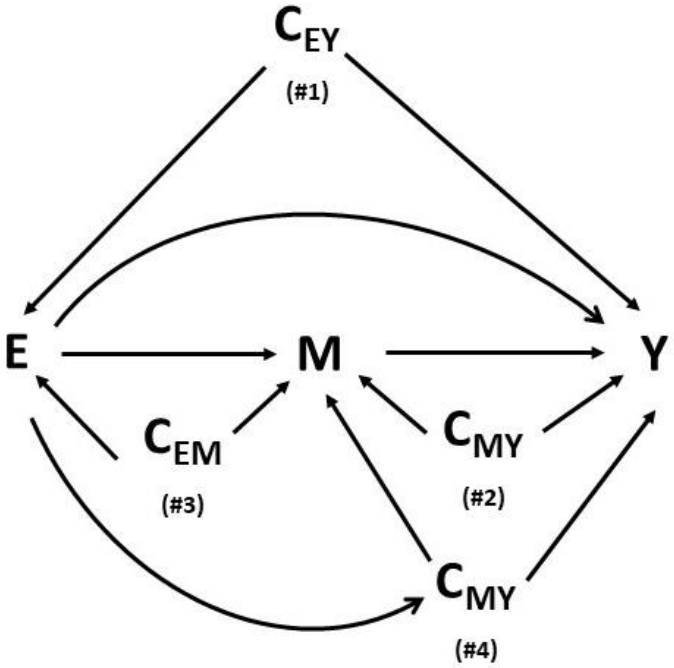
(1) No exposure-outcome confounding (C_{EY})

(2) No mediator-outcome confounding (C_{MY})

(3) No exposure-mediator confounding (C_{EM})

(4) No mediator-outcome confounding affected by the exposure (C_{MY}).[126,127]

Figure A1. Directed acyclic graph (DAG) of the four assumptions needed to validly estimate direct and indirect effects in causal decomposition models. Abbreviations: E = exposure, Y = outcome, M = mediator, C_{EY} = exposure-outcome confounder, C_{MY} = mediator-outcome confounder, C_{EM} = exposure-mediator confounder.



G-estimation of structural nested mean models

G-estimation of a structural nested mean model was selected over other generalized methods (e.g., inverse probability-weighted marginal structural models and structural transformation) because these models are doubly robust, allowing for consistent estimation of

the CDE with either correct mediator or outcome model specification.[59,126] We first estimated the magnitude of the total Black-White disparity (i.e., the total effect of racism on SMM) using **eq. A1**. We do not hypothesize an exposure (race)-outcome (SMM) confounders, but we include the notation C_{EY} for completeness.

(eq. A1) $E[SMM|RACE, C_{EY}] = \delta_o + \delta_1 RACE + \delta_2 C_{EY}$

G-estimation of a structural nested mean model to estimate the CDE is a two-step process in which we first transform the SMM outcome to remove the effect of HDP (set HDP =0) and then estimate the effect of race on the transformed SMM outcome.[58,59] We performed the following modeling steps exemplified by Naimi et al. 2016.[59]

In step one, we ran a series of models to transform the outcome with the effect of the mediator removed.[59] For each individual (i), we modeled the probability of the mediator (HDP) as a function of the exposure (race) and mediator-outcome (HDP-SMM) confounders (**eq. A2**).[59] We again include the notation C_{EY} for completeness.

(eq. A2) $p(\widehat{HDP})_i = [1 + \exp(-\widehat{\lambda_0} - \widehat{\lambda_1} RACE_i - \widehat{\lambda_2} C_{EY_i} - \widehat{\lambda_3} C_{MY_i})]^{-1}$

We extracted the predicted probabilities of the mediator (HDP) and calculated the HDP residual by subtracting the predicted HDP probability from the observed HDP value (**eq. A3**).[59]

(eq. A3) $r(\widehat{HDP})_i = HDP_i - p(\widehat{HDP})_i$

Next, we regressed the outcome (SMM) against the exposure (race), mediator (HDP) residual, the interaction of the exposure (race) and mediator (HDP) residual, and the mediator-exposure (HDP-SMM) and mediator-outcome confounders (**eq. A4**).[59]

