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# IMPLEMENTING A NEGATIVE-PRESSURE ISOLATION WARD FOR A SURGE IN AIRBORNE-INFECTIOUS PATIENTS

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*Abstract


# ABSTRACT

Background: During a large-scale airborne infectious disease outbreak, the number of patients needing hospital-based healthcare services may exceed available negative-pressure isolation room capacity.

Methods: To test one method of increasing hospital surge capacity, a temporary negative-pressure isolation ward was established at a fully functioning hospital. Negative pressure was achieved in a 30-bed hospital ward by adjusting the ventilation system. Differential pressure was continuously measured at 22 locations, and ventilation airflow was characterized throughout the ward.

Results: The pressure on the test ward relative to the main hospital hallway was -29 Pa on average, approximately 10 times higher than the CDC guidance for airborne infection control. No occurrences of pressure reversal occurred at the entrances to the ward, even when staff entered the ward. Pressures within the ward changed, with some rooms becoming neutrally or slightly positively pressurized.

Conclusions: This study showed that establishing a temporary negative-pressure isolation ward is an effective method to increase surge capacity in a hospital.

Highlights

- A 30-bed negative pressure isolation ward was established on a functioning hospital
- The pressure relative to the main hospital was -29 Pa by adjusting the ventilation
- No occurrences of pressure reversal occurred at ward entrance
- Pressures on the ward changed to slightly positive
- Healthcare personnel should wear personal protective equipment on the ward

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**Keywords:** airborne infection isolation room, respiratory infection control, pandemic preparedness, surge capacity, bioterrorism, biodefense

## BACKGROUND

Infectious disease epidemics, such as Severe Acute Respiratory Syndrome in 2003, H1N1 influenza in 2009, and the outbreak of Middle Eastern Respiratory Syndrome starting in 2012, are public health threats that are best mitigated by deliberate planning at the health system level.[1-3] A robust response to a large-scale infectious disease outbreak is predicated, in part, on coordination between public health and healthcare delivery systems. [1,4,5] Hospital pandemic preparedness plans typically include protocols for handling a surge of infectious patients.[6] Hospitals need to respond rapidly if they are among the first-impacted by a highly contagious outbreak.[7]

The vast majority of U.S. hospitals utilize negative-pressure airborne infection isolation rooms (AIIRs) to house patients with suspected or confirmed airborne-transmissible infections. The pressure difference between an AIIR and the hospital corridor is recommended to be -2.5 Pa in the U.S.[8,9] It is also recommended to have an air exchange rate (AER) of 12 air changes per hour (ACH), of which 2 ACH must be outside air in an AIIR.[2,8] In approximately one-half of urban hospitals only 2-4% of rooms are equipped with negative pressure.[10] The number of patients needing healthcare services may rapidly exceed such a small AIIR capacity during an airborne-transmissible pandemic or bioterror event.[11]

There are no regulations stipulating surge capacity requirements for US hospitals. Guidance for intensive care unit (ICU) capacity has been published, ranging from 20% to 300% increase in bed numbers, depending on the type of incident.[5,6,11-14] One option to meet capacity needs would be to implement a temporary isolation ward that could house a large number of patients. To date, there are few studies detailing the effectiveness of temporary isolation wards

to be used during a surge. Rosenbaum et al. demonstrated during a hospital disaster preparedness drill that multiple HEPA-filtered negative air machines placed in a physical therapy gymnasium produced the recommended pressure and AER for negative-pressure isolation.[15] In another demonstration, a 3-unit temporary patient shelter was constructed out of plastic sheeting and ventilated using negative-air machines.[16] Containment was estimated using fluorescent tracer particles, and very high levels of containment were achieved (>99%) with AERs of 15 ACH.

While it is recognized that increased surge capacity is an important component of hospital preparedness, more knowledge and field experience are needed to guide decisions about increasing airborne surge capacity.[17] The purpose of this project was to demonstrate and test whether a functional hospital wing could be operated effectively as a negative-pressure isolation ward for an entire day. Data collected included: pressure differentials at the isolation ward's outer envelope, internal variability of pressure on the ward, performance of the temporary anteroom, pressure fluctuations when ingress/egress events occurred, flow rates and AERs in bedrooms, and UV-C fluxes in stairwells.

# MATERIAL AND METHODS

## Isolation Ward Layout

A functioning hospital in the San Francisco Bay Area, Northern California, was chosen as the study site. The project was completed in March of 2015. A temporary airborne isolation ward was located where it could be effectively isolated from the rest of the hospital. A ward on the top floor of the hospital was chosen because it had a dedicated air handling unit (AHU), a

dedicated bathroom exhaust system, a separate dedicated exhaust system for return registers in existing isolation rooms, and a fire-wall separating the ward from the rest of the hospital. Figure 1 depicts the ward layout.

***Figure 1.*** *Isolation ward layout and instrument locations.*

The ward was sealed from the rest of the hospital by closing the fire doors in one hallway (MHH, Figure 1) and by setting up a temporary anteroom in the other hallway (ANT, Figure 1). The temporary anteroom was constructed of a wood frame bolted to the ceiling. Plastic sheeting was taped to the ceiling frame, walls, and floors and fitted with two zippered-openings for doors. All doorways with access to the ward, as well as internal bedroom and bathroom doors, were kept closed during the study except for brief times during staff ingress or egress.

