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EVALUATION OF VENTILATION RATES THROUGH FOUR TYPES OF RAT CAGES

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ABSTRACT

Laboratory animal ventilation systems should provide a healthy and pleasant environment for both animals and animal caretakers. Microenvironment (cage) conditions that animals experience may be markedly different from the macroenvironment (room) conditions experienced by their caretakers. Specifying laboratory animal ventilation rates in terms of room air exchange rates often does not guarantee even minimally acceptable environments for the laboratory animals. Quantification of the cage ventilation rates is important to understand microenvironmental conditions and is needed by laboratory animal facility designers and operators. Cage ventilation rates at four room air velocities—0, 12, 50, and 100 fpm (0, 0.06, 0.25, and 0.5 m/s); five room airflow directions—0°, 45°, 90°, 135°, and 180° from the front cage surface; and four caging systems—micro-isolator, shoebox, wire-mesh multiple, and wire-mesh single—were measured using a thermal equilibrium calorimetry method. Cage ventilation rates ranged from 0.1 L/s (0.21 cfm) to 0.18 L/s (0.38 cfm) for micro-isolator, 0.6 L/s (1.3 cfm) to 1.7 L/s (3.6 cfm) for shoebox, 2 L/s (4.3 cfm) to 9 L/s (19 cfm) for double wire-mesh, and 0.9 L/s (2 cfm) to 7 L/s (15 cfm) for single wire-mesh cages.

INTRODUCTION

Laboratory animal ventilation should balance air quality, animal comfort, and energy efficiency to provide cage environments that optimize animal welfare and research efficiency. Conditions that optimize animal welfare automatically tend to optimize research efficiency because it is especially important in research to minimize unintended stressors. Additionally, the laboratory animal ventilation system should provide a healthful and pleasant environment for animal caretakers.

The guidelines and current industry practices usually achieve excellent environmental conditions for the caretakers by requiring 10 to 15 air changes per hour (ach). In fact, room air contaminants such as ammonia are typically less than 1 ppm when recommended cage sanitation and management practices are followed as well as the ventilation guidelines.

However, the environments that result for the laboratory animals—cage environments—may be unacceptable both in terms of animal welfare and research efficiency with most typical laboratory animal cage types even when the room environmental conditions meet or exceed guidelines (Zhang et al. 1991a). This finding supports the viewpoint that specifying laboratory animal ventilation systems in terms of room air exchange rates does not provide even minimally acceptable environments for the laboratory animals. Furthermore, the construction of ventilation system and operation costs often far exceed those of relatively similar systems used in other specialized applications—e.g., swine ventilation systems—which generally do achieve acceptable air quality conditions at the animals' levels.

The objectives of this study were to measure the cage ventilation rates and relate these to cage environmental conditions and relate cage ventilation rates to room air velocities and room airflow directions for four typical cage types.

LITERATURE REVIEW

Air quality within laboratory animal macroenvironments (rooms) and microenvironments (cages) is important for human operator and laboratory animal well-being and for reliability of experimental procedures (Besch 1980). Environmental conditions of laboratory animals are affected by factors such as ambient air temperature, humidity, air velocity, and gaseous and particulate concentrations (Woods 1980; Murakami 1971). In turn, these environmental factors can be altered significantly by the quality and quantity of supply air delivered to the airspaces.

Many researchers have recognized that microenvironmental conditions may be markedly different from those in the macroenvironment (Murakami 1971; Hirjarvi and Valiaho 1987), but most published regulations and guidelines are based on macroenvironmental requirements (ILAR 1973, 1976, 1985a, 1985b; NIH 1985; CFR 1984). These guides presume that adequate control of the microenvironment occurs indirectly through control of the macroenvironment. Current industry standards recommend 10 to 15 ach to ensure adequate ventilation (ILAR 1985a, 1985b).

