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Complete Manuscript Title: Hospital Preparedness, Mitigation, and Response to Hurricane Harvey in Harris County, Texas

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Hospital Preparedness, Mitigation, and Response to Hurricane Harvey in Harris County, Texas

Structured Abstract

Objective: This case study documents Harris County hospitals' flood preparedness and mitigation efforts prior to Hurricane Harvey, their collective response experience during Hurricane Harvey, and their lessons learned in the storm's aftermath.

Methods: The case study was constructed using a survey of hospital emergency managers, semi-structured interviews with local agencies involved in public health, emergency management, and healthcare, and an analysis of news reports and other documents from a variety of government agencies, local organizations, and hospitals themselves.

Results: Harris County hospitals learned their most valuable lessons through their direct and repeated experience with flooding over the years, leading to improved preparedness prior to Hurricane Harvey. Hospital emergency response successes included infrastructure improvements, staff resilience, advanced planning, and pre-established collaboration. However, hospitals still experienced challenges with staff burnout, roadway flooding, and patient evacuation.

Conclusions: Although the current state of hospital flood preparedness and mitigation is rather advanced and mature, it is advisable that Harris County takes steps to strengthen emergency management efforts in hospitals with fewer financial and staffing resources and less direct flood experience.

Keywords

Hospital, Hurricane Harvey, emergency preparedness, mitigation, flood

Institutional Review Board Approval

This study was deemed "exempt" by the University of Colorado Boulder Institutional Review Board.

INTRODUCTION

In August 2017, Hurricane Harvey made landfall as a Category 4 hurricane on the Texas coast, with its record-breaking rainfall flooding at least 25% of Harris County.[1] Preliminary reports revealed many hospitals in Harris County struggled with building flooding and damage, patient evacuation, and road access.[2] During extreme flooding events, hospitals are tasked with providing both routine and emergency healthcare services, often at surge capacity. Hurricane Harvey provided an opportunity to explore Harris County hospitals' successes and challenges during an extreme flooding event and to evaluate their current state of flood preparedness and mitigation. Given extreme flooding events are projected to increase in frequency and intensity across the U.S. over the next decade,[3] it is crucial to consider local case studies to better understand the full range of hospital flooding impacts, and to evaluate strategies to reduce future vulnerabilities.

This case study constructs a narrative detailing Harris County hospitals' flood preparedness and mitigation efforts prior to Hurricane Harvey, their collective experience during Hurricane Harvey, and their lessons learned in the storm's aftermath. This case study was constructed using surveys of hospital emergency managers, semi-structured interviews with local agencies involved in public health, emergency management, and healthcare, and an analysis of news reports and other documents from a variety of government agencies, local organizations,

and hospitals. Through the synthesis of data on hospitals across Harris County, this case study evaluates hospitals' emergency responses to Hurricane Harvey and creates an argument for adopting additional flood preparedness and mitigation measures in hospitals to prepare for future flooding events in coastal Texas and elsewhere.

METHODS

Survey and Interview Protocol

To construct a case study of Harris County hospitals' preparedness, mitigation, and response to Hurricane Harvey, we first developed an online survey for hospital emergency managers. The qualitative survey was designed to be applicable to all 80 non-psychiatric, whether affected by Hurricane Harvey or not, and was intended to directly explore these hospitals' successes and challenges during an extreme flooding event and evaluate their state of flood preparedness and mitigation. Five categories of questions were included in the survey: 1) general information about the survey respondent and their hospital; and the hospitals' 2) past experience with flooding (i.e., prior to Hurricane Harvey); 3) experience with flooding from Hurricane Harvey; 4) current state of flood preparedness/mitigation; and 5) barriers to flood preparedness/mitigation. A survey expert reviewed and refined an initial draft of the survey. The survey was administered online through Google Forms from May-December 2018.

Secondly, a similar key informant interview protocol was developed for interviews with local agencies involved in public health, emergency management, and healthcare in Harris County. While the survey provided hospital-specific responses by each emergency manager, the interview protocol was designed to supplement the surveys by exploring the same themes on a

county-wide scale. Therefore, the interview questions were adapted from the survey questions, with modifications to better suit the local agency target population and allow for a semi-structured format and open-ended answers. For example, whereas the survey asked individual hospitals to comment on their historical experience with flooding, the interview protocol instead asked local agencies to comment on the combined historical experiences of hospitals with flooding across Harris County. The interviews were conducted in-person in August 2018, lasting approximately 45 minutes each. The interviews were transcribed verbatim from audio recordings.

