### Title
Decisionmaking in hospital earthquake evacuation: Does distance from the epicenter matter?




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## ABSTRACT

**Study objective:** Over large expanses, the risk for hospital damage from an earthquake attenuates as the distance from the epicenter increases. This may not be true within the immediate disaster zone (near-field), however. The following study examines the impact of epicenter distance and ground motion on hospital evacuation and closure for those structures near the epicenter of the 1994 Northridge Earthquake, and the implications for patient evacuation.

**Methods:** This is a retrospective case-control study of all hospitals reporting off-site evacuations and/or permanent closure due to damage from the January 17, 1994 earthquake in Northridge, California, USA. Control hospitals were randomly identified from those facilities that did not evacuate patients. Distances from the epicenter and peak ground accelerations (PGAs) were calculated for each hospital from Trinet Shakemap data and compared.

**Results:** Eight hospitals evacuated patients (study group), 4 of which were condemned. These were compared to 8 hospitals that did not evacuate patients (control group). The median epicenter-to-hospital distance for evacuated facilities was 8.1 miles (IQR 4.0-17.2) while that for non-evacuated facilities was 14.1 miles (IRQ 10.5-17.0). The difference in

the median distances was 6.0 miles (95% CI -4.8 to 11.9 miles). The PGA had a median of 0.77g (IQR 0.53-0.85) for study hospitals and a median of 0.36g (IQR 0.24-0.50) for control hospitals, where 1g equals the force of gravity. The difference in median acceleration of 0.41 (95% CI 0.14 to 0.55) was significant (p=0.009).

**Conclusions:** The distances from the epicenter for evacuated and/or condemned facilities and control hospitals do not appear to differ in the near field. PGA is a superior indicator of the risk for hospital damage and evacuation. Physicians can obtain these data real-time from the internet and should transfer patients to facilities in areas of lower recorded PGA regardless of distance from the epicenter.

## INTRODUCTION

### Background

Earthquakes remain one the most devastating of natural phenomenon despite advances in the fields of structural engineering and medicine. As illustrated in a recent article in the New England Journal of Medicine, hospitals and their patients remain vulnerable to the temblors' destructive effects.[1] This is not just a problem for the Western United States, but impacts many industrialized nations, including Japan, Italy, Taiwan, and Indonesia. When hospitals are damaged and forced to evacuate patients, physicians are often involved early in decisions regarding which patients to transport and which facilities to select as receiving centers. As such, physicians should have a global understanding of how to select hospitals with low potential for earthquake damage to act as receiving sites for their patients. In addition, emergency managers coordinating the overall response to the earthquake must also determine hospitals at risk for evacuation and those likely to remain functional. These individuals are often involved in identifying destinations for evacuated patients.

In traditional medical earthquake research, it seems almost axiomatic that the farther away one is located from the epicenter, the less damage is observed to the healthcare system. This assumption is evident

in many medical and non-medical publications. Discussions of earthquake impact focus on the location of the epicenter, the distance of towns from this location, and the overall energy release of the temblor.[2,3]

When data are reported (intensity of ground shaking, mortality), they are often depicted graphically by symmetrically enlarging circles originating at the epicenter, implying this location is the area of greatest ground motion, and that a smooth decrease in effect occurs as distances increase.[2-4] Models used to predict earthquake mortality incorporate distance from the epicenter and global measures of earthquake intensity as though this inverse relationship of epicenter distance and earthquake impact apply at all locations.[3]

**Importance**

If this inverse relationship between epicenter distance and hospital damage is true, then physicians and incident managers should assume hospitals closest to the epicenter will be the most compromised. Patients requiring evacuation from such facilities should then be transported to hospitals located at greater distances from the epicenter.

In the 1994 Northridge earthquake, this is exactly what happened. Incident managers directed patients evacuated from two hospitals close to the epicenter to a hospital located over 20 miles away. However, these patients had to be moved a second time when the receiving hospital was,

itself, condemned and all its patients evacuated.[1] Reasons for evacuation and the numbers of patients that were actually evacuated during this event have been previously reported.[1] This observation calls into question whether decision-makers can rely on a strict relationship between epicenter distance and hospital durability in the immediate disaster zone (near field). Research has already demonstrated that epicenter distance is a poor predictor of earthquake-associated death and injury.[5]

Defining the near field is difficult. It is not an area that can be described by an arbitrarily distance from the epicenter. It is the area defined by significant damage to structures of interest. The distance from the epicenter encompassing these facilities will vary earthquake by earthquake and by structures being studied. Therefore, investigators defined the near field functionally as a circle with a radius from the epicenter to the farthest hospital forced to evacuate patients. Using larger distances does not make sense, as no hospital located at distances beyond this point evacuated patients.