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Recent studies of laboratory animal rooms by Zhang et al. (1991a) show that the ventilation rate to the rooms has little effect on the microenvironmental conditions, especially on ammonia concentration within the cage. In these studies, the rooms had 10.4 to 24 air changes per hour. Ammonia levels for all animal rooms were below 1 ppm, but within the cages ammonia levels varied from 0 to 55 ppm. Apparently ventilation rates of cages is one of the most important factors affecting microenvironmental conditions.

Further evidence of the problems with conventional laboratory animal housing is suggested by the efforts of Keller et al. (1983) to develop individually ventilated caging systems. They developed a forced-air, individually ventilated caging system using polyvinylchloride (PVC) tubing fitted to a rodent rack.

Wu et al. (1985) developed a novel forced-air ventilation system for rodent cages that supplied 2.1 cfm (1 L/s) of fresh air within the cage; the air velocity at rat level was around 26 fpm (0.13 m/s). These forced-air ventilation systems for cages reduced the ammonia concentration by increasing the ventilation rate within a cage, but they require extra equipment and increase the initial cost of the caging system. Therefore, the forced-air ventilation systems have not been widely accepted in laboratory animal facilities.

Intra-cage ventilation was studied by Keller et al. (1989) using a tracer gas method for three mouse caging systems: shoebox, shoebox with a flexible film isolator, and micro-isolator. Keller reported that the rates of air turnover within cages ranged from 0.7 to 16 liters per hour and that the differences among the cage air turnover rates were primarily due to the cage type and the housing status (occupied or unoccupied). The room air velocities and airflow directions are presumably important factors to cage ventilation rate but were not reported in Keller's study.

METHOD AND MEASUREMENTS

Method

The equilibrium thermal calorimetry method (Zhang et al. 1991b) was used in this study for evaluating the air exchange rate of cage airspaces. The method was suitable for opened airspaces, such as a rat cage, for which it is very difficult to install traditional flow measurement sensors. Thermal calorimetry is also harmless to the occupants of the airspace, suitable for small airspaces, and requires simple instrumentation. Procedures for using the equilibrium method are described as follows:

- Select a supplemental heat source, Q_s, for the airspace to be measured.
- Measure the temperatures and humidities of incoming air and the air within the cage when Q_s is not supplied and the cage system reaches its equilibrium state.
- Measure the temperatures and humidities of incoming air and the air within the cage when Q_s is applied and the cage system reaches its stage 2 equilibrium state.
- Calculate the enthalpy differences of air inside and outside the cage, Δh_1, Δh_2, for stage 1 and stage 2, respectively.
- Calculate heat transfer rates through the cage shell, Q_c.
- Calculate the volumetric air ventilation rate of the cage, q, using the following equation:

$$q = \frac{v_s}{\Delta h_2 - \Delta h_1}\left[Q_s - 3.6 \sum_{j=1}^{n} A_j U_j (\Delta T_{j2} - \Delta T_{j1})\right] \quad (1)$$

where

A	=	surface area of airspace shell, ft^2 (m^2);
U	=	heat conductance, $W/ft^2 \cdot °F$ ($W/m^2 \cdot °C$);
v_s	=	specific volume of air, ft^3/lb (m^3/kg);
n	=	total number of components of airspace shell (e.g., three interior walls, four exterior walls, one ceiling, and one floor;
ΔT_j	=	temperature difference across jth component of airspace shell, °F (°C);
1	=	first equilibrium state;
2	=	second equilibrium state;
j	=	jth component of airspace shell.

In an unoccupied cage, Δh_1 at equilibrium state 1 equals zero and Δh_2 equals the enthalpy difference of inside air and outside air. Thus, the measurements and calculation of the ventilation rate, q, are significantly simplified.

