Rapid #: -17308620

CROSS REF ID: **650717**

LENDER: **BOS :: Main Library**

BORROWER: **MYG :: Main Library**

TYPE:	Article CC:CCL
JOURNAL TITLE:	American journal of respiratory and critical care medicine
USER JOURNAL TITLE:	American Journal of Respiratory & Critical Care Medicine
ARTICLE TITLE:	Measuring ventilation of patient care areas in hospitals. Description of a new protocol.
ARTICLE AUTHOR:	R Menzies , K Schwartzman , V Loo , and J Pasztor
VOLUME:	152
ISSUE:	6
MONTH:	
YEAR:	1995
PAGES:	1992-1999
ISSN:	1073-449X
OCLC #:	

Processed by RapidX: 3/19/2021 7:47:41 AM

Measuring Ventilation of Patient Care Areas in Hospitals
Description of a New Protocol

RICHARD MENZIES, KEVIN SCHWARTZMAN, VIVIAN LOO, and JOE PASZTOR

Montreal Chest Institute and Respiratory Epidemiology Unit, McGill University, Montreal, Quebec, Canada

It has been recommended that ventilation of health care facilities should be monitored regularly to reduce the risk of nosocomial transmission of tuberculosis. We developed a simple method to measure air-change rates and direction of airflow in patient care areas. Pure carbon dioxide (CO_2) was released at 13.5 L/min for 5 min, then measured for 30 min within the room and outside in the hallway. Smoke tubes were also used to measure direction of airflow. Doors and windows (if openable) were manipulated. This protocol, when conducted in five offices in 30 patient care areas in two hospitals, provided good mixing and reproducible decay curves, with less than 15% coefficient of variation for repeated measures over a wide range of air-change rates. Manipulation of door and/or window produced significant changes in air-change rates and airflow direction, although calculated air-change rates were more variable. Smoke tube measurements were inconsistent, agreed poorly with evidence of CO_2 movement from room to hall, and were strongly affected by room to hallway temperature differentials. CO_2 release and measurement proved to be a simple, yet reliable, method to measure air-change rates and the effect of door or window manipulation. Smoke tube measurements were not reliable to characterize direction of airflow. Menzies R, Schwartzman K, Loo V, and Pasztor J. Measuring ventilation of patient care areas in hospitals: description of a new protocol.

AM J RESPIR CRIT CARE MED 1995;152:1992–9.

Nosocomial transmission of tuberculosis has received considerable attention in recent years. Several major outbreaks have occurred as a result of the increasing incidence of active tuberculosis (1), emergence of drug-resistant strains, and occurrence of HIV infection among patients (2–4). As a result, a number of authorities have recommended measures to reduce the risk of nosocomial transmission of tuberculosis, a key feature of which is increased ventilation of patient care areas (5, 6).

Because properly designed and constructed ventilation systems may fail to function properly within a few years (7), regular verification of ventilation has been recommended (5, 8), although by unspecified methods. In a recent extensive review of environmental control, methods of measurement of ventilation were not mentioned (9). Inadequate ventilation was identified as a contributing factor in 11 reports of nosocomial outbreaks published within the last 15 yr. However, measurement methods were: not described (10–12), based on design specifications (13, 14), CO_2 concentrations (13, 15), anemometers to measure airflow out of supply air and into return air ducts (3, 16), paper strips (4), or smoke tubes (2, 3, 13, 16, 17). Problems with these methods include that actual ventilation may be very different from design (7), CO_2 is valid to measure outdoor air delivery expressed as cubic feet per minute *per person*, but not for air change rates (18), anemometers are unreliable because of unpredictable airflow patterns (19), while paper strips and smoke tubes estimate direction of airflow only. In addition, direction of airflow may vary depending on whether the bathroom door or (2) hallway doors (20) are opened or closed, and it may be different if measured at the bottom compared with the top of the door (3).

Accurate measurement of air-change rates requires tracer gas methods (21–23). Most of these methods would be impractical for hospital infection control departments because they require sophisticated equipment for the release, collection, and measurement of the tracer gas. Carbon dioxide is a potential tracer gas (22) that is nontoxic, easily measured with direct reading instruments, inexpensive, and often already available in many hospitals because CO_2 is used in pulmonary function laboratories. We have developed a simple protocol using CO_2 as a "tracer gas" to estimate air-change rates per hour and direction of airflow in patient care areas. Smoke tubes were compared with this new methodology.

METHODS

Preliminary Work

For initial work, CO_2 studies were performed in a single room with a volume of 42 M^3. CO_2 was released at a single site, and measurements taken every 5 min at eight sites within the room and at one site in the hall outside the room during release, and as the concentration declined after the end of release (referred to hereafter as *decay*). The first series of tests were made to determine the effect of fan operation on reproducibility of CO_2 measurements and calculated air-change rates. CO_2 was released once without any fan operation, a second time with an 18-inch fan operating during release only, and a third time with the fan operating throughout release and decay. In the second series of tests, the rate and total amount of CO_2 released was varied to establish the parameters

(Received in original form December 12, 1994 and in revised form March 24, 1995)

Supported by the Montreal Chest Research Institute and the Association Pulmonaire du Quebec.

Dr. Menzies is the recipient of a Chercheur Clinicien Award from the Fonds de Recherche en Santé de Quebec.

Correspondence and requests for reprints should be addressed to Dr. Richard Menzies, Montreal Chest Institute, 3650 St. Urbain St., Montreal, QC H2X 2P4, Canada.

needed to consistently achieve peak concentrations of five to six times baseline.

To estimate the variability of the air-change rates when calculated under different conditions within the room, CO_2 releases were repeated five times with the windows closed, and five more times with the windows open, in each of three naturally ventilated rooms. During each release the door was closed during release and the first 20 min of decay, then opened for the final 10 min. To estimate the effect of position of CO_2 measurements, CO_2 was measured at two sites within the room 2 m apart. To estimate variability of the method at high air-change rates, five consecutive releases were performed in a sputum induction room known to have 15 air changes per hour.