(eq. A4) $E[SMM|RACE, HDP, C_{XY}, C_{MY}] = \gamma_0 + \gamma_1 r(\widehat{HDP})_i + \gamma_2 RACE_i * r(\widehat{HDP})_i + \gamma_3 C_{EY} + \gamma_4 C_{MY}$

For each individual, we created a transformed outcome (SMM) with the mediator (HDP) effect removed (**eq. A5**).[59]

(eq. A5) $\widetilde{SMM}_i = SMM_i - \widehat{\lambda_1} HDP_i - \widehat{\lambda_2} RACE_i * HDP_i$

In step 2, we estimated the effect of race on SMM, not through the mediator (HDP).[59] We modeled the probability of the exposure (race) in an empty model because there were no exposure-outcome confounders (**eq. A6**).

(eq. A6) $p(\widehat{RACE})_i = [1 + \exp(-\widehat{\lambda_0} - \widehat{\lambda_1} C_{EY_i})]^{-1}$

We extracted the exposure (race) predicted probabilities and calculated the race residual by subtracting the predicted race probability from the observed race value (**eq. A7**).[59]

(eq. A7) $r(\widehat{RACE})_i = RACE_i - p(\widehat{RACE})_i$

Lastly, we modeled the transformed outcome (SMM) regressing on the exposure (race) residual (**eq. A8**).[59]

(eq. A8) $E\left[\widetilde{SMM} \mid X, C_{EY}\right] = \psi_0 + \psi_1 r(RACE)_i + \psi_2 C_{EY}$

Given all assumptions hold, $\widehat{\psi_1}$ is the CDE (HDP = 0).[59] The standard error of the CDE was used to calculate conservative 95% confidence intervals. If all assumptions hold, the proportion of the disparity eliminated is estimated by $\frac{\widehat{\delta_1} - \widehat{\psi_1}}{\widehat{\delta_1}}$.[58,59]

Difference Method

The difference method relies on fitting two models.[58] The first model with the race regressed on SMM, controlling for confounders of the exposure-outcome (C_{EY}) and mediator-outcome confounders (C_{MY}) (**eq. A9**).[58] The second model is fitted with race and HDP regressed on SMM, controlling for C_{EY} and C_{MY} (**eq. A10**).[58] Note that we hypothesize there are no exposure-outcome confounders; however, we include the notation in the model for completeness.

(eq. A9) $E[SMM|RACE, C_{EY}, C_{MY}] = \alpha_o + \alpha_1 RACE + \alpha_2 C_{EY} + \alpha_3 C_{MY}$

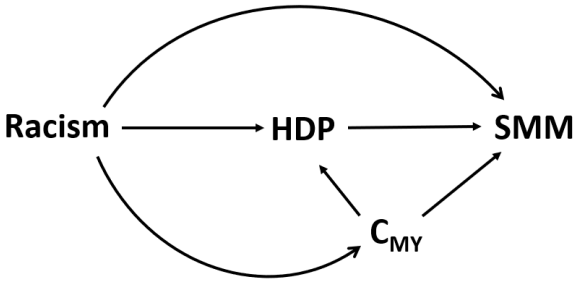
(eq. A10) $E[SMM|RACE, HDP, C_{EY}, C_{MY}] = \beta_o + \beta_1 RACE + \beta_2 HDP + \beta_3 C_{EY} + \beta_4 C_{MY}$

If all causal effect assumptions hold and there is no interaction of race and HDP, then β_1 will validly estimate CDE(HDP=0), and the proportion of the disparity eliminated by HDP is estimated by $(\widehat{\alpha_1} - \widehat{\beta_1})/\widehat{\alpha_1}$.[58,59] However, $\widehat{\alpha_1}$ will not equal the total effect (α_1) if C_{MY} is a descendent of race, if other assumptions do not hold, and if there is a race-mediator interaction.[58,59]