Cage Types

Four types of cages were investigated in this study: micro-isolator, polycarbonate shoebox with mesh top, stainless steel wire-mesh for double-rat housing, and stainless steel wire-mesh for single-rat housing (hereafter referred to as isolator, shoebox, wire-mesh double, and wire-mesh single, respectively). These four types of cages were selected from laboratory rat facilities at a U.S university and are widely used in other laboratory rat facilities. Configurations of the four types of cages are illustrated in Figure 1 and data used in the following sections are specified in Table 1.

Supplemental Heat (Q_s)

From the current available data, the sensible heat production rate of a 0.66-lb (300-g) rat is approximately 2.5 W (ASHRAE 1989). A 5-W heating bulb was chosen as the supplemental heat source (Q_s), which simulates the heat production that a pair of 0.66-lb (300-g) rats approximately produce. Since part of the heat can be transferred by short wavelength radiation through the polycarbonate cage shell but cannot go through the stainless steel

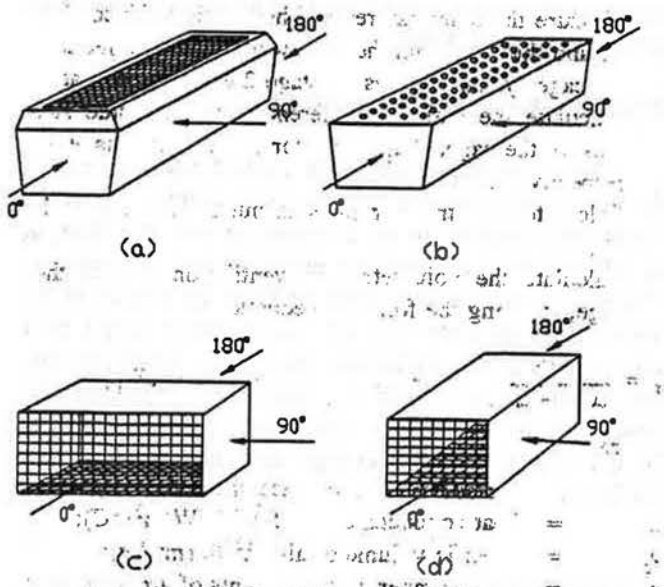

Figure 1 *Sketches of caging systems; (a) micro-isolator; (b) polycarbanate shoebox with metal mesh top; (c) wire-mesh for multiple rats; (d) wire-mesh for single rat. Arrows in the figure refer to room air directions. Plain and hidden surfaces are solid.*

cage shell, a guarded heat box was used to block the radiant heat loss through the cage shell. The guarded heat box was made of black galvanized sheet steel with a high heat conductivity value and had dimensions of 8 by 2 by 2 inches (20 by 5 by 5 cm), which is approximately the volume of a pair of 0.66-lb (300-g) rats. The heat box was located 1 inch (2.5 cm) above the cage floor and at the center of the floor area.

Room Air Movement

Air velocities across cages were controlled by using a 6-inch (15-cm) variable-speed fan. Four levels of room air velocities—0, 12, 50, and 100 fpm (0, 0.06, 0.2, and 0.5 m/s)—were selected for this study. These air velocities were considered to bracket typical room air velocities in existing laboratory rat facilities (Zhang et al. 1991a). Room air velocities were measured at a point 3 inches (7.5 cm) before the room air reached the cage. Directions of room airflow were 0°, 45°, 90°, 135°, and 180°, as shown in Figure 1.

Cage Temperature Measurements

Average temperatures within cage airspaces were measured at four locations, and each point was the mid-point of a cage upper corner and an adjacent heat box corner. The locations of temperature-sensing points had to be selected carefully to achieve the best mean temperature evaluation. It was observed that air temperatures within cage airspaces vary from one corner to another because of incomplete mixing of the air. The four-location temperature measurement gave a mean air temperature within the cages. Humidity ratio of the room air was measured using a mechanically aspirated psychrometer.