## Ventilation Design and Control

During the demonstration, the AHU was operated with supply airflow reduced to 60% of its normal operating speed and exhaust airflow operating at capacity. The AHU was an air-to-air, constant-air-volume system, set to 100% outside air/100% exhaust manually for this study. All return and exhaust air was directly released through on-roof stacks with no mixing or recirculation. This ventilation scheme generated -29 Pa of pressure across closed fire doors in the main hospital hallway, while limiting nuisance noise on the ward produced by the AHU.

Two HEPA-filtered negative-air machines (MICROCON MAP800, Biological Controls) were operated at 1104 $m^3$/hour to establish negative pressure in the temporary anteroom and

were exhausted into the MHH. Negative-air machine flow rates were set such that the anteroom pressure was highly negative relative to the main hospital hallway, yet not as negatively pressurized as the isolation ward, to direct air flow towards the isolation ward.

During planning visits, pressure measurements collected from the stairwells indicated that they were positively pressurized relative to the ward, limiting the possibility of infectious particles escaping through these spaces except when stairwell doors were opened. One solution to ensure any escaping particles are disinfected was to install upper-room germicidal ultraviolet lamps. These lamps (non-louvered GL-188, Lumalier Corp.) were installed near the door in each stairwell internal to the ward at a height of 2.1 m. UV-C fluxes were measured in both stairwells using a radiometer (Model IL1400A, International Light, Inc.) with an SEL240 UV-C sensor. UV-C measurements were collected in a grid at two distances away from each lamp with the radiometer probe facing the wall on which the lamps were hung. Prior to the demonstration, UV-C lamps were burnt-in for over 100 hours.

## Instrumentation and Data Collection

Two pressure sensors (DG-700, The Energy Conservatory) were used to monitor the ward's outer negative-pressure envelope. Fifteen pressure sensors (Model T-VER-PXU-X, Veris Industries/Onset Computer Corp.) were connected to six data loggers (Model UX120-006M, Onset Computer Corp.) and monitored internal pressure variability on the ward between bedrooms, bathrooms, and the IWH. Pressure sensor probe locations, instrument names, and dataset names are included in Table 2. Reported accuracy for the DG-700 is 0.15 Pa for pressures below 1.5 Pa, and 1% of the reading at higher pressures. Three side-by-side comparisons for the two DG-700s resulted in excellent agreement. Reported accuracy for the

OP sensors is 0.5-1 Pa. In preliminary side-by-side comparisons, good agreement was observed between DG-700s and OP sensors.

A balometer (Model ABT701, TSI Inc.) was used to measure supply, return, and exhaust register flow rates. Table 2 contains the sum of all measured flow rates for the supply, return, and exhaust registers for each room. One return register in the isolation room could not be accessed, and the return register could also not be accessed in the UTL room. AERs were calculated by dividing the highest summed register flow (supply, return, or exhaust) by the room volume.

## Data Analysis

Data time series were split into five time periods for analysis: pre-test (3/17/2015 17:05 – 3/18/2015 13:10; 20 hours), ramp-up (3/18/2015 13:10 – 13:53; 42 minutes), negative-pressure demonstration (3/18/2015 13:53 – 3/19/2015 13:14; 23 hours), ramp-down (3/19/2015 13:14 – 13:54; 40 minutes), and post-test (3/19/2015 13:54 – 3/20/2015 9:32; 20 hours). Ramp-up and ramp-down periods are not considered for data summaries because they include transition periods when the isolation ward, temporary anteroom, and UV-C lamps were being set up or taken down. The temporary anteroom and UV luminaries were operated throughout the 23-hour negative-pressure demonstration phase.

D*oor-opening* events were separated from the *static* pressures on the ward using the average static pressure conditions. All data falling outside of boundaries along a smoothed line fit through the data were identified as door-opening events, and all data within the boundaries

were considered static pressure conditions. Internal pressures were typically smaller, more uncertain, and less temporally variable than outer envelope pressures.

# RESULTS

## *Air Exchange Rates, Pressures, and UV-C Flux*

Table 1 contains room size, sums of supply, return, and exhaust flow rates, and the estimated AER for each room during each phase of the project. BED1 and BED3 had AERs near or above the suggested AER for hospital bedrooms of 4-6 ACH.[8] Bedrooms lacking supply flow (BED2 and BED4) had reduced AERs.