To estimate their variability, smoke tube measurements (smoke tube manufactured by GASTECH, Canada) were taken at six locations around the doorway (two at the top, two at the middle, and two at the bottom) of five naturally ventilated rooms, under four conditions, i.e., with window closed or open and door closed or open. Environmental conditions were varied as follows for each set of measurements: (*1*) temperature in the room 2 to 3° C warmer than in the hall; (*2*) temperature in the room the same as in the hall; (*3*) temperature in the room 2 to 3° C less than in the hall. In total, 72 smoke tube measurements were made at the doorway of each of the five rooms. Smoke release was performed with the smoke tubes held parallel to the plane of the door (i.e., not pointing in or out of the room).

Field Study

CO_2 release and decay as well as smoke tube measurements were conducted in 30 patient care areas in two tertiary-care hospitals in Montreal. The areas studied included 23 single-occupant isolation rooms, four multioccupant nonisolation patient rooms, two bronchoscopy rooms, and one sputum induction room.

Patients were absent from the room while measurements were made, although the technician was present in the room. First the room was inspected, area and volume were measured, and location of window, hallway, and bathroom doors, supply, and return air vents were noted. Temperature, humidity, and air velocity were measured with a hot wire anemometer; this was calibrated weekly with a psychrometer.

Pure CO_2 was released at 13.5 L/min for 5 min from a point 1 m above the head of the bed, considered the breathing zone of a patient in bed. An 18-inch fan was operated through release and turned off at the end of release. The hallway door was kept closed during release and for the first 20 min of decay, then open for the last 10 min of decay. The windows were closed throughout the first release, then (if openable) were opened 10 cm, and the entire release and measurement procedure was repeated.

CO_2 was measured with an ADC infrared direct-reading instrument every minute for 2 min prior to release as a baseline, during release, and for 30 min after release. Two instruments were used, one located at the breathing zone of the patient and the other 1 m outside the patient's door in the hallway. Both CO_2 instruments were calibrated daily to zero using dry nitrogen and to 2,000 ppm using a standard concentration of CO_2. All gases were supplied by Matheson Gas Products Canada.

Smoke tubes were used to measure direction of airflow at the window when closed and when open (if openable), at supply and return air vents, and at bathroom and hallway doors when closed and when open. Smoke tube measurements were conducted on the hallway door at six points: the two top and bottom corners as well as midway on each side.

Analysis

In all tables and figures, CO_2 concentrations measured prerelease (baseline) were subtracted from concentrations measured during release and decay, i.e., only the difference from the baseline measurements are shown. Air changes per hour were calculated under four conditions: (*1*) door closed and window closed, (*2*) door open and window closed, (*3*) door closed and window open, and (*4*) door open and window open, using the following formula (21, 22): $(\text{Log } C_{peak} - \text{Log } C_t)/(t/60)$ where $\text{Log } C_{peak}$ = natural log of peak CO_2 concentration; $\text{Log } C_t$ = natural log of CO_2 concentration at t; t = time in minutes to end of interval or for CO_2 concentration to return to baseline.

Agreement of different measures used was calculated as suggested by Fleiss (24) for categorical variables of three or more levels.

RESULTS

Preliminary Work

When the fan was used during release, there was much less difference between concentrations measured simultaneously at eight different sites within the room; the coefficient of variation of these measures was less than 3%. However, there was little difference when the fan was kept on after release ended, so the protocol was simplified to fan operation during release only. When CO_2 release was varied, a release of 13.5 L/min for 5 min was found to achieve concentrations consistently five to six times greater than baseline.

With the door and window closed CO_2 decay in the room was slow, and CO_2 concentrations in the hallway were not significantly above baseline. When the door to the room was open there was a rapid and significant increase in CO_2 concentrations in the hallway, whereas CO_2 concentrations decayed more rapidly within the room. When the CO_2 release was conducted with the window open, CO_2 concentration increased in the hall, even with the door closed, although this increased more when the door was open while decay in CO_2 concentration within the room was more rapid. In summary, this method could demonstrate movement of air from room to hallway, and it allowed calculation of air-change rates under different conditions.

Results of the 10 repeated measures in each of three naturally ventilated rooms are shown in Table 1. Under the most controlled conditions, i.e., with door and window both closed, the calculated air-change rates were highly consistent in all three rooms. Results were more variable when the door or window was open, and much more variable with both door and window open. These trends can also be seen in Figure 1, which shows results of all 10 releases in one room. The effect of opening the door on rapidity of decay could be easily distinguished when the window was closed, but it was less evident during the window-open release. Finally, when five releases were performed in the sputum induction room with the exhaust fan on and door (with louvered grill) closed, the decay curves were highly similar (Figure 2). Calculated mean air-change rate was 15.3 per hour with a standard deviation of 1.4 for a coefficient of variation of only 9%, indicating very reproducible results at high air-change rates as well.

In the first method of calculation shown in Table 1, decay was calculated for the interval between the peak concentration and the time when the concentration fell to within 2 standard deviations of baseline or the end of the interval, i.e., when the door was opened (25 min) or the end of measurements (35 min). In the second method concentrations at the beginning and end of each interval were used to calculate air-change rates. The two methods of calculation differed mainly at high air-change rates, i.e., when concentrations returned to baseline before the end of the interval—a frequent occurrence when the door and window were both open. Therefore, for all future calculations the first method was chosen.

For all initial work CO_2 was measured at two sites within the room. The first site was at the release point and was considered equivalent to the breathing zone of the patient, i.e., where the head of the bed would be in a hospital room. The second point was 2 m nearer to the door, considered equivalent to just beyond the foot of the bed. When the two sets of measurements were compared (Site 1 versus Site 2 in Table 1), results were very similar, although reproducibility was slightly greater for measurements taken at the breathing zone of the patient. Therefore, for the field study all CO_2 measurements within the room were made at a position over the head of the bed, i.e., the breathing zone of the patient.