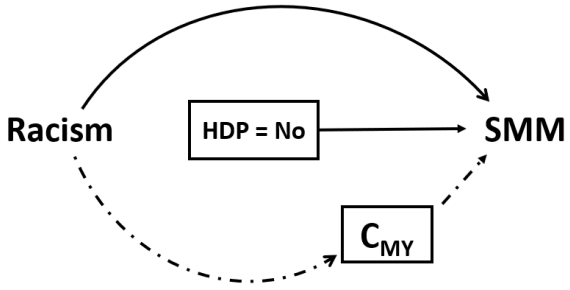
To motivate why regression methods cannot estimate the CDE, consider the following DAG where an exposure (racism) is a cause of the mediator (HDP) and the outcome (SMM), HDP is a cause of SMM, and there is a confounder of the HDP-SMM effect (C_{MY}), which is a descendent of racism (**Figure A2**):

Figure A2. Directed acyclic graph for racism and SMM (A2.1) before adjustment for the mediator (HDP) and mediator-outcome confounders (CMY), and (A2.2) after adjustment for HDP and CMY. The dashed line in A2.2 indicates part of the unbiased effect of racism on SMM that is blocked through the adjustment of C_{MY}.

A2.1)



A2.2)



To validly estimate the CDE, we must adjust for C_{MY}. Yet, statistical adjustment of C_{MY} blocks part of the exposure effect on the path Racism→C_{MY}→SMM which is not due to bias (**Figure A2.2**). Special methods, such as g-estimation of a structural nested mean model, are needed to both incorporate the exposure-mediator interaction as well as separately estimate the effect of racism through the mediator-outcome confounding variable and the biasing path from the intermediate through the confounding variable.[59]

Under the difference method, we estimated a total effect $\widehat{\alpha_1}$ of 47.3 (95% CI: 43.7, 51.0), resulting in an estimated 19% of the disparity eliminated (**Appendix eq. A9**). Difference between the total effect estimated by **Appendix eq. A1** and the difference method (**Appendix eq. A9**) is consistent with our expectation that assumption #4 was violated. When applying the difference method, the CDE was estimated as 38.2 (95% CI: 35.9, 41.7), explaining 31% of the Black-White disparity (**Table A13**).

Table A13. Comparison of the estimated total effect, CDE, and proportion eliminated for the effect of race and SMM through the mediator HDP using the difference method..

	Total Effect* (95% CI)	CDE* (95% CI)	Proportion Eliminated
HDP	55.7 (52.2, 59.0)	38.2 (35.9, 41.7)	31%

*Total effect and CDE represent the excess risk among NH Black women (Black-White Rate Difference per 10,000 hospitalizations)

Aim 3 Appendix

Exposure Variable ACS Codes

Relative income inequality and racial segregation measures were calculated using the following 2010-2019 5-year estimates from the American Community Survey variables at the census tract level[100]:

- B19013_001: Median household income in the past 12 months (inflation-adjusted dollars)
- B17001_001: Poverty status in the past 12 months by sex by age – total number of individuals
    - B17001_002: number of individuals, income below the poverty level in the past 12 months
- B03002_001: Hispanic or Latino origin by race – total number of individuals
    - B03002_003: number of individuals, White race alone and non-Hispanic ethnicity

Table A14. Georgia median household income and proportion of NH White residents by year, from the 2010-2019 five-year American Community Survey (ACS).

Year	Average HH Median Income	80% state median household income	150% state median household income	Average proportion NH White residents
2010	$50,651	$40,521	$75,976	56%
2011	$50,936	$40,749	$76,404	56%
2012	$50,660	$40,528	$75,990	55%
2013	$50,323	$40,258	$75,484	55%
2014	$50,481	$40,385	$75,722	55%
2015	$50,811	$40,649	$76,216	54%
2016	$52,323	$41,858	$78,484	54%
2017	$54,650	$43,720	$81,975	54%
2018	$57,214	$45,771	$85,821	53%
2019	$60,027	$48,021	$90,040	53%

Sensitivity Analysis Exposure Definition

Given the imprecision of estimated race-specific rates, we evaluated exposure definition sensitivity for pooled estimates only.