Participant Recruitment

The 80 non-psychiatric hospitals in Harris County, Texas were established using Homeland Infrastructure Foundation-Level Data.[4] An effort was made to identify an emergency manager from all 80 hospitals using several methods, including repeated phone calls and emails with the hospitals, referrals, and Google and LinkedIn searches. The emergency managers identified were then contacted directly via email with an invitation to participate in the survey, including a consent form, details on the survey's purpose and length, and a compensation offer. In the case of non-response, two follow-up emails were sent. To improve access and trust with the target hospital emergency managers, the SouthEast Texas Regional Advisory Council (SETRAC) also attempted to increase response rates by disseminating the invitation to participate through their internal email list. Out of 80 hospitals in Harris County, three hospitals' emergency managers (4%) accepted and responded to the survey.

To explore the same themes on a county-wide scale, we additionally sought the perspective of local public health, emergency management, and healthcare agencies in Harris

County by conducting in-person interviews with key informants from several agencies. These local agencies were specifically selected for their trusted perspectives and comprehensive knowledge of both hospital experiences during Hurricane Harvey and hospital flood preparedness and mitigation efforts on a county-wide scale. The local agency representatives were identified via the agency's website, contacted directly via email, and provided with an invitation to participate in an interview, including a consent form, details on the interview's purpose and length, and a compensation offer. Out of five agencies contacted, four agencies (80%) accepted and were interviewed.

Individuals who responded to the survey or interview were aggregated with their respective hospitals or agencies, which were then de-identified to protect their identities (Table 1). *Surveyed* hospitals are referred to with letters (e.g., Hospital A) and *interviewed* local agencies are referred to with numbers (e.g., Agency 1).

Secondary Sources

Lastly, in addition to the survey and key informant interviews, secondary data sources were incorporated into the analysis and provided crucial information about the experiences of Harris County hospitals for which we did not receive survey responses, and also serving to validate the key informant interview findings. These secondary sources were identified through a thorough scan of Google searches and vetted for reliability and rigor. Search keywords included hospital, Hurricane Harvey, flood, and inundation, paired with specific Harris County hospital names. The secondary sources are categorized as follows: news reports (n=31), peer-reviewed journal articles (n=1), documents from government agencies (n=2), documents from local agencies (n=3), and hospital websites (n=10).

Combined Analysis of Survey, Interview, and Secondary Sources

An inductive approach was used to organize and condense the survey, interview, and secondary source data into coherent key themes related to hospital preparedness, mitigation, and response to Hurricane Harvey. After many close readings of the survey and interview results and secondary data sources, several key themes emerged and are presented below with selected quotes from surveys and interviews presented to demonstrate each theme.

RESULTS

Historical Experience with Flooding and Mitigation before Hurricane Harvey

Most Harris County hospitals learned their most valuable lessons about flood mitigation from their historical experience with previous storms such as Tropical Storm Allison (2001), the Memorial Day Flood (2015) and the Tax Day Flood (2016). Although not directly impacted by Hurricanes Katrina and Sandy, Harris County's hospitals were able to learn from the experiences of affected hospitals during those flooding events in New Orleans and New York, respectively.[5] These lessons led to the implementation of several flood mitigation efforts over the past decade across Harris County prior to Hurricane Harvey.

> "I think the greatest impact on hospitals in our history has been Tropical Storm Allison. The entire Texas Medical Center (TMC) was impacted, which brought about great opportunities for flood mitigation and the Medical Center now has various flood protection devices installed, which include flood gates, flood walls, submarine doors. So

they've made a lot of capital improvements and infrastructure retrofits to protect their buildings and facilities." - *Agency 3*

Additionally, many hospitals within the TMC moved their first floor operations and utilities to higher floors, and planned for redundancy in their basic operating systems to ensure continuity of services during future flooding events.[2] After Tropical Storm Allison, the TMC also installed skywalk bridges between buildings, allowing for patient transportation above ground. Some skywalks were fitted with a protective film to provide wind resistance and hold broken glass in place. The TMC, with Rice University's assistance, developed the real-time Flood Alert System that combines radar, rain gage and flood stage data, and hydrologic modeling to forecast flooding and suggest when flood gates should be deployed.[6]

Not all hospitals in Harris County were able to implement sophisticated flood mitigation efforts after Tropical Storm Allison like the TMC. Some smaller hospitals had limited resources available, while others had little to no previous experience with flooding and lacked the seasoned perspective of those that have flooded repeatedly.