Field Study

In the field study 30 patient care rooms were measured, of which

TABLE 1

EFFECT OF MEASUREMENT SITES, CONDITIONS IN ROOM, AND METHOD OF CALCULATION ON ACPH RESULTS*

	Calculation 1†						Calculation 2‡		
	Site 1			Site 2			Site 1		
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
Window closed									
Door closed	1.5	0.2	15	1.6	0.3	18	1.5	0.2	15
Door open	6.3	2.0	31	6.3	2.6	40	6.1	2.0	36
Window open									
Door closed	4.5	1.4	31	4.4	1.4	32	4.5	1.4	31
Door open	32.8	18.8	57	41.5	33	77	21.0	7.8	38

Definition of abbreviations: ACPH = air changes per hour; CV = coefficient of condition.

* Five repeated measures in each of three rooms.

† All peak concentrations are found automatically using arrays. Low concentrations: If value falls within 2 SD (150 ppm) of baseline, then that time and concentration is used. Otherwise the concentration at end of interval (25 or 35 min) is used.

‡ Peak and low calculations at fixed times of 5 and 25 min for door closed and 26 and 35 min for door open.

§ Near point of CO_2 release equivalent to theoretical breathing zone of patient in bed.

‖ Two meters distance (theoretical point below the foot of the bed).

23 had natural ventilation (some with bathroom exhaust), three had active supply ventilation only, two had active exhaust ventilation only, and two had active supply and return air (exhaust) systems. As shown in Table 2, with window and door closed, almost all naturally ventilated rooms had inadequate air-change rates, even those with bathroom exhausts. Some rooms with active supply air or exhaust air had adequate air-change rates, and in the two (isolation) rooms with active supply and return (exhaust) air-change rates exceeded 10 per hour. With door and/or window open, air-change rates were significantly higher, but in almost all rooms this occurred because of movement of air from the room into the hallway. In general, room temperature was lower and air movement greater as air-change rates increased.

An example of a naturally ventilated room with bathroom exhaust is shown in Figure 3. In this room opening the door, or the window, dramatically increased the rapidity of CO_2 decay and at the same time increased concentration of CO_2 in the hall, indicating rapid movement of air from the room into the hallway. A room with active supply but passive return ventilation is shown in Figure 4; the increase in CO_2 concentrations in the

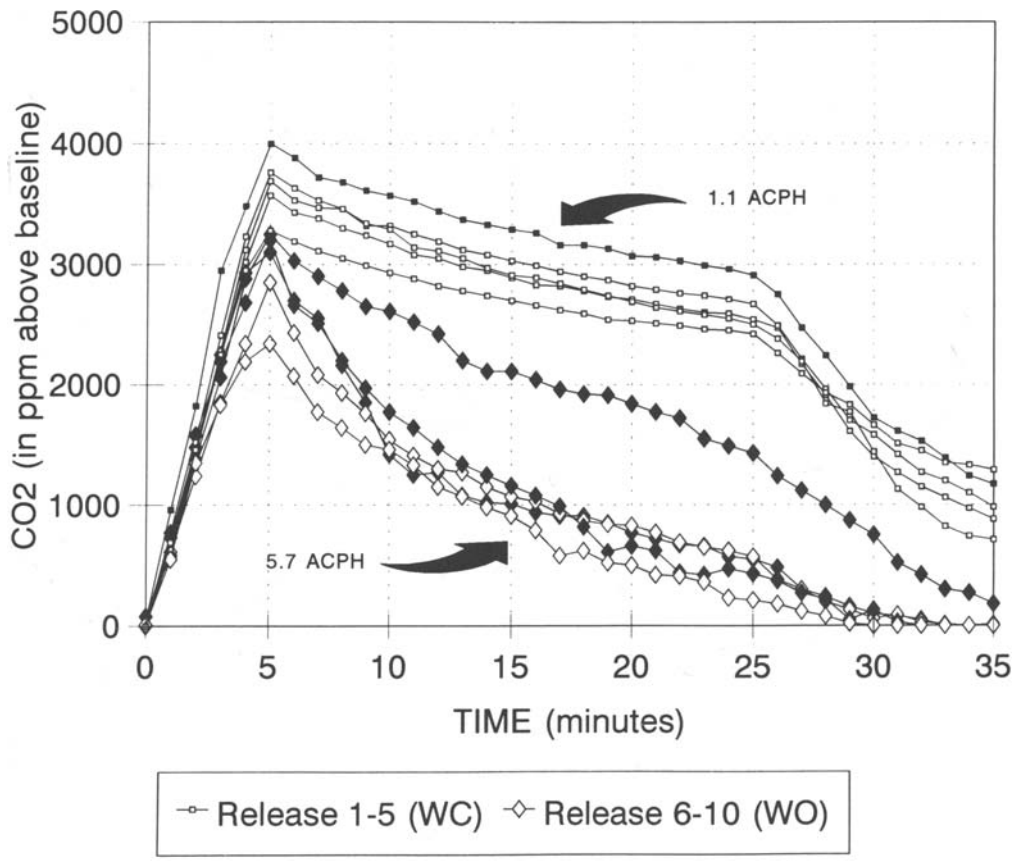

Figure 1. Repeated releases in naturally ventilated room. Window closed: release 1–5. Window open: release 6–10. (Door closed 0–25 min, door opened 26–35 min.)

TABLE 2
DETERMINANTS OF AIR CHANGES PER HOUR

Factor	Rooms (*n*)	Categories of Air Changes/Hour: < 5 (%)	5–10 (%)	> 10 (%)
All patient care areas, n = 30				
Type of ventilation*				
Natural ± bathroom exhaust	23	96	4	–
Supply only	3	67	–	33
Exhaust only	2	50	–	50
Supply ± exhaust	2	–	–	100
Naturally ventilated ± bathroom exhaust, n = 23				
Conditions in room				
Window Door				
Closed closed	23	96	4	–
Closed open	23	48	30	22
Open closed	23	30	35	35
Open open	23	4	9	87
Temperature, °C				
Window closed	23	24.2	27.5†	–
Window open	23	24.1	23.9	22.9
Air velocity, m/s				
Window closed	23	0.01	0.01	–
Window open	23	0.01	0.02	0.11

* Air changes/hour shown for window closed and door closed only.
† Based on one room only.

hallway clearly demonstrate that the room was under positive pressure. Finally, an isolation room with active supply and return air providing high air-change rates under negative pressure is shown in Figure 5. The hallway measures remained at the baseline level, with virtually no change throughout the entire series of measurements, indicating no movement of air from the room to the corridor.