The measurement of temperatures and humidities was conducted in unoccupied cages with simulated rats. For this particular study, live rats were not used because:

- It is difficult to measure the mean air temperature within the cage airspace because the rats may smell, chew, and move the sensors.
- Superposition of the supplemental heat over the heat production of rats within the cage would result in a higher air temperature and cause erroneously high cage air exchanges.
- The heat production rates of rats would change in response to the higher temperature. Variation of rat heat production would introduce large errors when using the equilibrium calorimetry method (Zhang et al. 1991b).

Calibration of Heat Conductance of Cages

When evaluating heat loss through the cage shell, heat conductance of the cage shell must be determined. Being a function of the conductivity of cage materials and the heat convection coefficient of cage shell surfaces, the overall heat conductance, U, is a function of cage material, shape, surface roughness, and airflow. U-values can be determined for each cage at each room air velocity using the following procedure:

TABLE 1
Specification of Cages

Cage Type	Material	Calibration Area* ft² (m²)	Shell Surface Area+ ft² (m²)	Volume ft³ (m³)	Rats per Cage
Isolator filter-top	Polycarbonate	4.63 (0.43)	5.49 (0.51)	.89 (.0253)	2
Shoebox mesh-top	Polycarbonate	4.63 (0.43)	4.52 (0.42)	35.3 (.019)	2
Wire-mesh multiple	Stainless steel	4.7 (0.44)	2.8 (0.26)	.63 (.0179)	2
Wire-mesh single	Stainless steel	2.6 (0.24)	1.78 (0.165)	.28 (.0079)	1

*Enclosed surface area used for calibration of heat conductance.
+Solid surface area measured from the cage enclosure.

- Completely enclose the cage airspace with the same material as the cage material so that there is no air leakage to the room airspace. When a supplemental heat source, Q_s, is applied within the enclosed cage airspace, the cage air temperature will reach a steady state. Since there is no air exchange between the cage and the room, heat (Q_s) can only be dissipated through the cage shell.
- Measure the steady-state air temperature within the cage and the room temperature and calculate the difference of these two temperatures, ΔT.
- Measure the area of the enclosed cage (A) and determine U using the equation $U = Q_s/(A\Delta T)$.

This U-value is the average heat conductance of all enclosed cage surfaces. The differences of U-values from the enclosed cage calibration and the real open cages may come from the following error sources:

- *Flow pattern changes*. A real cage has some surfaces (e.g., the front and the bottom of a wire-mesh cage) open to room airspace. An enclosed cage during U calibration changed the cage configuration and hence changed the flow patterns across the cage surfaces. These flow pattern changes introduce differences in the convective heat transfer coefficient.
- *Incomplete mixing of air*. Temperatures within a cage airspace are not uniform, especially when a point supplemental heat source (e.g., a rat in the cage) is applied. Since the equilibrium calorimetry method is based on an assumption of complete mixing, the average temperature within the cage airspace should be carefully evaluated. Cage air temperatures were measured at the same four points for calibration and the real cage in this study. The gradient of cage air temperature was expected to be different from the calibration to a real cage.
- Effects of flow pattern change and incomplete mixing on U-value calibration may be large for these wire-mesh cages because of front and bottom open surfaces. These effects were expected to be negligible for isolator and shoebox cages because they only have open surfaces on the top.

RESULTS AND DISCUSSIONS

Results

A total of 80 trials were made for the measurements—four caging systems, four room air velocities approaching the cage, and five airflow directions (4 by 4 by 5). The 0° direction refers to the room air flowing perpendicularly into the cage front surface and 180° refers to airflow into the rear surface (Figure 1). Results of the measurements and calculations are listed in Table 2, and cage ventilation rates under different room airflow directions versus room air velocities for four caging systems are plotted in Figures 2 through 4.