Perceptions of Hospital Flood Risk before Hurricane Harvey

Interviews with four local public health, emergency management, and healthcare agencies revealed there is no consensus on the exact number of Harris County hospitals located within FEMA flood hazard areas. One agency estimated likely more than half of Harris County's hospitals were at risk of flooding, based on the fact the county has a complex network of waterways with many flood hazard areas. However, the flood hazard areas are not perfect predictors of where flooding will occur.[4]

"One of the unique things about Harris County is that it has 22 watersheds, so it's not just one river that we're working with in the community, it's an entire bayou and drainage system that's pretty complex. Just because [...] your infrastructure is outside that flood zone doesn't necessarily mean you're not susceptible to flooding" - *Agency 3*

Similarly, there was no consensus on whether each Harris County hospital was aware of their flood risk. Agency 3 was under the impression not many hospitals were likely aware of their vulnerability, whereas Agencies 1 and 2 felt confident hospital emergency managers were aware of their hospital's location inside or outside FEMA flood hazard areas. However, all agencies interviewed expressed concern this awareness could change in the future, since FEMA continually updates flood hazard areas, such that hospitals might find themselves located within a flood hazard area when they were not previously.

Hospital Emergency Response Successes during Hurricane Harvey

A) Infrastructure Improvements

Despite many hospitals reporting being surrounded by water during Hurricane Harvey, with flooded roads impeding access, very few experienced serious flooding within their buildings.[7,8] This finding indicated the most remarkable success during Hurricane Harvey was the significant infrastructure improvements that prevented most hospitals from experiencing internal flooding similar to that resulting from Tropical Storm Allison.[9]

Following Tropical Storm Allison, many hospitals in Harris County implemented infrastructure improvements including flood gates, above ground generators, water pump

systems, and submarine doors.[2,10] The hospitals within the TMC alone invested approximately $50 million in infrastructure improvements that, for the most part, prevented major flooding inside those hospitals during Hurricane Harvey.[7,11] All three hospitals surveyed provided examples of the infrastructure renovations and retrofits undertaken in the years preceding Hurricane Harvey, and although we were unable to confirm the degree to which these infrastructure improvements prevented flooding, our survey and interviews indicated the improvements played an important role.

B) Advanced Planning

Two forms of advanced planning proved to be particularly successful during Hurricane Harvey. First was using the Hospital Emergency Incident Command System (HEICS), a hospital-specific version of the Incident Command System (ICS), which has long been recognized as an effective protocol for preparing hospital staff for emergencies through a pre-established hierarchical structure and task-specific positions.[12] During Hurricane Harvey, HEICS proved largely successful, since hospitals had proactively trained staff members, identified an emergency response personnel hierarchy, assigned responsibilities, and created emergency event procedures.[9]

Second, through years of table-top exercises, simulations, and drills, hospitals were able to successfully assess and modify emergency plans and procedures in preparation for a crisis scenario like Hurricane Harvey.[13,14] Hospitals were thus able to make quick decisions before Hurricane Harvey's arrival. For example, many hospitals notified patients that elective outpatient surgeries and non-essential appointments would be cancelled to conserve critical supplies and dedicate staff members to continuing inpatient care, such as chemotherapy and dialysis.[5,15]

Similarly, in the days prior to Hurricane Harvey, hospitals began augmenting critical supplies stockpiles including linens, medications, food, and water.[9]

C) Hospital Staff Dedication

The third emergency response success during Hurricane Harvey was the dedication demonstrated by the hospital staff. In preparation for Hurricane Harvey, hospitals formed ride-out and recovery teams composed of physicians, nurses, doctors, and technicians.[14] The ride-out teams arrived before the hurricane and remained on-site throughout the hurricane, while recovery teams arrived afterward to relieve the ride-out teams.[9] Individuals in ride-out teams worked 12-hour shifts and slept in makeshift quarters within the hospital.[5,11]