Comparison with Smoke Tubes

In all 30 rooms direction of airflow was assessed using smoke tubes at six points around the doorway on four occasions, i.e., with door open or closed and window open or closed. As shown in Table 3, smoke tube patterns were labeled "into" the room if smoke moved inward at any point of the door even if there was no movement elsewhere, and "out" was similarly defined. A "mixed" pattern was defined as smoke movement simultaneously inward and outward at different points of the doorway. "No movement" was defined as when there was no movement at all six points of the doorway. Approximately one third of all measurements indicated a mixed pattern at the doorway; this was seen with all conditions in the room, all but one type of ventilation, and at all air-change rates. No air movement at the doorway was detected at all levels of air-change rates and all types of ventilation, although mainly when the window was closed. With the window open smoke flowed out of the room into the hall on 42% of occasions compared with 22% when the window was closed. This was generally consistent with the finding that the ratio of CO_2 concentration in the hall to the room was lowest with door and window closed, slightly higher with window open but door closed, much higher with window closed yet door open, and highest with both window and door open. However, despite this similarity of trends with the two measures there was little apparent direct agreement between these two indicators of direction of airflow as seen in Table 3. As well there was no association between smoke tube pattern at the door and air-change rates within the room.

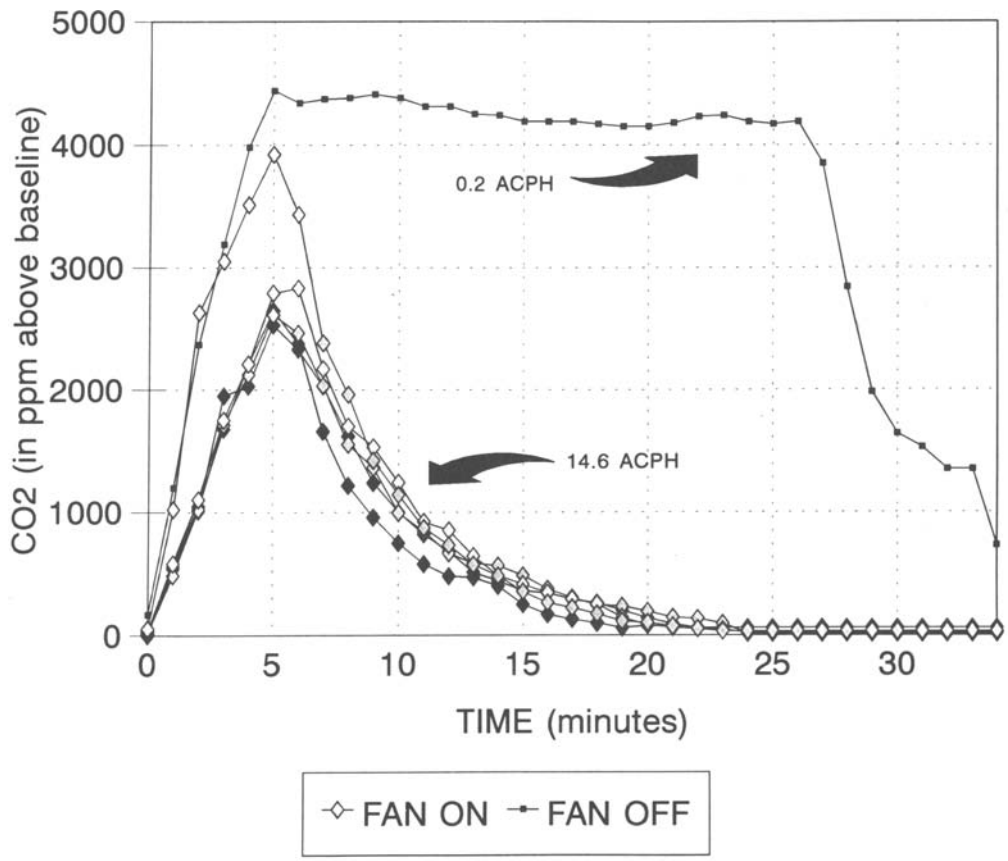

Figure 2. Repeated releases with mechanical exhaust system. Off: 1 release. On: 5 releases. (Door opened after 25 min.)