Sensitivity Analysis #1: Racial Segregation Category #1

We first varied the operationalization of the racial segregation measure, which was defined using a more common "absolute" definition of concentrated POC (greater than 50%) and concentrated NH White (>60%).[97] We further created a non-concentrated stratum (50-60% NH White).

Table A15. Additive statistical interaction of census tract-level relative income inequality and racial segregation on SMM risk, Georgia 2010-2019, NH Black and NH White women, alternate racial segregation operationalization #1.

Relative Income Inequality	**Relative Racial Segregation**									RD (95%) for NH White ethnoracial composition within strata of income inequality	RD (95%) for concentrated POC ethnoracial composition within strata of income inequality
	Concentrated NH White (>60%)			Non-Concentrated Racial (50-60% White)			Concentrated POC (> 50%)				
	N SMM/ Deliveries	SMM Rate per 10,000 (95% CI)	RD per 10,000 (95% CI)	N SMM/Deliveries	SMM Rate per 10,000 (95% CI)	RD per 10,000 (95% CI)	N SMM/ Deliveries	SMM Rate per 10,000 (95% CI)	RD per 10,000 (95% CI)		
Concentrated Affluence	727/92,008	79.0 (73.3, 84.7)	-24.6 (-33.9, -15.2)	92/11,035	83.4 (66.4, 100.3)	-20.2 (-37.8, -0.71)	70/8,983	77.9 (59.7, 96.1)	-25.6 (-45.3, -6.0)	-4.4 (-22.3, 13.5)	-5.3 (-30.3, 19.4)
Non-Concentrated	2,733/295,519	92.5 (89.0, 95.9	-11.1 (-19.4, -3.0)	742/71,643	103.6 (96.2, 111.0)	0.0	2,396/200,044	119.8 (115.0, 124.5)	16.2 (7.2, 24.9)	-11.1 (-19.4, -3.0)	16.2 (7.2, 24.9)
Concentrated Poverty	532/55,001	96.7 (88.5, 104.9)	-6.8 (-17.9, 4.2)	365/32,753	111.4 (100.1, 122.8)	7.9 (-5.5, 21.7)	2,786/218,467	127.5 (122.8, 132.2)	24.0 (15.2, 32.7)	-14.7 (-28.7, -0.71)	16.1 (3.8, 28.4)
RD (95% CI) for affluent income inequality within strata of racial segregation			-13.5 (-20.1, -6.8)			-20.2 (-37.8, -0.71)			-41.8 (-60.6, -23.1)		
RD (95% CI) for concentrated poverty income inequality within strata of racial segregation			4.2 (-4.6, 13.1)			7.9 (-5.5, 21.7)			7.8 (1.1, 14.4)		

Sensitivity Analysis #2: Racial Segregation Category #2

A second operationalization of the racial segregation measure was explored, which was defined using a more extreme definition of concentrated NH White (>80%).[92,93,97]

Table A16. Additive statistical interaction of census tract-level relative income inequality and racial segregation on SMM risk, Georgia 2010-2019, NH Black and NH White women, alternate racial segregation operationalization #2.