> "From the very beginning, all staff are told they are essential. We have three times the number of people required to run the hospital listed as willing and personally prepared to show up and support the hospital in an emergency. The culture is greatly supportive of this and one of our greatest strengths." - *Hospital C*

In many cases, roadway flooding meant ride-out teams remained on-site longer than anticipated. Reports also indicated some dedicated staff walked through deep water or kayaked to reach their hospitals.[16] Individuals in ride-out teams additionally found themselves filling roles outside their job descriptions to meet the needs of the patients in their care.[17] In an extreme case, doctors at Lyndon B. Johnson Hospital were required to perform brain surgery—the first in the hospital's history—because they could not safely transfer the patient to a hospital that regularly performed brain surgery.[18]

D) Collaboration

The fourth emergency response success during Hurricane Harvey, which emerged during interviews with local agencies, was the importance of pre-established partnerships and collaboration. During a disaster, knowing the contacts for partner organizations and maintaining routine communication is essential for quick response.

> "In terms of collaboration, I think we do a really good job. We don't do a good job of publicly outlining the collaboration. So most people think we're in two different silos, which is not the case." - *Agency 2*

Despite the agreement among survey and interview respondents regarding the importance of collaboration between hospitals and partner organizations, each of the four local agencies interviewed expressed that staffing needs, time constraints, and costs were large barriers to collaborating more with hospitals. Two agencies noted in an ideal world they would have a larger planning team, with at least one individual dedicated to interfacing with other partner organizations and hospitals.

> "There is coordination; however, the larger hospitals and more urban geographic areas experience a greater sophistication in their preparedness collaboration. There are areas of the state where coordination exists, yet immediate access to resources can be delayed either because of distance or fewer personnel. The goal of federal agencies, state and local governments, and hospitals is to facilitate as much coordination as possible."

- *Agency 4*

The surveys, interviews, and secondary source analysis all echoed that SETRAC is an important asset to the Harris County healthcare system. SETRAC connects local hospitals and partner organizations and provides assistance in communication, cooperation, and collaboration, and supports the Catastrophic Medical Operations Center (CMOC), which is responsible for coordinating hospital closures, patient transport, and medical resource requests during emergency events.[19,20]

> "I think you'll be hard-pressed to find any other hospital preparedness program or regional system that's better prepared than here. I think we probably have one of the most advanced Catastrophic Medical Operations Center (CMOC) that we know works and has demonstrated it works in the past. And they continue to improve." - *Agency 3*

Overall, the hospital surveys and interviews with local agencies revealed robust partnerships and a high level of collaboration in Harris County, as well as a sense of pride in their collective response to Hurricane Harvey.

Hospital Emergency Response Challenges during Hurricane Harvey

A) Mobility and Access

The combination of hospital surveys, interviews with local agencies, and secondary sources conveyed the most salient challenges hospitals faced during Hurricane Harvey were access issues, as many major roadways were underwater for extended periods of time, with

floodwaters surrounding some hospitals in Harris County.[2,7] Roadway flooding largely prevented using traditional transportation methods like cars and ambulances to deliver staff and individuals in need of care to the area's hospitals, thus necessitating alternative transportation methods, such as airboats and helicopters. Additionally, critical hospital supply shipments were often unable to be delivered, causing food and medication shortages.[15,21]

> "Mobility and access. Mobility relative to getting supplies in and out. Access for people who needed to get to those hospitals, because there were a number of areas particularly along the major highways where people couldn't travel around the city." - *Agency 2*

In response to these widespread hospital mobility and access issues, Agency 2 also commented conversations between Harris County and the Texas Department of Transportation (TxDOT) are already underway, to strengthen partnerships and improve transportation resilience for the healthcare sector during future flooding events.