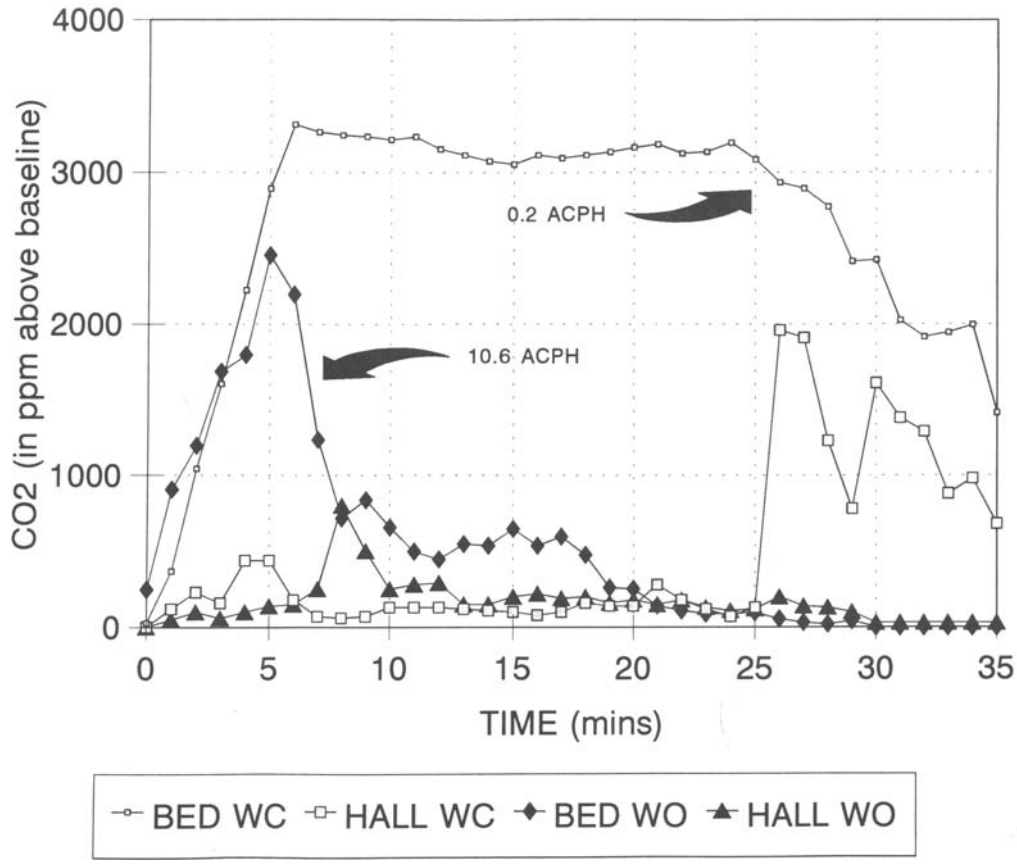

Figure 3. Natural ventilation with bathroom exhaust. Two releases: window closed and window opened. (Door opened after 25 min.)

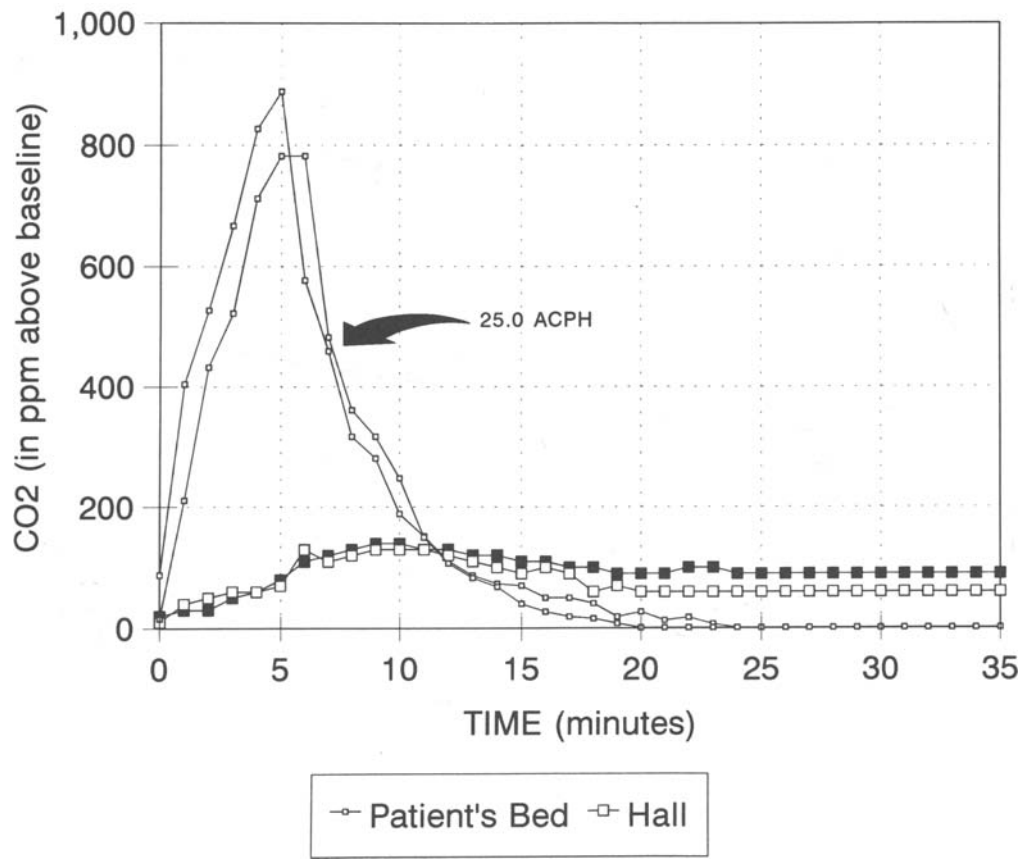

Figure 4. Mechanical ventilation: active supply, passive return. Two releases with sealed windows. (Door opened after 25 min.)