Fresh Air Exchange Rates into Cages

The air exchange rate, q, in Table 2 refers to the rate of room airflow into a cage or cage airflow out to the room. Note that the *room air* exchange rate of a cage, q, is different from the *fresh air* exchange rate of a cage, q_i. The subscript i indicates fresh air from the outside of the room. This assumes that the concentration levels of a contaminant gas or particulate are C_c, C_r, and 0 for cage air, room air, and fresh air, respectively. Because the content of the concerned contaminant should be the same in the cage-fresh air exchange and the cage-room air exchange,

$$q_i(C_c + C_r) = q\,C_c, \tag{2}$$

the relationship between q_i and q can be obtained from Equation 3:

$$q_i = \frac{C_c}{C_c + C_r}\,q. \tag{3}$$

Equation 3 shows that the fresh air exchange rate, q_i, is always smaller than the room air exchange rate to the cage, q, because the factor $C_c/(C_c + C_r)$ is always less than 1.

Cage Ventilation Requirements

Guidelines and standards (ILAR 1973, 1977; Besch 1980) recommend a ventilation rate of 0.8 cfm (0.385 L/s) per rat with 15 room air changes per hour. This 15 air changes per hour was presumably enough air to meet the 0.8 cfm (0.385 L/s) per rat ventilation requirement. If cage air could be mixed completely with room air, the requirement of 0.8 cfm (0.385 L/s) per rat would be satisfied without difficulty. For example, a 25 by 16 by 10 ft (8 by 5 by 3 m) room can house 700 rats at its full capacity. If the room is ventilated at 15 ach, then the ventilation rate per rat will be 1.5 cfm (0.7 L/s), which is almost double the recommended 0.8 cfm (0.385 L/s). The recommendations of room air changes per hour are usually fulfilled by designers of animal facilities, but the ventilation rate per animal within the cage is usually not evaluated.

Micro-Isolator Cage

As listed in Table 2, the micro-isolator cage room exceeds the 15-ach recommendations, but the cage air ventilation rates are 0.21 to 0.4 cfm (0.1 to 0.18 L/s), which is already lower than the 0.8 cfm (0.385 L/s) per rat requirement. Moreover, the common practice is to house two rats in a micro-isolator, which only allows 0.1 cfm (0.05 L/s) per rat. Consequently, micro-isolator cages with these measurements have poor environmental conditions because of the low ventilation rates.