When earth scientists publish earthquake data, their work does not reflect assumptions about damage and distance. Their graphic depictions of energy release are characterized by more complex ameboid shapes.[6,7] Here, a smooth relationship between epicenter distance and earthquake intensity in the near field does not exist.

While an inverse relationship between earthquake impact on hospital function and epicenter distance is clearly true over large distances (hundreds of miles), it remains unclear if it also applies to smaller distances that characterize the immediate disaster zone. If this relationship does not hold for areas relatively close to the epicenter, then common assumptions about hospital structural and non-structural integrity following an earthquake will need modification. This will force new strategies for the early identification of hospitals at potential risk for significant compromise and selecting destinations for patients evacuated from such damaged facilities. One possible alternative is to use peak ground acceleration (PGA) as a measure of the risk for hospital damage. Seismologists recognize PGA as a predictor of building damage for earthquakes. It has been measured for years and is reflected in the indexes developed by seismologists to describe observed building damage; the Modified Mercalli Index and Instrumental Intensity Scale. In a recent study, PGA was highly predictive of fatal and nonfatal injury after California earthquakes while distance from the epicenter demonstrated no such relationship.[5] It is well known that the vast majority of injuries and deaths directly resulting from earthquakes are due to structural damage. Therefore, these data provide further evidence that PGA predicts potential structural damage as manifested by deaths and injuries. Lastly, this

information is rapidly available on the internet after an earthquake in many areas.

### Goals of This Investigation

This study had two primary objectives. First, investigators examined the relationship between epicenter distance and hospital damage/evacuation for facilities in the immediate disaster zone. Second, they explored whether the amount of strong ground motion (measured by PGA) at the hospital site was a better predictor of hospital damage and need for evacuation.

## MATERIALS AND METHODS

### Theoretical Model

The conceptual model for this study relies on several earthquake facts not widely appreciated. The epicenter of an earthquake is not the area of greatest shaking. It is the surface location directly above the buried fault where the earth movement that generates the temblor first begins. The advantage of identifying the epicenter is that it serves as a point of reference to describe the earthquake's rough location and computers can determine its location within minutes of the event. However, the areas of greatest ground movement may actually be located

miles away, influenced by soil composition and direction of the fault rupture.

To state this in the form of a testable hypothesis, assume that distance from the epicenter is a predictor of hospital damage and evacuation within the near-field. One would assume that most damaged/evacuated hospitals would be located closer to the epicenter and most undamaged hospitals located farther away. Therefore, the median epicenter-to-hospital distance for damaged institutions should be less than that for undamaged facilities.

The second hypothesis assumes the amount of ground shaking predicts hospital failure and evacuation. Under this hypothesis, damaged facilities should have higher PGAs than undamaged ones.

**Study Design**

This is a retrospective case-control observational investigation of all acute care hospitals reporting off-site evacuations and/or permanent closure due to damage from the January 17, 1994 Northridge Earthquake in Los Angeles County, California, USA. Investigators compared the median distance from the epicenter for evacuated hospitals with that of an equal number of randomly selected hospitals located in the near-field but not evacuating patients. They also compared the median degree of ground shaking measured by PGA experienced by both hospital groups.

Investigators defined the near field functionally as a circle with a radius from the epicenter to the farthest hospital forced to evacuate patients, a distance of 21.8 miles.

**Setting**

Investigators conducted a study of all acute care hospitals in Los Angeles County, California, reporting at least one inpatient evacuation to another facility secondary to damage from the magnitude 6.7 Northridge Earthquake. The study was approved by the institutional review board of the Los Angeles Biomedical Research Institute at the Harbor-University of California Los Angeles (UCLA) Medical Center.

**Selection of Participants**

Eligible hospitals were identified through review of records from the Los Angeles County Department of Health Services and the California Office of Statewide Health Planning and Development. Existing regulations required hospitals to report damage assessment and patient evacuation. These two agencies are responsible for collecting and reviewing such data. Hospitals were eligible for inclusion in the study if they evacuated at least one inpatient to another acute care facility secondary to damage from the earthquake.