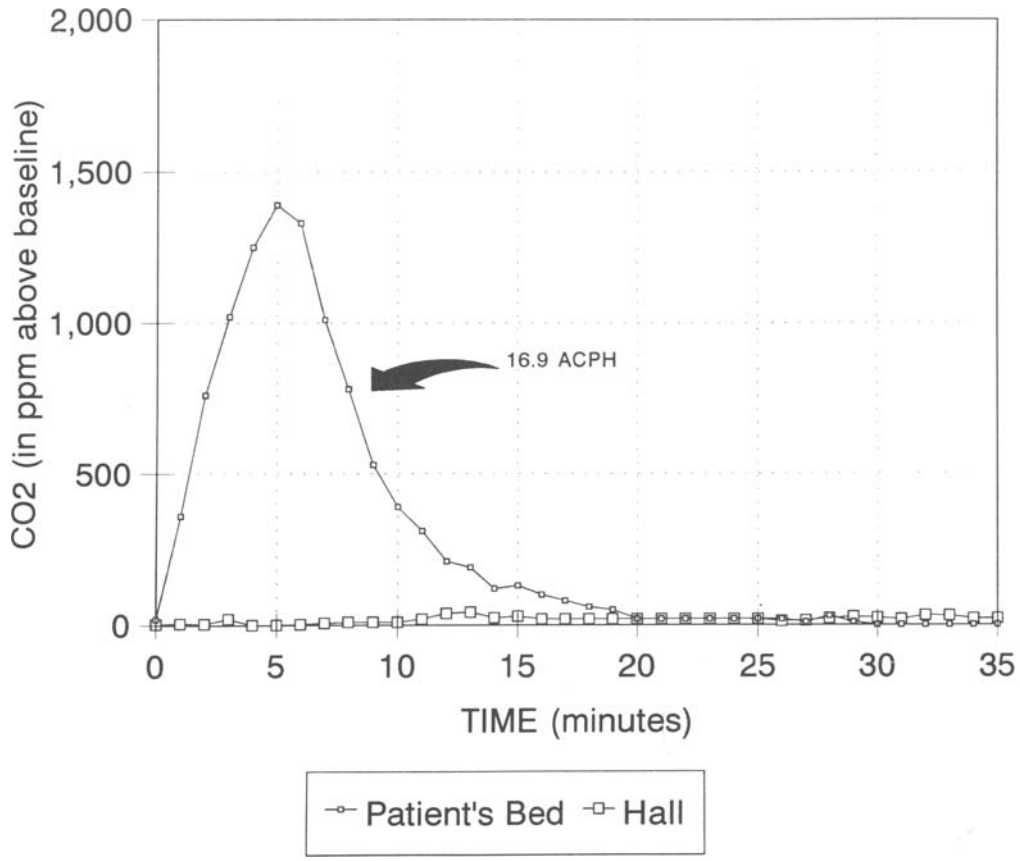

Figure 5. Mechanical ventilation: active supply and return. One release with sealed windows. (Door opened after 25 min.)

TABLE 3

DETERMINANTS OF SMOKE TUBE PATTERNS*

Factor	Rooms (*n*)	Smoke Tube Pattern at Door: Into Room (%)	Mixed (%)	Out of Room (%)	No Movement (%)
Ventilation type (window & door closed only)					
Natural ± bath exhaust	23	26	31	17	26
Supply only	3		33	33	33
Exhaust only	2		50		50
Supply and exhaust	2				100
Conditions in room†					
Window Door					
Closed closed	30	20	30	17	33
Closed open	30	3	50	27	20
Open closed	27	33	15	48	4
Open open	27	26	30	37	7
Air change per hour‡					
< 5	50	22	28	28	22
5–10	18	22	33	39	6
> 10	46	33	12	33	22
CO_2 hall:room ratio§					
Window Door					
Closed closed	30	0.05	0.06	0.10	0.07
Closed open	30	0.33	0.49	0.27	0.26
Open closed	27	0.11	0.07	0.15	0.20
Open open	27	0.40	0.48	0.40	—‖

* All 30 rooms measured under four conditions.
† In three rooms windows were not openable.
‡ Calculated from CO_2 decay measurements.
§ Ratio of simultaneous CO_2 measurements in hallway to within room at breathing zone.
‖ Only two rooms. In both CO_2 levels returned to baseline before door opened.

Because of the poor agreement of obvious CO_2 movement into the hallway with smoke tube measures (Table 3), smoke tube measurements were compared with differing definitions of what constituted significant CO_2 movement from the room into the hallway. As seen in Table 4, despite using increasingly stringent definitions by which to define movement of air from the room into the hallway, there was still poor agreement with the smoke tube pattern. In addition, there was little agreement between the direction of airflow measured by smoke tubes positioned at the bottom and measurements taken at other points of the door (Table 5).

As shown in Table 6, smoke tube measurements were taken in five naturally ventilated rooms while the temperatures within the room were experimentally manipulated. If the room was warmer than the hall, air flowed in at the bottom of the doorway and out at the top; these patterns were reversed if the room was cooler. Of all 60 measurements made when the windows were closed, airflow was inward at the bottom on 14 occasions; at the same time, air flowed out at the top of the door in 11 instances (79%). There was no air movement at any point of the door on

TABLE 4

AGREEMENT OF SMOKE TUBE PATTERN OF AIRFLOW WITH CO_2 LEVEL DETECTED IN HALLWAY

Definition of CO_2 Leak	(*n*)	Measure of Agreement: Crude (%)	Kappa
CO_2 above baseline	114	32	0.2
CO_2 5% above baseline	114	37	0.29
CO_2 10% above baseline	114	44	0.35
CO_2 2 SD above baseline	114	40	0.33

TABLE 5

AGREEMENT OF SMOKE TUBE PATTERN AT BOTTOM OF DOOR WITH THE REST OF THE DOOR*

	Measures (*n*)	Into Room at Bottom (%)	Agreement Bottom with Rest of Door: Crude (%)	Agreement Bottom with Rest of Door: Kappa†
Condition‡				
Window Door				
Closed closed	30	0	47	0.41
Closed open	30	7	30	0.24
Open closed	27	11	33	0.28
Open open	27	26	60	0.55
Air changes/hour				
< 5	50	4	42	0.32
5–10	18	11	28	0.25
> 10	46	17	48	0.39

* All 30 patient care areas.
† Kappa calculated for agreement of two categorical variables of three levels each (24).
‡ In three rooms windows were not openable.

TABLE 6

EFFECT OF ROOM-TO-HALL TEMPERATURE DIFFERENTIAL ON SMOKE TUBE PATTERNS AT DOORWAY

	Temperature Difference (°C)	Total (*n*)	Smoke Tube Patterns: Bottom In (*n*)	Bottom Out (*n*)	Top In (*n*)	Top Out (*n*)
Room warmer						
Window Door						
Closed closed	2.5	5	5	0	1	1
Closed open	2.5	5	5	0	0	5
Open closed	3.8	5	0	5	0	5
Open open	3.8	5	1	4	1	4
Room same						
Window Door						
Closed closed	0.2	5	2	0	1	0
Closed open	0.2	5	1	2	3	0
Open closed	0.6	5	0	5	0	5
Open open	0.6	5	0	5	0	1
Room cooler						
Window Door						
Closed closed	2.8	5	1	2	2	0
Closed open	2.8	5	0	5	5	0
Open closed	3.0	5	0	5	0	5
Open open	3.0	5	0	5	4	1

seven occasions. Air moved outward at the bottom of the door on 38 occasions; simultaneously, airflow was inward at the top in 18 at these instances (48%). On one occasion air moved in at one side of the bottom of the door and out on the other side. When the window was opened air tended to move out of the room into the hall at both top and bottom irrespective of the room-to-hallway temperature differential. This rapid movement of air occurred because outdoor temperatures at that time were between 5 and 10° C and the offices were on the ground floor. Therefore, cooler air rushed into the building through the ground level windows because of the stack effect in the warmer four-storey building.