**Table 1.** Volumetric Flow ($m^3$/h) and Air Exchange Rates (1/h) Measured During the Demonstration.

| | | BED1 | BTH1 | BED2 | BTH2 | BED3 | BTH3 | BED4 | ISR* | ISA | ISB | UTL** | ANT | IWH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Surface Area [$m^2$] | | 25.5 | 6.9 | 29.8 | 5.3 | 25.5 | 6.9 | 25.5 | 18.1 | 5.7 | 6.3 | 15.6 | 11.9 | - |
| Volume [$m^3$] | | 69.9 | 16.9 | 81.8 | 13.0 | 69.9 | 16.9 | 69.9 | 49.6 | 15.6 | 15.3 | 47.5 | 32.6 | - |
| Pre-Test | ∑Supply | 505 | - | 0 | - | 395 | - | 0 | 327 | 121 | - | 154 | - | 4745 |
| | ∑Return | 319 | - | 443 | - | 356 | - | 270 | 529 | 337 | - | N/A | - | - |
| | ∑Exhaust | - | 189 | - | 230 | - | 172 | - | - | - | 398 | - | - | - |
| | AER | 7.2 | 11.1 | 5.4 | 17.7 | 5.6 | 10.1 | 3.9 | 10.7 | 21.6 | 26.0 | 3.2 | - | - |
| Neg. Pressure Demo | ∑Supply | 432 | - | 0 | - | 396 | - | 0 | 346 | 135 | - | 164 | - | 3781 |
| | ∑Return | 343 | - | 482 | - | 386 | - | 325 | 563 | 347 | - | N/A | - | - |
| | ∑Exhaust | - | 161 | - | 200 | - | 159 | - | - | - | 385 | - | 2209 | - |
| | AER | 6.2 | 9.5 | 5.9 | 15.4 | 5.7 | 9.4 | 4.6 | 11.4 | 22.2 | 25.2 | 3.5 | 67.7 | - |
| Post-Test | ∑Supply | 391 | - | 0 | - | 433 | - | 0 | N/A | 136 | - | N/A | - | N/A |
| | ∑Return | 340 | - | 425 | - | 391 | - | 297 | N/A | 306 | - | N/A | - | - |
| | ∑Exhaust | - | 170 | - | 195 | - | 170 | - | - | - | 382 | - | - | - |
| | AER | 5.6 | 10.0 | 5.2 | 15.0 | 6.2 | 10.0 | 4.3 | N/A | 19.6 | 25.0 | N/A | - | - |

* Only two of three return registers were measured, so total return and air exchange rates listed here are underestimates of actual rates. Estimating the AER for ISR using the design flow rate for the unmeasured register resulted in pre-test and demonstration phase AERs of 15.5 and 16.1 ACH, respectively.

** The UTL return register could not be accessed for measurements.

Means and standard deviations of static pressures are presented in Table 2. Mean isolation ward pressures during the negative pressure demonstration were about -29 Pa, both across the closed fire doors and the temporary anteroom. The pressure gradient across the anteroom had higher-pressure differences on the ANT-MHH side than the IWH-ANT side, which was the intended design.

**Table 2.** Static Pressure Data Measured During the Demonstration.

| | Instrument Name (Hub/Channel) | Dataset Name ([-] - [+] Probe Locations) | Pre-Test Phase Mean (±STD, Pa) | Neg.-Pressure Demonstration Mean (±STD, Pa) | Post-Test Phase Mean (±STD, Pa) | Comments |
|---|---|---|---|---|---|---|
| Outer Envelope | DG-700-01 (Ch. A) | IWH-MHH$_1$ | 0.0 (0.1) | -28.9 (0.9) | - | Across Fire Doors |
| | DG-700-02 (Ch. B) | IWH-MHH$_2$ | - | -28.8 (0.9) | - | Across Anteroom |
| | DG-700-01 (Ch. B) | ANT-MHH | 0.0 (0.2) | -17.5 (2.4) | - | |
| | - | IWH-ANT | - | -11.2 (1.9) | - | Sub. Estimate |
| Stairwells | DG-700-02 (Ch. A) | ANT-STR1 | - | -20.9 (2.6 ) | - | |
| | - | IWH-STR1 | - | -32.2 (1.7) | - | Sub. Estimate |
| | OP-08 (OH-03) | IWH-STR2 | -4.4 (1.3) | -22.2 (0.9) | -3.4 (0.9) | |
| Isolation Room | OP-01 (OH-01) | ISR-IWH | -19.1 (3.1) | -17.7 (0.2) | -19.5 (0.2) | |
| | OP-02 (OH-01) | ISR-ISA | -7.4 (1.2) | -7.1 (0.1) | -7.7 (0.1) | |
| | - | ISA-IWH | -11.7 (1.9) | -10.7 (0.2) | -11.8 (0.2) | Sub. Estimate |
| | OP-03 (OH-01) | ISB-ISR | -4.4 (0.7) | -4.1 (0.1) | -4.5 (0.1) | |
| Bedrooms and Bathrooms | OP-11 (OH-04) | BED1-IWH | 0.0 (0.1) | 0.5 (0.1) | -0.1 (0.1) | |
| | OP-10 (OH-04) | BTH1-BED1 | -1.4 (0.2) | -1.3 (0.2) | -1.4(0.2) | |
| | OP-14 (OH-06) | BED2-IWH | -0.5 (1.2) | -0.6 (1.0) | -0.1 (0.1) | |
| | OP-15 (OH-06) | BTH2-BED2 | -1.6 (1.4) | -1.7 (0.7) | -1.7(1.6) | |
| | OP-07 (OH-03) | BED3-IWH | -0.6 (0.1) | -0.1 (0.2) | -0.6 (0.1) | |
| | OP-06 (OH-03) | BTH3-BED3$_1$ | -1.5 (0.3) | -1.4 (0.2) | -1.7 (0.2) | |
| | OP-09 (OH-03) | BTH3-BED3$_2$ | -1.3 (0.3) | -1.2 (0.2) | -1.4 (0.2) | Duplicate |
| | OP-04 (OH-02) | BED4-IWH | -1.6 (0.6) | -1.2 (0.1) | -1.7 (0.5) | |
| | OP-05 (OH-02) | BTH3-BED4 | -0.3 (0.3) | 0.0 (0.1) | -0.3 (0.3) | |
| Utility Closet | OP-12 (OH-05) | UTL-IWH$_1$ | 0.0 (0.1) | 0.2 (0.1) | -0.1 (0.1) | |
| | OP-13 (OH-05) | UTL-IWH$_2$ | 0.1 (0.1) | 0.3(0.1) | 0.1 (0.1) | Duplicate |