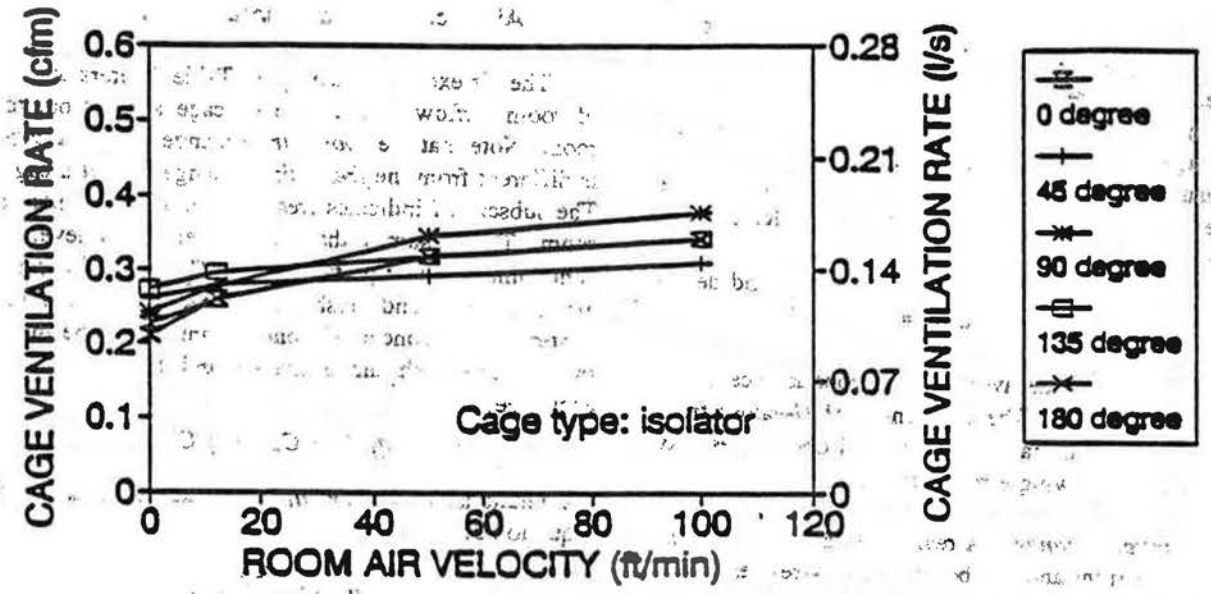

Figure 2 *Relationships of cage ventilation rates to room air velocities and room airflow directions for micro-isolator cage. Supplemental heat in cage is 5 W.*

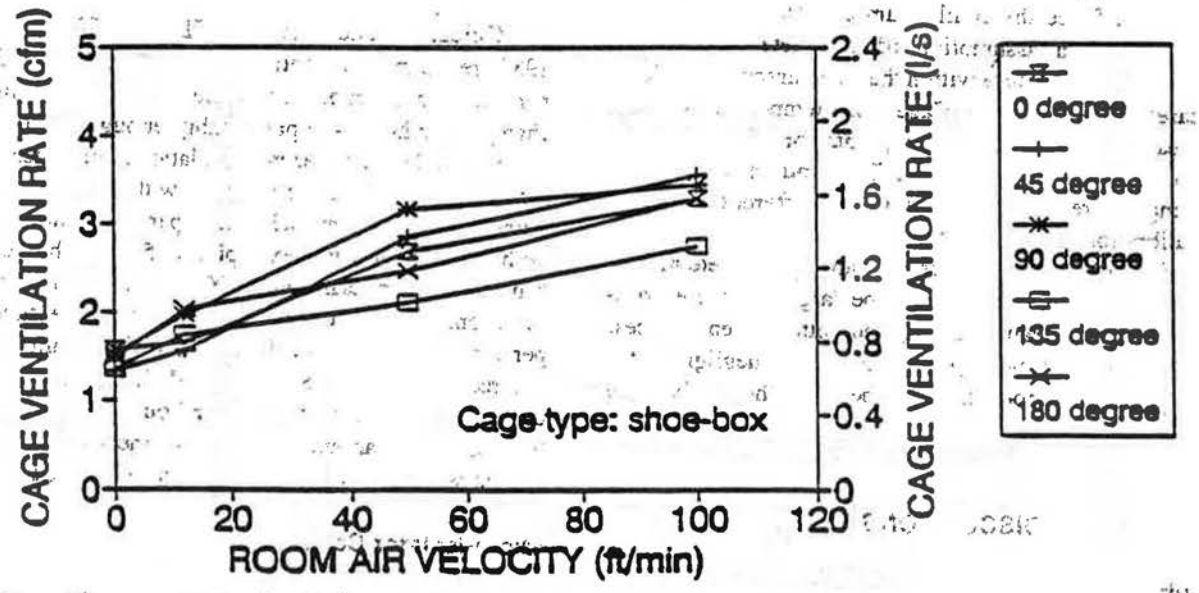

Figure 3 *Relationships of cage ventilation rates to room air velocities and room airflow directions for shoebox cage. Supplemental heat in cage is 5 W.*