B) Planning

Hurricane Harvey was not only a historic rainfall event lasting over a week, but its strength was largely unexpected.[22] SETRAC reported that Harris County hospitals would have made preparations for the storm much earlier if they knew Hurricane Harvey would make a relatively direct landfall as a Category 4 hurricane.[23] Even with procedures in place, hospitals had very little warning of the impending hurricane and flooding, hastening decisions on evacuating patients or sheltering in place. Overall, very few at-risk hospitals evacuated all patients before the flooding.[2,24] Because there is a high risk level involved in moving injured and

ill patients, only patients in the most critical conditions were considered for evacuation during Hurricane Harvey. Additionally, transporting patients during a hurricane is difficult since each patient needs to be individually matched with a hospital both far from the hurricane's path and able to take in patients.[23,25,26]

Another unplanned situation arose from lack of communication with first responders, who were responsible for delivering individuals to safety who were evacuated from their homes or high water. Roadway flooding often meant people were dropped off at the nearest hospital, rather than the nearest shelter, even when no medical attention was needed.[21,27]

> "There were so many areas that were inundated and people being evacuated or rescued from their homes, and the easiest option for a lot of first responders is to bring them to hospitals. We even saw that in helicopter evacuations and they were just overwhelming the TMC with the evacuations of people rescued from homes and being dropped off at a hospital." - *Agency 3*

Similarly, hospitals had issues maintaining their phone lines due to calls from individuals trapped at home with health issues, and other hospitals trying to evacuate their patients.[26,28] Lastly, hospitals were overwhelmed by requests from the general public to fill prescriptions because many retail pharmacies were either inaccessible due to flooding or had trouble maintaining sufficient medication stock.[9] Despite advanced planning, this influx of individuals, calls, and requests overwhelmed the available resources at receiving hospitals.[21]

C) Staffing

Although hospital staff demonstrated remarkable dedication, as detailed above, many hospitals still struggled with staffing concerns during Hurricane Harvey, echoed in all three hospitals' surveys. Most notably, staff were often unable to get to work due to the extended flooding, or they were unavailable on short notice when some hospitals delayed declaring a ride-out — both contributing to understaffed ride-out teams.[17] Hospital A also indicated preparedness concerns related to a lack of situational awareness within the Hospital Emergency Incident Command System (HEICS) structure.

> "[The] decision to declare ride-out was made too late, which meant critical personnel were not available and could not reach the hospital in time; lack of situational awareness within Incident Command structure meant proper incident management did not occur; logistical resources were strained; overall preparedness was missing." - *Hospital A*

Additionally, with many staff remaining on site to complete 12-hour shifts, or unable to leave due to flooded roads, hospitals were forced to create makeshift quarters separate from the patients to provide staff sleeping space.[29,30] Many hospital staff members in ride-out teams experienced anxiety and burnout, and could have benefited from support services developed specifically for hospital staff and their families.[14,21] As Agency 1 stated in an interview, it is important to remember hospital staff are also undergoing a personal disaster during these emergency events.

Barriers to Hospital Flood Preparedness Efforts in Harris County

Some hospitals and local agencies in Harris County responded they had few barriers to hospital emergency management efforts from their repeated experience with extreme flooding events. As one hospital emergency manager stated:

> "I don't believe we have barriers—because of past problems, the organization is now fully committed to disaster preparedness" - *Hospital A*

Neither political resistance nor uncertainty about future flooding were considered barriers to emergency management, according to most survey and interview participants, since well-informed regulatory agencies provided guidance on best practices and flood risk.

However, financial issues and staffing were mentioned in other survey responses and interviews as the biggest barriers preventing preparedness and mitigation efforts in hospitals. Agencies 1 and 2 explained both for-profit and not-for-profit hospitals are responsible for balancing the need for stronger flood emergency management efforts and the associated costs of implementing those efforts and hiring the necessary staff.

Two unpredicted barriers to flood mitigation efforts, both involving local utilities, were identified through the interviews with local agencies. First, many hospital facilities in Harris County, and within the TMC in particular, are fully integrated into the City of Houston's utility services, which include water and sewage. Since these utilities can fail during extreme flooding events, the TMC's hospitals would ideally prefer an independent system, requiring a massive capital infrastructure project. Another barrier to flood mitigation efforts stems from Harris County's power lines, which are strung above-ground on poles and are often damaged during high wind events, creating extensive power outages. However, unlike many other Texas cities,

there has been hesitancy to bury the power lines underground because Harris County in particular is susceptible to flooding and subsidence, which also pose a threat to power lines. These two utilities-related challenges to flood mitigation were echoed by the U.S. Department of Homeland Security's 2018 National Preparedness Report, which identified infrastructure interdependencies as a top challenge to disaster response and recovery across the country.[31]