Many internal pressures measured between bedrooms and the IWH became less negative during the negative-pressure demonstration. Pressure differences across the AIIR anteroom were higher on the ISA-IWH side than on the ISR-ISA side. Bedroom-IWH pressures were much smaller than those measured on the ward's outer envelope.

In stairwell 1, the UV-C flux ranged from 10-20 μW/cm$^2$ at a height of 2.4 m. An exponential decline in UV-C flux was observed with height in both stairwells, as expected. At a height of 1.8 m the UV-C flux ranged from 0.2-0.4 μW/cm$^2$. At lower heights, fluxes were less

impacted by the distance away from the lamp, likely because much of the light at lower heights was the result of reflection from upper-room surfaces, resulting in a homogenized spatial variability. UV-C fluxes of 20-40 $\mu W/cm^2$ are recommended for disinfecting tuberculosis.[18] Flux levels at lower heights were within recommended levels for human safety.[19]

## Temporal Variability of Pressure Differentials

To explore temporal variability, smoothed pressure time series are plotted in Figures 2a and 2b. Figure 2a shows that the IWH-MHH and IWH-STR2 were relatively unchanged throughout the negative-pressure demonstration. There was also typically little temporal variability in internal pressures, with the exception of BED2. BED2 was used as a family and visitor room, and it was not possible to keep the door of this room closed throughout the demonstration.

**Figure 2.** smoothed pressure time series of (a) outer envelope and isolation room pressure differentials and (b) internal pressure differentials. Vertical lines split pre-test, ramp-up, demonstration, ramp-down, and post-test time periods.

## Door-Opening Events

Figure 3 depicts the door-opening events compared to the steady-state pressure conditions on the ward for the outer-envelope and the ISR-IWH pressure differences. Door-opening events made up 5.7% of the outer-envelope pressure time series and 2.3% of the ISR-IWH time series. Besides the ISR-IWH pressure difference, other internal pressures did not vary

with door-opening events that occurred at the outer-edge of the ward's pressure envelope. Internal pressures were impacted when bedrooms and bathrooms were entered, but these were rare compared to frequent traffic by hospital staff in and out of the ward. Ward door opening events resulted in pressures typically changing to around 0 to -5 Pa. Most ingress/egress events occurred on the fire door hallway side, the side without the anteroom, as this allowed easier access. The ANT-STR1 and IWH-STR2 differences tended to only reduce to near-zero values when stairwell doors were opened, otherwise negative-pressure was maintained even when the ward was opened at other locations. The ISR-IWH pressure difference typically became more negative when the ward was depressurized, and only decreased when the AIIR was entered.

To understand the dynamics of pressure changes during door-opening events, we calculated the length of each event, the maximum pressure reached (Figure 4), the median pressure during the event, and whether the event resulted in a positive pressure. These parameters helped identify potential deficits in ability to contain airborne infectious particles on the ward during healthcare worker (HCW) ingress or egress. Door-opening events lasted 7.5 second on average, and the longest event lasted 50 seconds. Events where fire doors were not closed tightly were longer than 30 seconds. Brief pressure fluctuation events with negative median and maximum pressures are pictured as blue clusters in Figures 4c-f. For the IWH-MHH time series (Figures 4a and 4b), only one event was identified where pressures became slightly positive. No events were identified where ANT-MHH pressures became positive. Stairwells had more positive-pressure generating door-opening events. The ISR-ISA pressure difference exhibited the highest number of positive-pressure generating events.

**Figure 3.** Static pressure time series (blue markers), door opening events (red markers, grey line), trimmed-mean time series (black line), and door-opening event identification boundaries (green lines) for the outer pressure envelope during the negative-pressure demonstration.

**Figure 4.** Door-opening event maximum pressures and event lengths, with markers colored by the median pressure measured during the event.

## DISCUSSION

This project demonstrated that a temporary airborne isolation ward capable of sustained negative pressure in excess of national infection control guidelines can be designed and operated for 24 hours. In a real-life scenario, there will most likely be a need for increasing surge capacity for much longer periods. The successful maintenance of a negatively pressurized ward over long durations is achievable from an engineering standpoint following the data presented here, but there may be other clinical factors that need to be addressed for this approach to be successful in reality. More studies may be needed to show the effectiveness of such an isolation ward in maintaining surge capacity over longer periods and in terms of clinical endpoints of infection control.