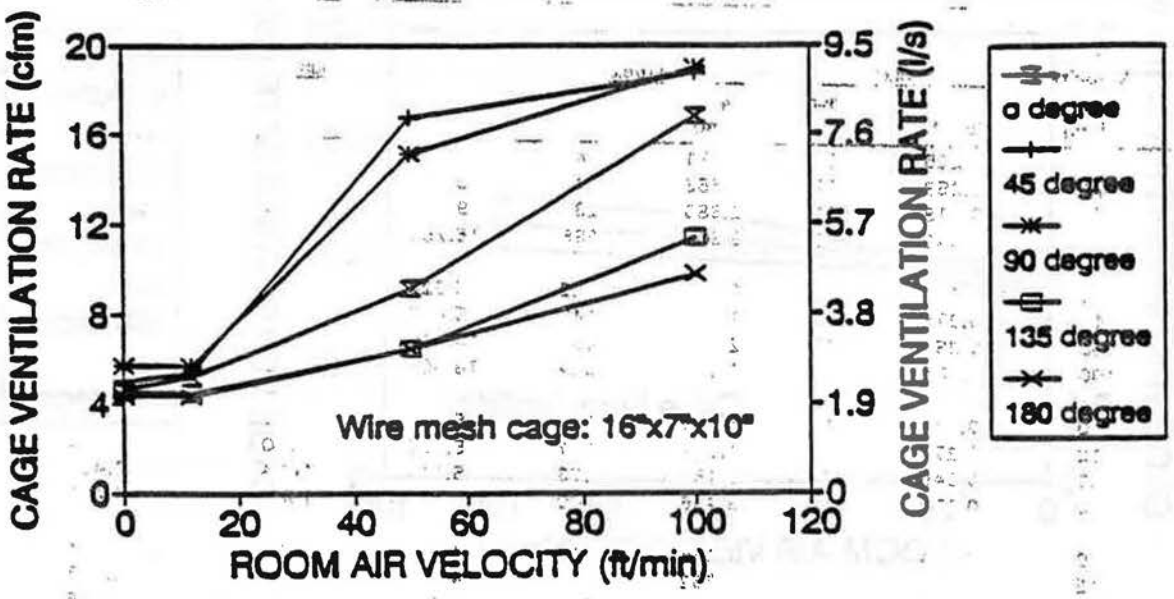

Figure 4 *Relationships of cage ventilation rates to room air velocities and room airflow directions for wire-mesh double cage. Supplemental heat in cage is 5 W.*

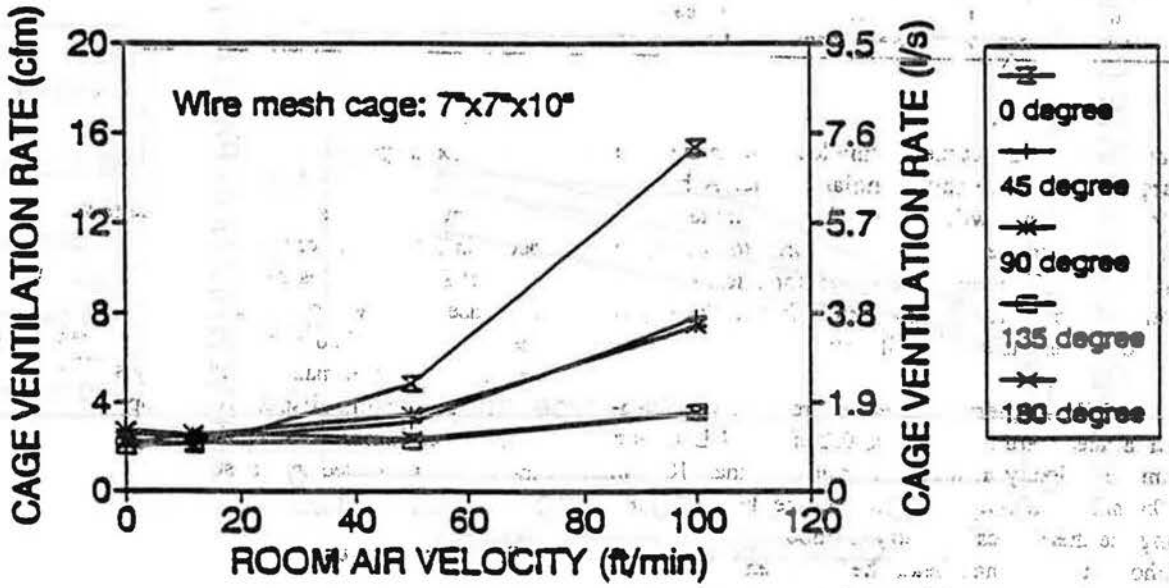

Figure 5 *Relationships of cage ventilation rates to room air velocities and room airflow directions for wire-mesh single cage. Supplemental heat in cage is 5 W.*