DISCUSSION

The analysis of surveys, interviews, and secondary sources revealed Harris County hospitals learned their most valuable lessons about flood preparedness and mitigation through their direct and repeated experience with flooding over the years. These lessons led to improved preparedness and the implementation of several sophisticated flood mitigation projects across Harris County prior to Hurricane Harvey. The most remarkable hospital emergency response successes were the infrastructure improvements in many hospitals that prevented devastation similar to that from Tropical Storm Allison. Additional successes included hospital staff dedication and resilience, advanced planning and preparation aided by using emergency exercises and the HEICS structure, and pre-established collaboration with local partner organizations (SETRAC, in particular) and government agencies at multiple levels.

Despite these successes, hospitals still experienced challenges, such as staff burnout and prolonged roadway flooding that restricted the transportation of supplies, patients, and staff to hospitals. Overall, Hurricane Harvey's path and strength was unanticipated, leading to a breakdown of advanced planning, particularly related to evacuating and transporting patients out of the area while simultaneously managing an influx of patients, phone calls, and requests. These results are consistent with the findings of several reports written after Hurricane Harvey.[19-21]

The current state of flood preparedness and mitigation in Harris County hospitals is rather advanced and mature, validated by the tangible sense of pride in the collective preparation and response to Hurricane Harvey. However, in light of the remaining challenges, Harris County could take additional steps to bolster emergency management efforts in hospitals with fewer financial and staffing resources and less direct flood experience, and could address the county-wide utilities challenges described above. In the year following Hurricane Harvey, Harris County hospitals have already started preparing for the next big hurricane by updating policies, creating an inter-institutional information portal, seeking funding to improve transportation resilience, and purchasing high-water vehicles.[32]

Limitations and Future Work

This case study had a few limitations worth noting. First, this study focused specifically on Hurricane Harvey's impacts on hospitals in Harris County, meaning the results may not be generalizable to other cities or other extreme weather events. However, the successes, challenges, and lessons learned presented in this case study are valuable and have potential to motivate other cities' hospitals to engage in extreme weather emergency preparedness and mitigation, perhaps without previously experiencing an extreme weather event of their own. Second, the survey responses were limited in number and reach. The hospitals that responded to the survey are all large, urban hospitals with substantial financial and staff resources at their disposal for flood preparedness and mitigation efforts, which is not necessarily representative of the average hospital in Harris County, or other locations across the U.S. To supplement the survey and semi-structured interviews with additional county-wide perspectives, we also synthesized news reports and other relevant documents, but it is important to note that secondary

sources may have lower reliability or accuracy than primary sources. Third, this study had a singular focus on hospitals, rather than the healthcare system as a whole, which could have included walk-in emergency rooms, primary car, nursing homes, dialysis centers, pharmacies, and emergency medical services. Lastly, hospital emergency managers and local agencies may have a tendency to highlight successes rather than challenges, potentially biasing findings.

Future work should consider implementing a standardized approach to evaluating hospital emergency preparedness, mitigation, and response to extreme weather events to allow comparisons and sharing of lessons learned across regions.

CONCLUSIONS

This case study aimed to contribute to efforts aimed at improving critical healthcare infrastructure to better prepare for, respond to, and recover from future catastrophic flooding events like Hurricane Harvey. Although this case study focuses on the evaluation of Harris County's healthcare system response to one specific extreme weather event, the methodologies employed could be easily reproduced in other cities and for other events. With extreme flooding predicted to become more frequent and intense in various regions across the U.S. over the next decade,[3,33,34] it is now more important than ever to focus specifically on flooding's impacts on healthcare infrastructure.

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584 **Table 1:** Survey and Interview Participants.
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Hospital or Agency Identifier	Number of Survey Respondents or Interview Participants	Type of Hospital or Agency	Survey or Interview
Hospital A	1	Large, urban hospital	Survey
Hospital B	1	Large, urban hospital	Survey
Hospital C	1	Large, urban hospital	Survey
Agency 1	2	Public health	Interview
Agency 2	1	Local government	Interview
Agency 3	2	Emergency management	Interview
Agency 4	1	Healthcare association	Interview

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