The pressure difference between an AIIR and hospital corridor is recommended to be -2.5 Pa in the U.S., with an AER of 12 ACH, of which 2 ACH must be outside air.[2,8,9] Through dilution of airborne particles and limiting air migration volume, isolation rooms significantly reduce the likelihood of airborne particles escaping into adjacent corridors.[20] While it is clear

from previous studies that increased containment is observed with AIIR pressure differentials greater than -2.5 Pa,[20] an optimal pressure has not been determined.[21]

It was decided for this project to achieve a sizeable pressure difference on the ward while keeping nuisance noise to the staff, patients, and visitors at a minimum. We were able attain a pressure difference of -29 Pa before the noise on the ward became an issue. It was determined that this approach was warranted considering the ramifications of failing to contain an airborne disease. Using this approach, we demonstrated negative pressure could be maintained throughout the ward, even during door opening and dynamic HCW movements.

During the demonstration, all but one bathrooms on the ward stayed negatively pressurized relative to the adjacent bedrooms (BTH3-BED4 became neutrally pressured). Bathrooms must be kept pressurized to prevent odors and bathroom-related contamination from escaping.[22] Bathroom AERs were particularly high to remove odors, while bedrooms were at the recommended level of 6 ACH or lower (Table 2).[8]

A main goal of a ventilation system is to provide thermal comfort for building occupants. An additional goal in a hospital is infection control, thus many systems are 100% outside air and have higher air exchange rates than typical office buildings. When supply air is reduced, there may not be sufficient conditioned air serving the rooms and the occupants may feel more uncomfortable. This situation would be less in milder climates. This project was conducted in a milder climate, the San Francisco Bay Area where at the time of the study in March 2015, the mean temperature for the week of the study was 16 °C, with a minimum of 8 °C and a maximum of 24 °C. During the study, we received one complaint from a nurse who commented that the air felt dry.

The speed of the ward's AHU supply fan was reduced for the demonstration to control ventilation rates. Another option would be to control individual room dampers, which for this hospital would have added an additional layer of complexity that was beyond the scope of the demonstration. As a result, some room airflow changes within the ward were not entirely predictable. As expected, an overall reduction in supply flows was observed during the negative-pressure demonstration, but there was significant room-to-room variability. This variability resulted in two rooms within the ward (BED1 and UTL) becoming neutrally or positively pressurized during the demonstration. In BED1, the difference between the supply and return flow decreased from 186 to 89 $m^3$/h during the pre-test and demonstration phases, respectively. Interestingly, room-to-room variability in ventilation flow changes was not limited to supply flow changes, but often return flows increased and exhaust flows decreased when negative pressure was implemented. Despite our findings that airflow reversals were rarely encountered, they are possible even when pressure gradients far exceed CDC guidelines (as seen on the ward in BED1 and UTL). Therefore, it is prudent for HCWs and visitors to wear airborne precautions (eg., an N95 respirator) while residing on these wards, whether in patient rooms or common areas.

During a surge of ill patients, a hierarchy of hospital infection control measures should be implemented,[23] including engineering controls, administrative controls, and personal protective equipment (PPE). This approach was used to help curtail the resurgence of TB in the 1990s. While engineering controls are important for the creation of an effective negative-pressure isolation ward, administrative controls (eg., patient triage and proper ingress and egress of patients and visitors) and proper donning and doffing of PPE are essential

components of infection control and prevention that work in concert. Early in the course of a high-consequence infectious disease outbreak when large numbers of ill patients require healthcare services, it may be necessary for hospital engineers to rapidly convert a routinely functioning ward to a negative-pressure isolation ward. We have demonstrated that this type of conversion may be achieved in approximately 40 minutes, including installation and troubleshooting of the anteroom.

At our demonstration site, project personnel and hospital staff decided that in addition to demonstrating the temporary isolation ward, supplemental infection control strategies would be included. These strategies included a temporary hall anteroom and UV-C lamps in stairwells. The temporary anteroom showed appropriate pressure and ventilation conditions to contain airborne contamination, although at times during door-opening events the anteroom-associated pressure differences were highly variable, probably due to its design and construction. In six minutes, 99.9% removal efficiency in the temporary anteroom could be achieved, assuming unobstructed air movement.[2]

Anteroom use is often recommended for airborne infection control.[20,24] The optimal anteroom pressure differentials and flow rates for aerosol containment with consideration of HCWs moving through doorways have not been determined. Studies have shown that opening the doors of isolation rooms can generate flow across the doorway.[25-27] Inducing a pressure difference, however, across a door can decrease the air volume exchange across the door.[25,28] For this demonstration it would have been optimal to construct an anteroom at each hallway entrance to the temporary isolation ward (we only constructed one to minimize project complexity). With two hallway-anterooms, one would be used as a clean anteroom for ingress

and PPE donning, and the other would be a potentially contaminated anteroom for egress and PPE doffing.

Upper-room germicidal UV-C fluxes were appropriate for disinfecting any escaping contamination. Lamps were installed as close to doors as possible to irradiate any air volume exchange due to door opening. They were accepted by the staff on the ward, which contributed to the knowledge gained about how surge capacity interventions are viewed by staff.