Relative Income Inequality	**Relative Racial Segregation**									RD (95%) for NH White comp. within strata of income inequality	RD (95%) for concentrated POC comp. within strata of income inequality
	Concentrated NH White (>80%)			Non-Concentrated Racial (50-80% White)			Concentrated POC (> 50%)				
	N SMM/ Deliveries	SMM Rate per 10,000 (95% CI)	RD per 10,000 (95% CI)	N SMM/Deliveries	SMM Rate per 10,000 (95% CI)	RD per 10,000 (95% CI)	N SMM/ Deliveries	SMM Rate per 10,000 (95% CI)	RD per 10,000 (95% CI)		
Conc. Affluence	356/ 44,501	80.0 (71.7, 88.3)	-19.2 (-28.3, -10.0)	463/ 58,542	79.1 (71.9, 86.3)	-20.1 (-28.1, -11.8)	70/ 8,983	77.9 (59.7, 96.1)	-21.3 (-39.9, -2.7)	1.0 (-10.0, 11.9)	-1.2 (-20.7, 18.4)
Mixed-Income	1,028/ 120,437	85.4 (80.2, 90.6)	-13.8 (-20.3, -7.2)	2,447/ 246,725	99.2 (95.3, 103.1)	0.0	2,396/ 200,044	119.8 (115.0, 124.5)	20.6 (14.4, 26.8)	-13.8 (-20.3, -7.2)	20.6 (14.4, 26.8)
Conc. Poverty	122/ 16,456	74.1 (61.0, 87.2)	-25.0 (-38.7, -11.4)	775/ 71,298	108.7 (101.1, 116.3)	9.5 (1.1, 18.2)	2,786/ 218,467	127.5 (122.8, 132.2)	28.3 (22.2, 34.5)	-34.6 (-49.7, -19.4)	18.8 (9.9, 27.8)
RD (95% CI) for affluent income inequality within strata of racial segregation			-5.4 (-15.1, 4.4)			-20.1 (-28.1, -11.8)			-41.8 (-60.6, -23.1)		
RD (95% CI) for concentrated poverty income inequality within strata of racial segregation			-11.2 (-25.3, 2.9)			9.5 (1.1, 18.2)			7.8 (1.1, 14.4)		
Measure of interaction on additive scale (extremes):					55.5 (30.1, 78.9)						

Sensitivity Analysis #3: Income Inequality Category #1

We explored an alternate operationalization of the income inequality measure based on more extreme income inequality strata. Specifically, extremely concentrated affluence (proportion living in poverty <10% and median household income >200% state mean), relatively concentrated affluence (proportion living in poverty <10% and median household income between 150-200% of state mean), relatively concentrated poverty (proportion living in poverty ≥20% and median household income between 50-80% of state mean), extremely concentrated poverty (proportion living in poverty ≥20% and median household income <50% of state mean), and mixed-income (census tracts not in the above groups).

Table A17. Additive statistical interaction of census tract-level relative income inequality and racial segregation on SMM risk, Georgia 2010-2019, NH Black and NH White women, alternate income inequality operationalization #1.

Relative Income Inequality	**Relative Racial Segregation**						RD (95%) for racial composition within strata of income inequality
	Concentrated NH White			Concentrated POC			
	N SMM/ Deliveries	SMM Rate per 10,000 (95% CI)	RD per 10,000 (95% CI)	N SMM/ Deliveries	SMM Rate per 10,000 (95% CI)	RD per 10,000 (95% CI)	
Extreme Concentrated Affluence	243/ 32,035	75.9 (66.4, 85.4)	-17.9 (-27.6, -7.5)	20/ 2,447	81.7 (46.1, 117.4)	-12.0 (-47.9, 23.8)	5.9 (-31.0, 42.8)
Relative Concentrated Affluence	538/ 66,391	81.0 (74.2, 87.9)	-12.7 (-20.1, -5.0)	88/ 11,153	78.9 (62.5, 95.3)	-14.9 (-31.6, 1.9)	-2.1 (-19.9, 15.6)
Non-Concentrated	3,191/ 340,282	93.8 (90.5, 97.0)	0.0	2,680/ 226,924	118.1 (113.7, 122.5)	24.3 (18.8, 29.8)	24.3 (18.8, 29.8)
Relative Concentrated Poverty	664/ 67,145	98.9 (91.4, 106.4)	5.1 (-2.9, 13.4)	2,042/ 161,367	126.5 (121.1, 132.0)	32.8 (26.4, 39.1)	27.7 (18.4, 36.9)
Extreme Concentrated Poverty	67/ 5,866	114.2 (87.0, 141.4)	20.4 (-4.9, 50.0)	910/ 71,843	126.7 (118.4, 134.8)	32.9 (24.1, 41.7)	12.4 (-15.9, 40.8)
RD (95% CI) for extreme concentrated affluent income inequality within strata of racial segregation			-17.9 (-27.6, -7.5)			-36.4 (-72.3, -0.4)	
RD (95% CI) for relative concentrated affluent income inequality within strata of racial segregation			-12.7 (-20.1, -5.0)			-39.2 (-56.2, -22.2)	
RD (95% CI) for relative concentrated poverty income inequality within strata of racial segregation			5.1 (-2.9, 13.4)			8.4 (1.4, 15.4)	
RD (95% CI) for extreme concentrated poverty income inequality within strata of racial segregation			20.4 (-4.9, 50.0)			8.6 (-0.7, 17.9)	
Measure of interaction on additive scale (extremes):			6.6 (-44.0, 49.6)				