DISCUSSION

This report describes the development and application of a relatively simple, inexpensive, and reproducible method to determine air-change rates and direction of airflow in patient care areas in hospitals. Smoke tubes, the standard method for estimating airflow direction, proved unreliable.

Regular verification of ventilation conditions is considered important (5, 8, 9), because systems may fail to provide adequate ventilation after some time because of normal wear and tear (7). Accuracy in measurement of ventilation has never been addressed by regulatory agencies (5, 8) even though measurement that overestimates ventilation may result in greater risk of exposure to workers because inadequacies are missed, whereas underestimation of ventilation may result in citation, fines (8), and/or recommendations for expensive refurbishing of the ventilation systems. In addition, accurate ventilation measurements are important in order to estimate exposure of health care workers in outbreak investigations or population-based surveys.

Smoke tubes are inexpensive, and they are very simple tests to administer, record, and interpret. As a result they are in widespread use, are recommended by one authoritative agency (5), and are the most frequent method used to assess ventilation in outbreak investigations (2, 3, 13, 16, 17). The accuracy of smoke tubes has usually not been questioned; in one study reversal of smoke flow direction was noted when doors to the room or bathroom doors were manipulated, which was assumed to indicate true changes in airflow (20). In the only study where smoke tube measures were reported for the top and bottom of doorways, mixed patterns were found in half (3), similar to the present findings. In this study, when room to hallway temperature differentials were created, circular movement of air at the doorway could be demonstrated. Agreement was poor between smoke tube measurements and obvious visual evidence of CO_2 movement from the room into the hallway.

Because the results of smoke tubes and CO_2 provided conflicting results with regard to airflow from patients' rooms, and there is no gold standard, it would be valid to question which was more reliable. In the preliminary phase of this study, CO_2 release provided highly reproducible estimates of a wide range of air-change rates in repeated trials and after manipulation of conditions as was shown in Figures 1 and 2. The more rapid decay within the room, together with an obvious rise in CO_2 concentration in the hallway with the door open (Figure 3) or closed (Figure 4), provided visually compelling evidence of airflow out of the patient room.

Could this rise in CO_2 have been due to diffusion of CO_2 rather than convection or air movement? The diffusion coefficient of CO_2 at 21° C is 0.52 ft^2 per hour or 0.0008 m^2 per minute. With a room-to-hall difference in concentration of 2,000 ppm, diffusion of CO_2 to a point 1 m from the door in the hallway would result in an increase in concentration of 1.6 ppm in 1 min. Therefore, the rapid rise seen in Figure 3 must have been due to convection, or air movement, rather than diffusion. An additional advantage of the use of CO_2 released from the head of the bed is that this more closely simulates release of infectious droplets from a patient. The appearance of CO_2 in the hallway implies that bioaerosols would also move outward, meaning that nosocomial transmission to workers and other patients could occur – even if they never enter the isolation room.

The protocol used in this study was developed from standard tracer gas techniques used to study ventilation in large buildings (21–23). In large spaces, tracer gases other than CO_2 must be used (21, 23) because it is not possible to release sufficient CO_2 to raise the concentration enough above baseline so that decay can then be measured. This is particularly true in occupied buildings because of the production of CO_2 by the occupants. However, CO_2 can be used as a tracer gas if the space is small enough so that release can result in concentrations that are four to five times higher than baseline, good mixing can be achieved, and contribution of CO_2 by occupants is relatively small.

In this study, it proved feasible to release enough CO_2 so that baseline concentrations increased by four to five times in small enclosed patient care areas. In some hospital rooms, the peak CO_2 concentrations were only 900 ppm above baseline. This occurred only in rooms with high air-change rates in which baseline CO_2 concentrations were low so that peak concentrations were still more than three times baseline. Although less than intended, nevertheless the air-change rates were easily calculated and reproducible.

Good mixing of the tracer gas is important to ensure that the decline in concentration reflects dilution from air exchange and not simply continued mixing within the room. Evidence of good mixing was provided by minimal variation between different sites in the same room in the preliminary study, linear decay of the log-transformed concentration of CO_2 (log data not shown), and by reproducibility of repeated measures of air-change rate. All of these conditions were met when a large fan was operated during the release, meaning that this aspect of the protocol was essential to achieve accurate reproducible estimates of air-change rates. During the release and measurement, the sole occupant of the room (i.e., the technician) would have produced at most 0.3 L/min of pure CO_2 (18, 19), i.e., less than 3% of the 13.5 L/min of pure CO_2 released as part of the protocol. Therefore, the contribution of the human occupant should not have interfered with the estimates of air-change rates.

This protocol could be easily applied in many hospitals where frequent accurate measurement of ventilation in patient care areas is required. The technique itself is simple, and calculation of air-change rates requires only a pocket calculator. The only other instrument required is a direct reading infrared or electrochemical CO_2 detector. If measurements at multiple sites are required, air samples can be collected with 50-ml syringes simultaneously at several sites and analysis completed later. CO_2 detectors that provide minute-to-minute digital read-out, accurate to within 10 parts per million, are available for $1,500 to $2,000. This is certainly cost effective when compared with the cost of refurbishing ventilation systems. CO_2 itself is safe, nontoxic, and inexpensive; all tests described in this report were conducted with one tank of pure CO_2 at a cost of approximately $100.00. The protocol described is rapid; air-change rates were estimated in 20 to 30 min. The manipulation of doors and windows means that ventilation can be estimated under different conditions that may be present at different times of the day or different seasons of the year.