According to the Institute of Medicine's report on medical surge capacity,[5] cost of pandemic preparedness is important to consider when developing a plan, and tents, temporary housing materials, disaster response trailers, and HEPA-filtered negative-air machines are expensive purchases. Temporary patient housing options and gymnasiums also do not typically provide amenities found in hospital bedrooms such as oxygen supply lines, various medical devices and equipment, and a bathroom with a toilet and shower. Because of these limitations, using existing hospital spaces and ventilation systems to establish a surge ward could be an improvement on previous negative-pressure isolation ward designs. Supplemental methods to increase surge capacity, such as reverse-triage,[29] reducing non-urgent hospital admissions,[12] and delaying certain types of surgery,[30] could provide the room availability needed to establish a surge ward in a functioning hospital.

In contradistinction, the key challenges we faced in this project were months of planning and coordination with hospital administrative processes that are typical for any U.S. healthcare facility. Close collaboration and cooperation involved numerous departments and disciplines, including infection control and prevention, nursing and hospice services, occupational health, environmental agents service, safety services, medical center leadership, and engineering

services. The engineering and hospital infection control departments helped design the temporary ward plan, and input from nursing leadership on the ward was vital for determining what would be possible during the surge demonstration. Hospital leadership was briefed with the full plan in the weeks prior to the demonstration. When conducting such a project at a functioning hospital it is essential to balance the needs of the patients, hospital staff and requirements for a successful demonstration.

## CONCLUSIONS

Our demonstration affirms that a temporary negative pressure isolation ward may be an effective way to increase surge capacity during a large-scale outbreak of an airborne-transmissible infectious disease. Even though air pressure differentials well exceeded CDC guidelines, airflow reversals still occurred. These reversals only occurred within the ward and not between the hall anteroom and the rest of the hospital, thus still containing a possible outbreak. Accordingly, it is prudent for healthcare personnel to wear personal protective equipment when working on temporary negative-negative pressure isolation wards.

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# Supplemental Information


**Figure S1.** Pictures of the temporary anteroom installment: (top left) external ingress view, (top right) external egress view, (bottom left) internal ingress view, and (bottom right) internal egress view.