Investigators also identified 25 functioning facilities located within the near-field that did not evacuate patients and entered their names into

a computer. Using a random selection program, an equal number of institutions from this group were identified to match the number of study hospitals. Investigators believed using eight hospitals as controls provided sufficient power to demonstrate a statistically significant difference between the two groups. All such facilities were located within Los Angeles County, although county location had no bearing on selection. These non-evacuated institutions were used as a control group to examine the impact of epicenter distance and severity of ground shaking on hospital function.

**Methods of Measurement**

Distance from the epicenter was calculated using Thomas Guide Digital Edition Version 4.1 software (copyright 2000 Thomas Bros. Maps). The software used latitude and longitude measurements to describe the location of the epicenter, and used addresses to identify hospital locations. These data are highly reliable and precise.

To provide an indicator of the stress hospital buildings experienced during the temblor, the authors obtained peak ground acceleration (PGA) readings for all hospital sites. PGA measures the intensity of ground motion and is recorded as a fraction of the acceleration of gravity. Higher fractions reflect greater ground motion. All readings are taken at the same time, measuring the maximal or peak ground acceleration associated with

a given episode of earth movement. All PGA readings for this study reflect ground motion from the initial shock, not subsequent aftershocks. The authors derived hospital PGA measurements from the Trinet Shakemap data.[8] This technique uses strong motion sensors placed throughout the region to generate a map demonstrating areas of equal ground shaking.[9] At the time of the Northridge Earthquake, approximately 180 sensors existed in the Southern California area. Sensor distribution varied considerably. In densely populated areas, sensors were separated by 2-3 miles. In sparsely populated areas, the distance between sensors could be in the order of 10-20 miles. Because the sensors are not always immediately adjacent to hospitals, the shaking attributed to a hospital's location is extrapolated from the nearest sensor. As such, the measurement possesses a degree of uncertainty. This difference between the degree of ground motion at the sensor's location and that experienced by the hospital depends on the soil conditions. For a sensor located 1 mile away from a hospital, the difference in PGA between the two locations will be negligible if the soil conditions are similar. In an extreme situation, where the sensor is on bedrock and the hospital on sandy soil, the difference in PGA could vary by as much as 100-150%. This degree of soil variability is not common and most extrapolated PGA readings accurately reflect ground motion at the hospital locations.

## Outcome Measures

Primary outcome measures were comparisons between the study hospital group and the control group with respect to the median distance from the epicenter and the median PGA. Since investigators could not control the number of study hospitals enrolled, they did not perform *a priori* calculations to determine a sample size and an effect size required to achieve statistical significance. However, a relevant number associated with a seismically significant difference can be obtained from the intensities associated with increasing degrees of ground motion shown in Table 1.[10] Seismically, an intensity of VI is considered the threshold for structural damage. Therefore, a difference in PGA of more than 0.18 g, which is associated with an intensity of VI, would be meaningful.

## Primary Data Analysis

All statistical analyses were conducted using SAS version 8.2 (SAS Institute, Cary, NC) or Stata version 9.2 (Stata Corp, College Station, Texas). Continuous or numerical variables are presented as medians with interquartile ranges (IQRs). Statistical significance was determined using the two-sided Wilcoxon rank sum test using a significance level of 0.05. Ninety-five percent CIs for the medians of continuous variables were calculated using the bias corrected accelerated bootstrap method.[11] Ninety-five percent confidence intervals for the differences in medians

were determined using the CENDIF command in Stata, with a Fisher's z transformaton.[12]

## RESULTS

### Characteristics of Study Subjects

Ninety-one acute care hospitals existed in Los Angeles County at the time of the earthquake. Eight of these hospitals (9%) reported off-site evacuation of at least one inpatient as a result of earthquake damage. Four were ultimately condemned. All eight facilities participated in the study. An equal number of control institutions were selected from the 25 facilities within the near field that did not evacuate inpatients. Locations for participating hospitals and the epicenter are graphically represented in Figure 1.