We conclude that smoke tubes, although inexpensive and simple, are unreliable, and that CO_2 release and measurement provide more accurate measurement of air-change rates and airflow direction. The protocol described using CO_2 is practical, reproducible, and relatively inexpensive, and it could be adopted by hospitals throughout North America as part of their strategy to limit airborne nosocomial transmission.

Acknowledgment: The writers thank the staff of the two hospitals for their collaboration in facilitating data gathering during the field trial.

References

1. Anonymous. 1993. Tuberculosis morbidity—United States, 1992. *Morb. Mortal. Wkly, Rep.* 42:363.
2. Beck-Sague, C., S. W. Dooley, M. D. Hutton, J. Otten, A. Breedan, J. T. Crawford, A. E. Pitchenik, C. Woodley, G. Cauthen, and W. R. Jarvis. 1992. Hospital outbreak of multi-drug resistant *Mycobacterium tuberculosis* infections: factors in transmission to staff and HIV-infected patients. *J.A.M.A.* 268:1280–1286.
3. Edlin, B. R., J. I. Tokars, M. H. Grieco, J. T. Crawford, J. Williams, E. M. Sordillo, K. R. One, J. O. Kilburn, S. W. Dooley, K. G. Castro, W. R. Jarvis, and S. D. Holmberg. 1992. An outbreak of multidrug resistant tuberculosis among hospitalized patients with the acquired immunodeficiency syndrome. *N. Engl. J. Med.* 326:1514–1521.
4. Daley, C. L., P. M. Small, G. F. Schecter, G. K. Schoolnik, R. A. McAdam, W. R. Jacobs, and P. C. Hopewell. 1992. An outbreak of tuberculosis with accelerated progression among persons infected with the human immunodeficiency virus. *N. Engl. J. Med.* 326:231–235.
5. Centers for Disease Control. 1993. Draft guidelines for preventing the transmission of tuberculosis in health care facilities, 2nd ed. *Fed. Reg.* 58:52810–52854.
6. American Thoracic Society. 1992. Control of tuberculosis in the United States. *Am. Rev. Respir. Dis.* 146:1623–1633.
7. Lindberg, P. R. 1993. Improving hospital ventilation systems for tuberculosis infection control. *In* K. M. Tomasik, editor. Plant, Technology, & Safety Management. Joint Commission on Accreditation of Healthcare Organizations, Oakbrook Terrace, IL. 19–23.
8. OSHA. 1993. OSHA enforcement policy and procedures for occupational exposure to tuberculosis. *Infect. Control Hosp. Epidemiol.* 14:694–699.
9. Segal-Maurer, S., and G. E. Kalkut. 1994. Environmental control of tuberculosis: continuing controversy. *Clin. Infect. Dis.* 19:299–308.
10. George, R. H., P. R. Gully, O. N. Gill, J. A. Innes, S. S. Bakshi, and M. Connolly. 1986. An outbreak of tuberculosis in a children's hospital. *J. Hosp. Infect.* 8:129–142.
11. Kantor, H. S., R. Poblete, and S. L. Pusateri. 1988. Nosocomial transmission of tuberculosis from unsuspected disease. *Am. J. Med.* 84: 833–838.
12. Catanzaro, A. 1982. Nosocomial tuberculosis. *Am. Rev. Respir. Dis.* 125:559–562.
13. Calder, R. A., P. Duclos, M. H. Wilder, V. L. Pryor, and W. J. Scheel. 1991. *Mycobacterium tuberculosis*: transmission in a health clinic. *Bull. Int. Union Tuberc. Lung Dis.* 66:103–106.
14. Haley, C. E., R. C. McDonald, L. Rossi, W. D. Jones, R. W. Haley, and J. P. Luby. 1989. Tuberculosis epidemic among hospital personnel. *Infect. Control Hosp. Epidemiol.* 10:204–210.
15. Nardell, E. A., J. Keegan, S. A. Cheney, and S. C. Etkind. 1991. Airborne infection: theoretical limits of protection achievable by building ventilation. *Am. Rev. Respir. Dis.* 144:302–306.
16. Hutton, M. D., W. W. Stead, G. M. Cauthen, A. B. Bloch, and W. M. Ewing. 1991. Nosocomial transmission of tuberculosis associated with a draining abscess. *J. Infect. Dis.* 161:286–295.
17. Fischl, M. A. 1991. Nosocomial transmission of multi-drug resistant tuberculosis among HIV-infected persons—Florida and New York, 1988–1991. *Morb. Mortal. Wkly. Rep.* 40:585–591.
18. Turner, W. A., and D. W. Bearg. 1989. Determining delivered quantities of outside air, CO_2, tracer gas, or both? *In* H. Burroughs, editor. The human equation: health and comfort. American Society of Heating Refigeration and Air Conditioning Engineers, Atlanta, GA. 117–121.
19. Tamblyn, R. T. 1988. Healthy building manual: systems, parameters, problems, and solutions. Energy, Mines, and Resources, Ottawa, Ontario, Canada.
20. Fraser, V. J., K. Johnson, J. Primack, M. Jones, G. Medoff, and W. C. Dunagan. 1993. Evaluation of rooms with negative pressure ventilation used for respiratory isolation in seven midwestern hospitals. *Infect. Control Hosp. Epidemiol.* 14:623–628.
21. Persily, A. K. 1988. Tracer gas techniques for studying building air exchange. U. S. Department of Commerce, National Bureau of Standards. Gaithersburg, MD.
22. American Standards and Test Material Committee. 1988. Standard test method for determining air leakage rate by tracer dilution. *In* Annual Book of ASTM Standards. American Standards and Test Materials. Washington, DC. 568–575.
23. Persily, A. K., and W. S. Dol. 1991. Field measurements of ventilation and ventilation effectiveness in an office/library building. *Indoor Air* 3:229–245.
24. Fleiss, J. L. 1981. Statistical methods for rates and proportions, 2nd ed. John Wiley & Sons, New York.