Sensitivity Analysis #4: Income Inequality Category #2

Lastly, we explore an alternative relative income inequality operationalization for the mixed-income category. Specifically, we excluded mixed-income neighborhoods which did not have a median household income between 81 and 149% of the Georgia median household income. Excluded census tracts were neighborhoods with a median household income greater than or equal to 150% of the Georgia median household income with a moderate or high proportion of individuals living below the federal poverty level (greater than or equal to 10%) (n census tracts = 12,696; 11% of original mixed-income category) and neighborhoods with a median household income less than or equal to 80% of the Georgia median household income with low or moderate proportions of individuals living below the federal poverty level (<20%) (n census tracts = 63,910; 2% of original mixed-income category).

Table A18. Additive statistical interaction of census tract-level relative income inequality and racial segregation on SMM risk, Georgia 2010-2019, NH Black and NH White women, alternate income inequality operationalization #2.

Relative Income Inequality	**Relative Racial Segregation**						RD per 10,000 (95%) for relative concentrated POC within strata of income inequality
	Relative Concentrated NH White			**Relative Concentrated POC**			
	N SMM/ Deliveries	SMM Rate per 10,000 (95% CI)	RD per 10,000 (95% CI)	N SMM/ Deliveries	SMM Rate per 10,000 (95% CI)	RD per 10,000 (95% CI)	
Relative Concentrated Affluence	781/98,426	79.3 (73.8, 84.9)	-13.3 (-19.8, -6.7)	108/13,600	79.4 (64.5, 94.3)	-13.3 (-28.6, 2.1)	0.1 (-15.9, 16.0)
Relative Mixed-Income	2,719/293,432	92.7 (89.2, 96.1)	0.0	2,952/233,210	116.9 (112.2, 121.7)	24.2 (18.4, 30.1)	24.2 (18.4, 30.1)
Relative Concentrated Poverty	731/73,011	100.1 (92.9, 107.4)	7.5 (-0.4, 15.6)	2,952/233,210	126.6 (122.0, 131.1)	33.9 (28.2, 39.6)	26.5 (17.9, 35.0)
RD per 10,000 (95% CI) for relative concentrated affluent income inequality within strata of racial segregation			-13.3 (-19.8, -6.7)			-37.5 (-53.1, -21.8)	
RD per 10,000 (95% CI) for relative concentrated poverty income inequality within strata of racial segregation			7.5 (-0.4, 15.6)			9.7 (3.1, 16.2)	
Measure of interaction on the additive scale (extremes):			26.4 (7.7, 43.8)				

Abbreviations: CI = confidence interval; NH = non-Hispanic; POC = persons of color; RD = rate difference; SMM = severe maternal morbidity

Regression Modeling Sensitivity Analyses

Table A19. Modeling sensitivity analysis #1: urbanicity adjustment.

Relative Income Inequality	**Relative Racial Segregation**		RD (95%) for concentrated POC within strata of income inequality
	Relative Concentrated NH White	Relative Concentrated POC	
	RD per 10,000 (95% CI)	RD per 10,000 (95% CI)	
Relative Concentrated Affluence	-13.7 (-20.2, -7.2)	-13.7 (-29.0, 1.6)	0.1 (-15.8, 16.0)
Mixed Income	0.0	24.9 (19.4, 30.5)	24.9 (19.4, 30.5)
Relative Concentrated Poverty	4.9 (-3.2, 13.3)	32.7 (27.3, 38.3)	27.8 (19.0, 36.6)
RD (95% CI) for concentrated affluent income inequality within strata of racial segregation	-13.7 (-20.2, -7.2)	-38.6 (-54.2, -23.0)	
RD (95% CI) for concentrated poverty income inequality within strata of racial segregation	4.9 (-3.2, 13.3)	7.8 (1.3, 14.2)	
Measure of interaction on additive scale:		27.7 (8.9, 45.3)	

Generalized Estimating Equations (GEE)

A GEE model is considered to account for potential clustering of individuals in census tract of residence, given that one might hypothesize that individual outcomes may be correlated if the neighborhood is important for understanding SMM.[144,146] We assumed an exchangeable correlation structure, which models the same correlation parameter for all individuals within the same census tract.[147]

Table A20. Modeling sensitivity analysis #2: GEE models with exchangeable correlation structure.