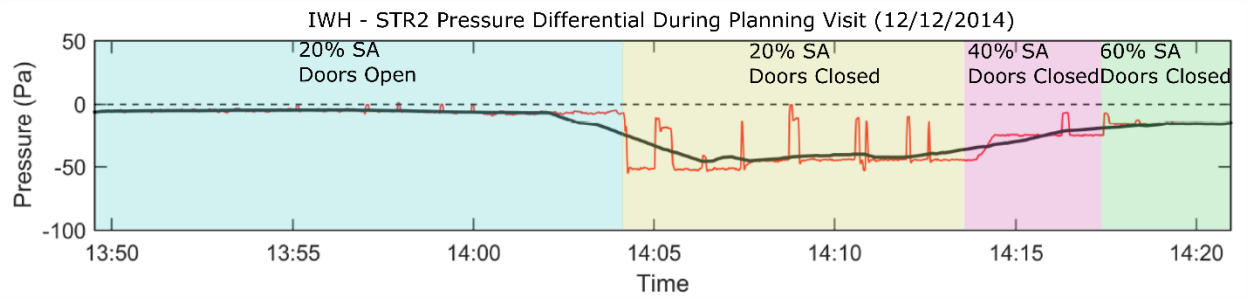


**Figure S2.** Planning visit stairwell pressure test (SA - supply air).

**Figure 1**

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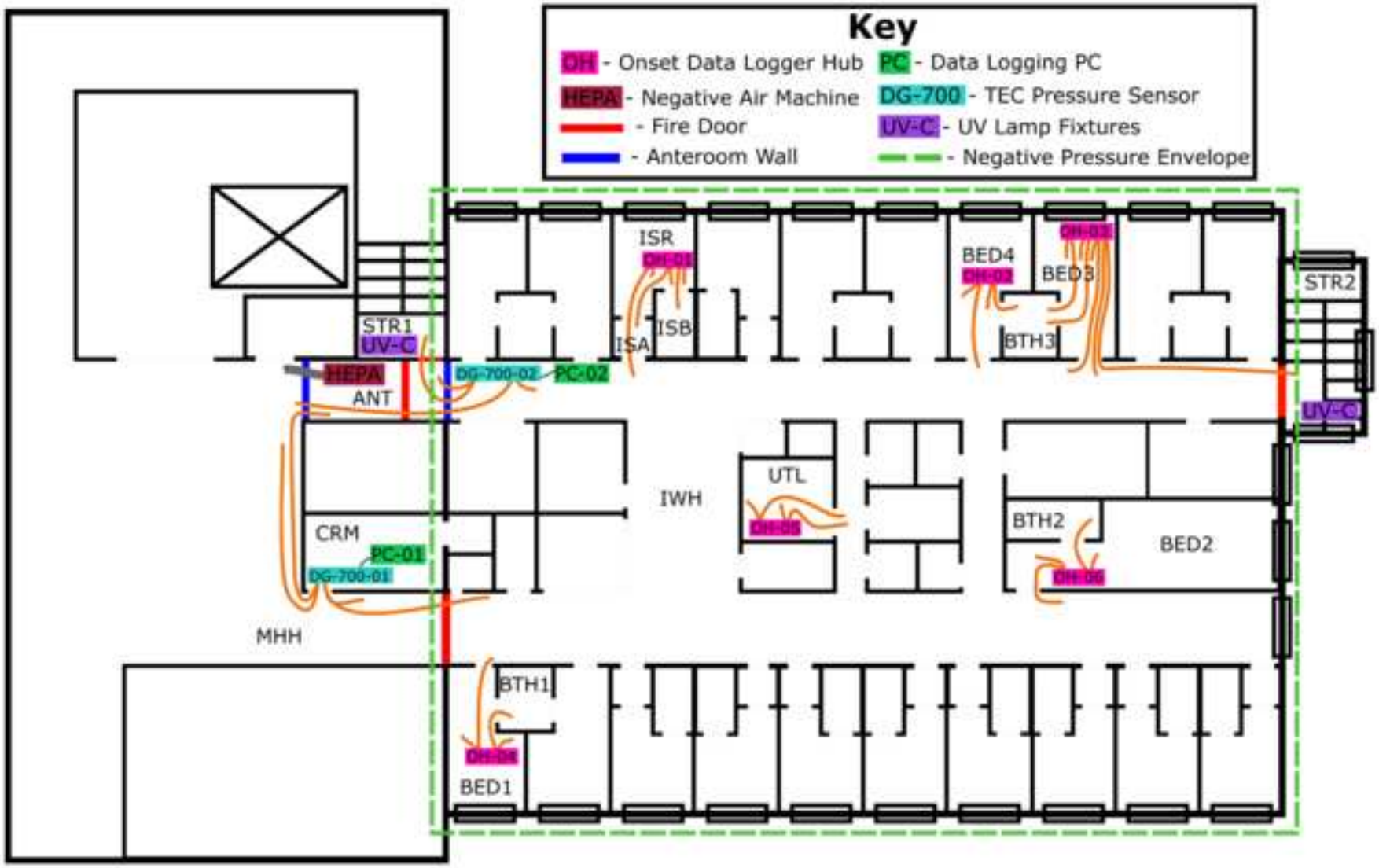


## Room Type Labels

MHH - Main Hospital Hallway
IWH - Isolation Ward Hallway
ANT - Temporary Anteroom
STR - Stairwell
BED - Bedroom
BTH - Bathroom
UTL - Utility Closet
CRM - Conference Room
ISR/ISA/ISB - Isolation Room/Anteroom/Bathroom

**Figure 2**

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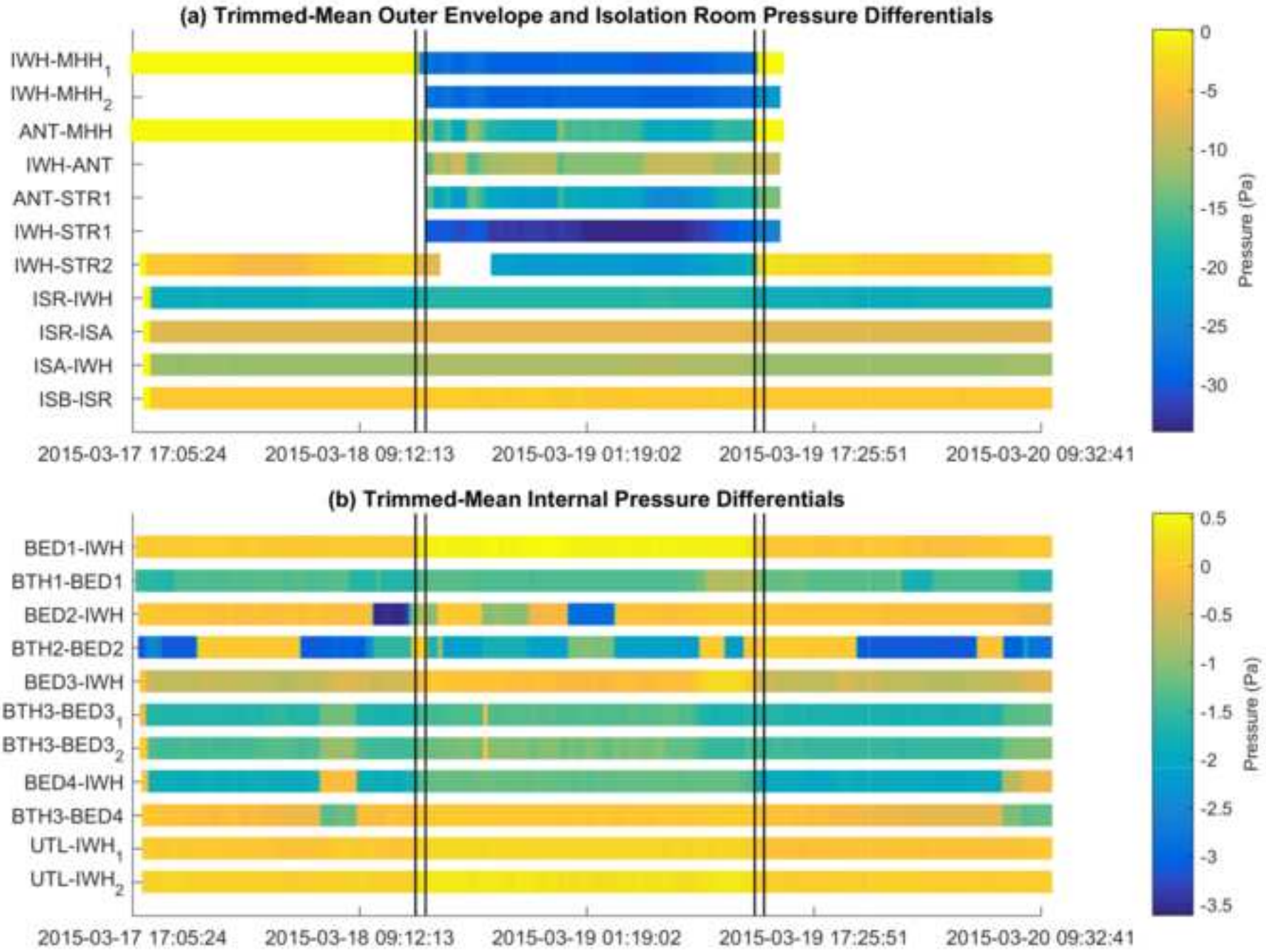