### Main Results

The epicenter distances and PGA values for study and control institutions are listed in Table 2. The distribution of distances from the epicenter for study hospitals had a median of 8.1 miles (95% CI 4.0 to 21.5 miles) and an IQR of 4.0 to 17.2 miles. The distribution of distances for control hospitals had a median of 14.1 miles (95% CI 8.4 to 17.3 miles) and an IQR of 10.5 to 17.0 miles (Figure 2). The observed difference in medians of 6.0 miles (95% CI -4.8 to 11.9 miles) was not statistically

significant because of the large overlap between the two distributions of distances and that the 95% CI includes zero.

In contrast, the distributions of PGAs of study and control hospitals had little overlap (Figure 2). The distribution of PGAs for study hospitals had a median of 0.77g (95% CI 0.53 to 0.89g) and an IQR of 0.53 to 0.85g while the PGAs for control hospitals had a median of 0.36g (95% CI 0.20 to 0.50g) and an IQR of 0.24 to 0.50g. The observed difference in medians of 0.41 (95% CI 0.14 to 0.55) was statistically significant (*P*=0.009).

An observed difference in median PGA of 0.41g is not only statistically significant, it is seismically important. The empirical association between increasing ground motion and structural damage categories is illustrated in Table 1. Measurements of PGA range from less than 0.0017g to greater than 1g. An earthquake producing 0.18g of acceleration is at the threshold for structural damage (intensity VI). Anything larger than this is associated with increasing structural damage and higher intensities. A difference of 0.41g will increase the intensity category and damage levels for all but the highest categories (IX and X).

## LIMITATIONS

The study has several limitations. The model on which the research project is based relies solely on the PGA as a predictor of potential hospital damage. It does not incorporate other variables such as the year of hospital construction (defining the building code in force at the time), direction of fault rupture, and soil characteristics. While these variables will exacerbate or ameliorate the overall impact of an earthquake on hospitals, the goal of the project was to create a simple model that assists physicians and emergency managers to rapidly and accurately select which hospitals are more or less likely to remain functional and safe for patient occupancy. Given that computers generate shakemaps depicting the areas of greater and lesser ground motion within 30 minutes after a temblor, the use of PGA is practical in this setting.[13] In addition, two of the hospitals forced to evacuate all inpatients following the Northridge earthquake, located 6.7 and 9.5 miles from the epicenter, were built after 1973, when the most current building codes were in effect. This suggests that the year of hospital construction may have limited impact. It also must be emphasized that the decision process for selection of destination facilities is complex and includes such issues as availability of specialty services, the existence of mutual aid agreements, and ease of transport. PGA represents just one factor in this process.

The measurement of PGA is sometimes extrapolated from the nearest sensor. It is possible that the actual PGA at the hospital location could be different than that measured at the sensor location. However, with approximately 180 sensors in place at the time of the earthquake, the possibility of significant differences between the PGA measured by the nearest sensor and that actually occurring at the majority of hospitals in densely populated areas is small. However, it is acknowledged that for any one hospital, there could be a substantial difference between the real and extrapolated PGA reading. Despite this extrapolation, the PGA values were highly associated with the need for evacuation.

The results from this study reflect hospital data from an industrialized country. They have limited applicability to under-developed nations with insufficient financial resources to create networks of ground motion sensors or support seismically sound hospital construction.

The study was not funded to gather data on more than eight control hospitals. So the confidence intervals are wide. Had the authors gathered data on more control hospitals, the confidence intervals for PGA and epicenter distance at these institutions would be narrower. However, this is unlikely to have changed the basic conclusions of the study, given using just eight control hospitals had the power to detect a clinically

(seismically) significant difference and that even with wide confidence intervals, no overlap occurred for PGA.

Lastly, the number of study hospitals is small, resulting in wide confidence intervals for estimated parameters. Nonetheless, it seems clear that PGA is more closely associated with the need for hospital evacuation than is distance from the epicenter. PGA likely represents the best rapidly-available parameter to use when choosing the destination facility for patients that must be evacuated from a damaged hospital.