Relative Income Inequality	**Relative Racial Segregation**		RD (95%) for concentrated POC within strata of income inequality
	Relative Concentrated NH White	Relative Concentrated POC	
	RD per 10,000 (95% CI)	RD per 10,000 (95% CI)	
Relative Concentrated Affluence	-14.0 (-20.5, -7.6)	-14.6 (-30.4, 1.3)	-0.6 (-16.7, 15.6)
Mixed Income	0.0	23.8 (17.7, 29.9)	23.8 (17.7, 29.9)
Relative Concentrated Poverty	4.9 (-3.7, 13.6)	32.1 (25.7, 38.4)	27.1 (17.7, 36.5)
RD (95% CI) for concentrated affluent income inequality within strata of racial segregation	-14.0 (-20.5, -7.6)	-38.4 (-54.4, -22.4)	
RD (95% CI) for concentrated poverty income inequality within strata of racial segregation	4.9 (-3.7, 13.6)	8.2 (1.6, 15.0)	
Measure of interaction on additive scale:		27.7 (9.0, 46.4)	

Eigenvector Spatial Filtering (ESF)

In a third model, we incorporated eigenvector spatial filtering methods to account for spatial dependence (correlation of the outcome in a geographic unit with its geographic neighbors).[145] At a high level, we use ESF to break the model residuals into spatially autocorrelated and nonspatial components.[145]

We specified a queen contiguity neighbor definition, which considers geographic units as neighbors if they are contiguous. We used the Moran's I specification to filter the variable, which is based on the matrix in **equation A11**, where I is an n-by-n identity matrix (n = total number of geographic units), and T indicates the matrix transpose operation.

(eq. A11) $Moran\ Specification\ Matrix: \left(I - \frac{11^T}{n}\right) C \left(I - \frac{11^T}{n}\right)$

The order of identified eigenvectors is with respect to the largest to smallest Moran's I. The Moran's I of each eigenvector can be estimated by equation **A12**:

(eq. A12) $Moran's\ I\ of\ Eigenvector$: $\frac{n}{1^T C 1}$

The eigenvectors are incorporated into the regression model as a component of the error term (e), where E is the spatial component (series of eigenvectors), γ is the coefficient defining the relationship to incorporate E, and the nonspatial component (ŋ):

(eq. A13) $e_i = \gamma E +$ ŋ

Table A21. Modeling sensitivity analysis #3: Eigenvector Spatial Filtering (ESF) with queen contiguity neighborhood definition.

Relative Income Inequality	**Relative Racial Segregation**		RD (95%) for concentrated POC within strata of income inequality
	Relative Concentrated NH White	Relative Concentrated POC	
	RD per 10,000 (95% CI)	RD per 10,000 (95% CI)	
Relative Concentrated Affluence	-10.8 (-17.9, -3.7)	-9.7 (-26.7, 7.2)	1.0 (-16.6, 18.7)
Mixed Income	0.0	27.2 (21.2, 33.3)	27.2 (21.2, 33.3)
Relative Concentrated Poverty	9.2 (0.5, 17.9)	35.1 (29.0, 41.2)	25.9 (16.4, 35.3)
RD (95% CI) for concentrated affluent income inequality within strata of racial segregation	-10.8 (-17.9, -3.7)	-37.0 (-54.2, -19.7)	
RD (95% CI) for concentrated poverty income inequality within strata of racial segregation	9.2 (0.5, 17.9)	7.8 (0.8, 14.8)	
Measure of interaction on additive scale:		26.2 (6.7, 44.0)	

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