**Figure 3**

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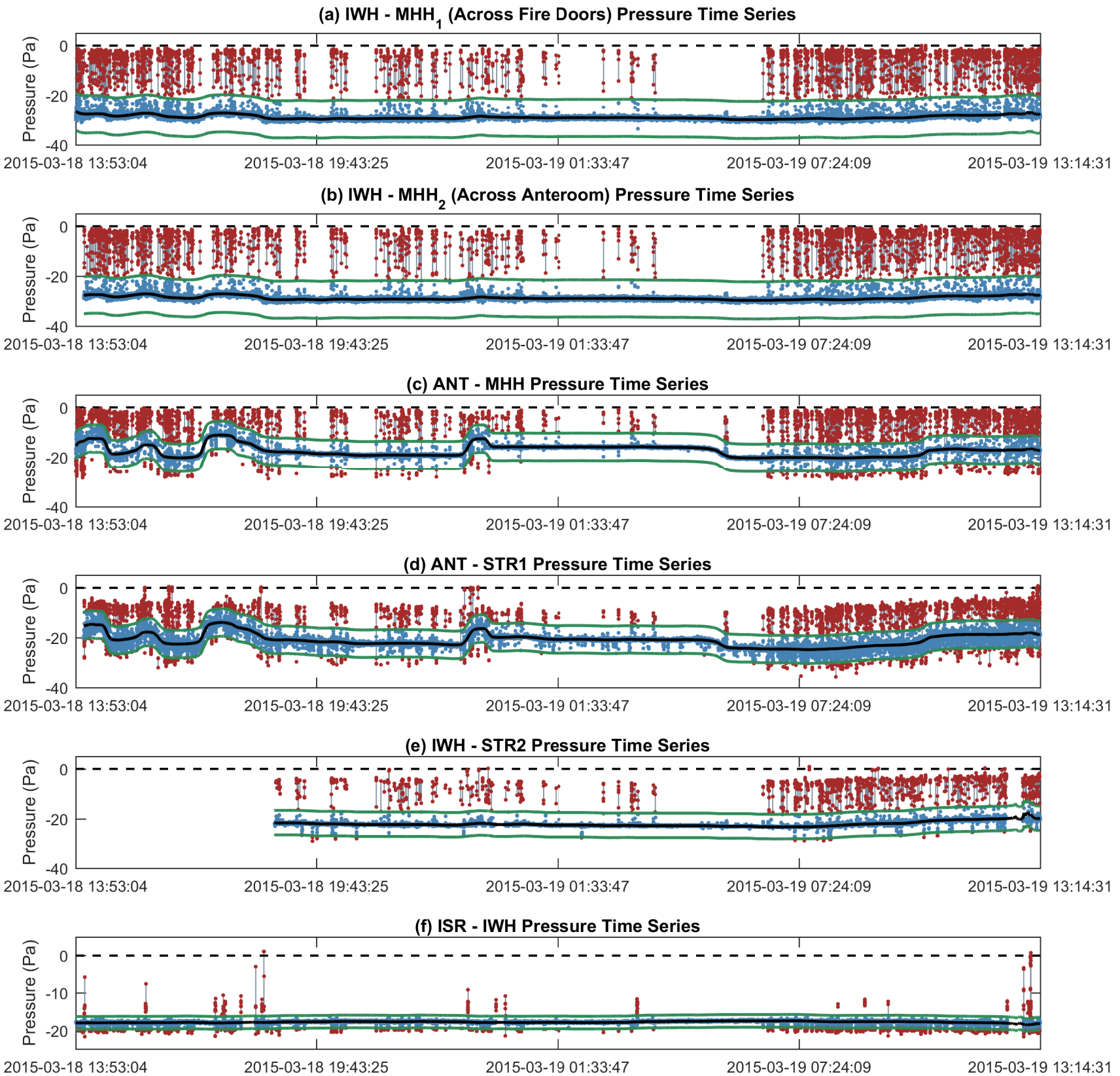

**Figure 4**

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