## DISCUSSION

Hospitals are frequently damaged by earthquakes. Some facilities sustain enough damage to partially or completely compromise function. These institutions may be forced to evacuate patients in the minutes to hours following the event. Physicians play a key role in this process by identifying which patients can be discharged home and those that will require evacuation to another acute care facility. Physicians also participate in the selection of appropriate receiving centers for the evacuated patients. In the Northridge Earthquake, the evacuation of 22 neonates from one institution was totally controlled by physicians, including obtaining helicopters for transportation.[1]

One of the major problems in hospital evacuation is selecting an appropriate facility to receive the displaced patients. This conundrum is faced by both physicians and emergency managers involved in the evacuation process. Traditionally, it has been assumed that hospitals at greater distances from the epicenter would remain functional and be good candidates to act as receiving centers. However, the data from this study suggest this assumption is incorrect for institutions located in the near-field. Investigators found no consistent difference in distance from the epicenter between evacuated and non-evacuated hospitals following the Northridge Earthquake. In fact, three of the four hospitals that were completely evacuated and condemned were located at the greatest distances from the epicenter among study hospitals (Table 2).

If epicenter distance fails to predict hospital durability, an alternative indicator is needed. PGA readings may be such an indicator. This study demonstrated a statistically and seismically significant difference between PGA readings for evacuated and non-evacuated hospitals in the near-field. Further, there was much less overlap in the distributions of PGA between study and control hospitals than for distance to the epicenter, making PGA a potentially useful predictor.

Using PGA measurements to identify receiving hospitals at low risk of damage has the additional advantage that the information is rapidly

available. Computers can analyze the data from ground motion sensors and create a shakemap depicting the distribution of the varying degrees of ground motion within 30 minutes after the earthquake. These sensors are durable and the vast majority do not sustain damage from the earthquake. Physicians and emergency managers with internet access can obtain these data real-time. By selecting hospitals to act as receiving centers in areas with low PGA readings, physicians and emergency managers can improve the probability that these institutions will retain the functional capability to accept their transferred patients. In addition, emergency managers can make estimates of the number of hospitals that may be damaged by noting which hospitals are located in areas of elevated PGA readings.

While contacting hospitals by telephone to determine whether they can accept evacuated patients is theoretically possible, this option frequently fails. Telephone lines are either damaged by the temblor or the system's capacity is saturated soon after the event due to large numbers of individuals placing calls simultaneously. It becomes essentially impossible for hospitals to use available electronic communication devices to obtain information about the status of surrounding facilities. If the communications system does function, it does so in an intermittent and unreliable fashion. Under such conditions, a method of establishing the

functional status of hospitals that does not depend on intact communications is required. The use of PGA readings is one option.

This study does not have the ability to define an absolute PGA reading below which all hospitals will remain functional. However, the data demonstrate that no hospital recording PGA readings below 0.46g sustained sufficient damage to force patient evacuation. This number can be used as an initial guideline, pending more definitive future research.

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**Table 1. Intensity descriptions with the corresponding peak ground accelerations.**

| Instrumental Intensity | Acceleration (%g) | Perceived Shaking | Potential Structural Damage |
|---|---|---|---|
| I | < 0.17 | Not Felt | None |
| II-III | 0.17 - 1.4 | Weak | None |
| IV | 1.4 - 3.9 | Light | None |
| V | 3.9 - 9.2 | Moderate | Very light |
| VI | 9.2 – 18 | Strong | Light |
| VII | 18 – 34 | Very Strong | Moderate |
| VIII | 34 – 65 | Severe | Moderate to Heavy |
| IX | 65 – 124 | Violent | Heavy |
| X+ | > 124 | Extreme | Very Heavy |

## Table 2. Geological Data for Hospitals

| Study Hospitals | | | | Control Hospitals | | | |
|---|---|---|---|---|---|---|---|
| | Distance from Epicenter (miles) | Peak Ground Acceleration (gravity) | Condemned | | Distance from Epicenter (miles) | Peak Ground Acceleration (gravity) | Condemned |
| Hospital 1 | 0.8 | 0.80 | No | Hospital A | 2.8 | 0.49 | No |
| Hospital 2 | 4.0 | 0.89 | No | Hospital B | 8.4 | 0.51 | No |
| Hospital 3 | 4.0 | 0.93 | Yes | Hospital C | 12.7 | 0.34 | No |
| Hospital 4 | 6.7 | 0.74 | No | Hospital D | 13.0 | 0.60 | No |
| Hospital 5 | 9.5 | 0.81 | No | Hospital E | 15.3 | 0.38 | No |
| Hospital 6 | 12.9 | 0.59 | Yes | Hospital F | 16.7 | 0.20 | No |
| Hospital 7 | 21.5 | 0.46 | Yes | Hospital G | 17.3 | 0.28 | No |
| Hospital 8 | 21.8 | 0.46 | Yes | Hospital H | 22.8 | 0.13 | No |

**Figure 1. Epicenter and hospital locations, Los Angeles County, California**

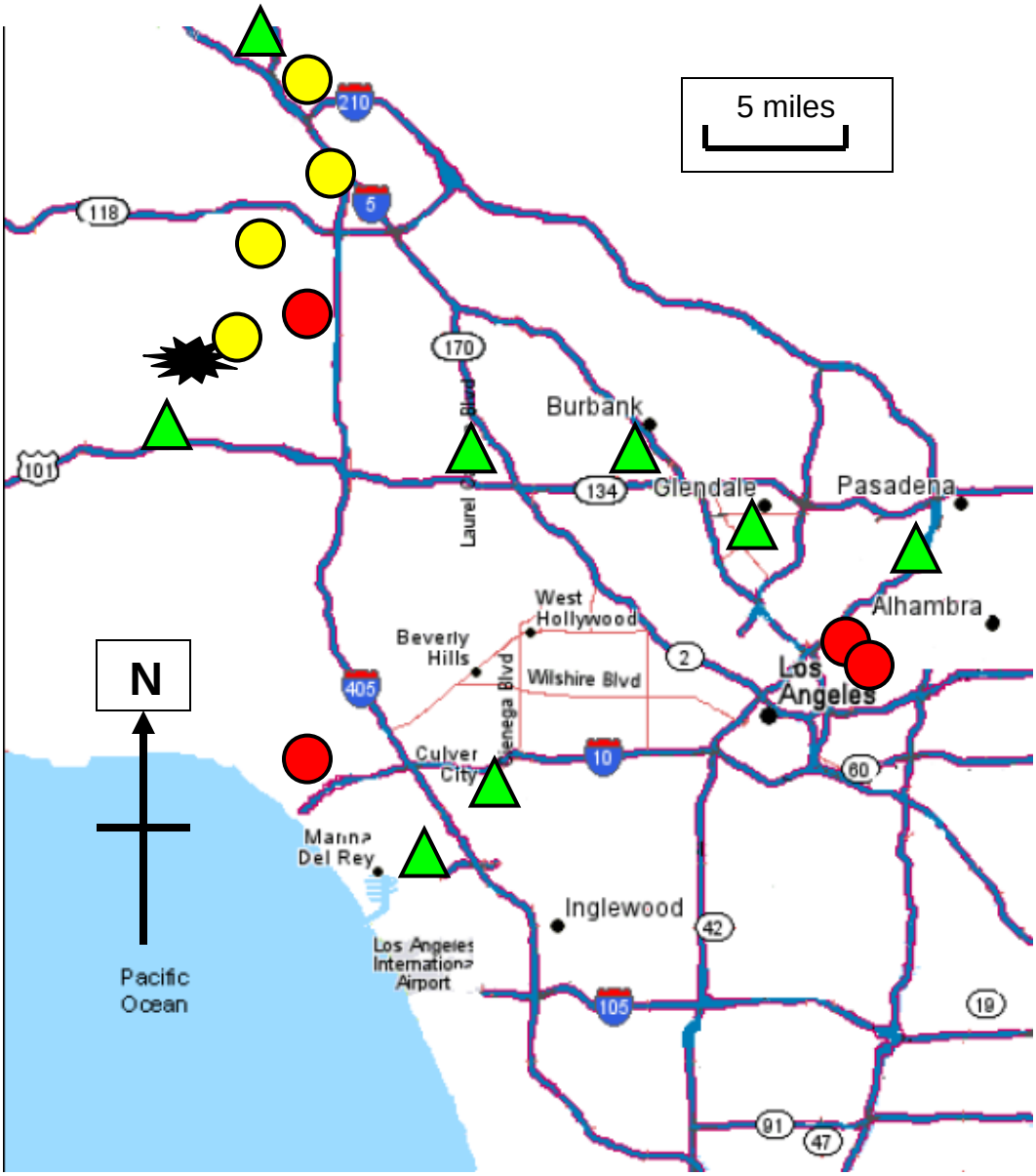


**Figure 1 legend**

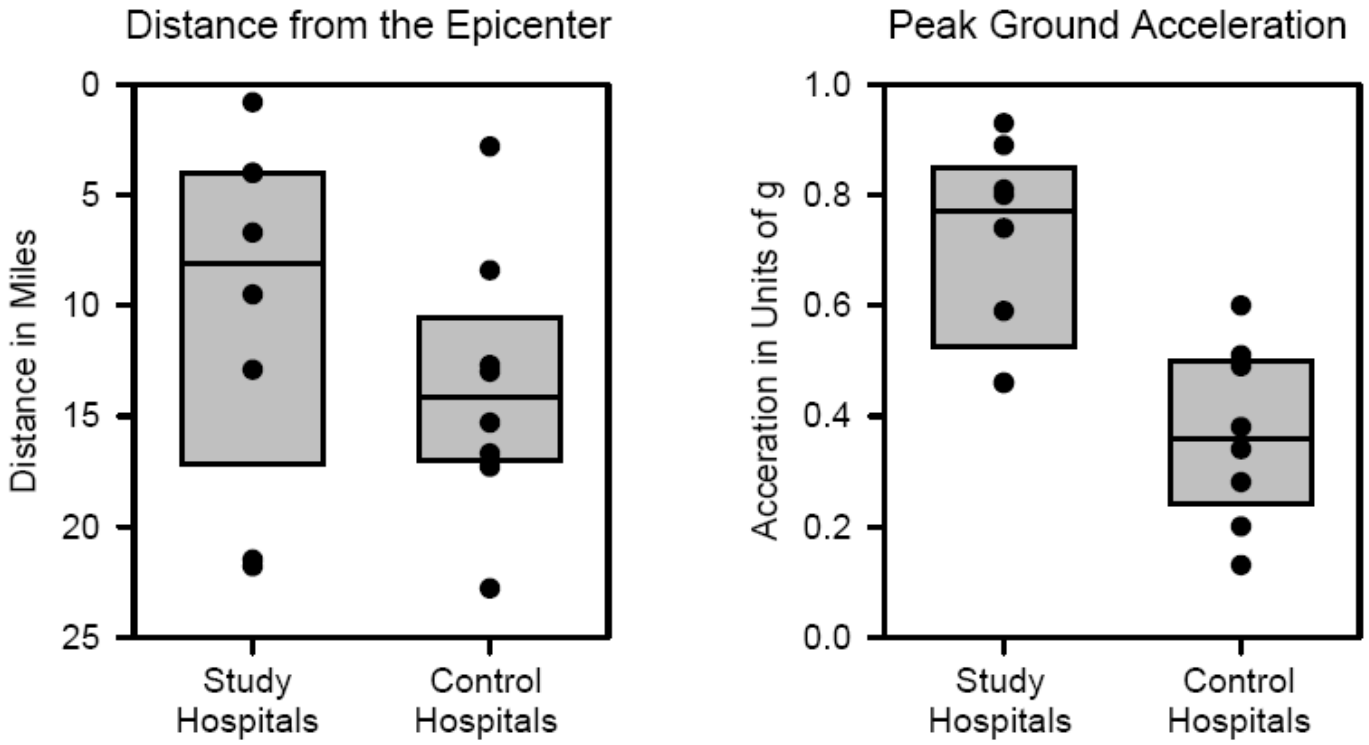
**Epicenter location**

**Evacuated hospitals**

**Evacuated and condemned hospitals**

**Control hospitals**

**Figure 2. Distribution of Distances from the Epicenter and PGAs for Study and Control Hospitals**



## TABLE CAPTIONS

Table 1: The Instrumental Intensity Scale. The letter g represents the force of gravity. Numbers listed as %g reflect the percentage of the force of gravity."

## FIGURE CAPTIONS

Figure 1: This map shows the geographic locations of the study and control hospitals, as well as the epicenter of the 1994 Northridge earthquake.

Figure 2: This figure shows the distribution of distances from the epicenter and peak ground accelerations (PGAs) for study and control hospitals. For each distribution, the box plots show the limits of the IQR ($25^{th}$ and $75^{th}$ percentiles) while the center line shows the median. The left panel demonstrates essentially complete overlap in the distribution of distances, even though the median distance to the epicenter is smaller for study hospitals than for controls. In contrast, the right panel demonstrates a higher degree of separation in PGA between study and control hospitals, with no overlap of the IQRs of the two distributions.