TABLE 2
Results of Measurements and Calculations

Angle of Airflow α	Air Velocity u (fpm)	Isolator q (cfm)	Isolator ach	Shoebox q (cfm)	Shoebox ach	Wire-Mesh Double q (cfm)	Wire-Mesh Double ach	Wire-Mesh Single q (cfm)	Wire-Mesh Single ach
0°	0	0.225	15	1.581	141	4.669	443	2.305	495
	12	0.259	17	1.653	148	5.209	494	2.072	445
	50	0.318	21	2.680	239	9.123	865	4.803	1032
	100	0.342	23	3.300	295	16.756	1590	15.367	3303
45°	0	0.257	17	1.360	122	5.028	477	2.605	560
	12	0.276	19	1.596	143	5.435	516	2.374	510
	50	0.287	19	2.905	260	16.820	1596	3.119	670
	100	0.306	21	3.630	324	18.900	1793	7.820	1681
90°	0	0.241	16	1.529	137	5.719	543	2.723	585
	12	0.277	19	1.977	177	5.692	540	2.583	555
	50	0.346	23	3.167	283	15.114	1434	3.480	748
	100	0.377	25	3.456	309	19.008	1803	7.403	1591
135°	0	0.274	18	1.365	122	4.498	427	2.016	433
	12	0.295	20	1.752	157	4.464	424	2.191	471
	50	0.317	21	2.107	188	6.437	611	2.246	483
	100	0.342	23	2.751	246	11.362	1078	3.531	759
180°	0	0.210	14	1.487	133	4.360	414	2.131	458
	12	0.260	17	2.039	182	4.322	410	2.585	556
	50	0.317	21	2.466	220	6.451	612	2.347	505
	100	0.342	23	3.299	295	9.741	924	3.537	760

α = room airflow direction with respect to cage.
u = room air velocity at cage front.
q = volumetric ventilation rate (room to cage or vice versa).
ach = air changes per hour between room air and cage air.

It should be noted that the heating load within the cage has a large effect on the cage ventilation rate. A heating source (rat) in the cage will increase the cage air temperature and hence increase the buoyancy force to accelerate the mass transfer. The ventilation rates for micro-isolator cages were also measured using a carbon dioxide tracer gas method and the results are as follows:

- With a 5-W supplemental heat source, the cage ventilation rates were measured as 0.2 cfm (0.1 L/s) with room air velocity at the cage front less than 10 fpm (0.05 m/s), which agrees well with the data measured using the thermal calorimetry method.
- Without supplemental heat, the cage ventilation rates were measured as 0.025 cfm (0.012 L/s) with room air velocity at the cage front less than 10 fpm (0.05 m/s), which is eight times less than the cage with a 5-W heat source.

Therefore, cage ventilation rates presented in Table 2 are almost the highest values for normal housing conditions (two 300-g rats in a cage). The smaller the rat, the lower the cage ventilation rate will be.

Shoebox Cage

Ventilation rates for a shoebox cage were estimated at between 1.5 and 3.6 cfm (0.7 and 1.7 L/s). The ventilation rates of shoebox cages depend on the type of top cover. In this case, the shoebox cage was covered with a sheet of mesh-metal that had about 20% open area to room airspace. In practice, many shoebox cages have a much larger open area to room-airspace (e.g., topped with wire-mesh) and the ventilation rates for those cages will be larger than the values measured in this study.

Wire-Mesh Cages

To simulate the cage rack, the tops of wire-mesh cages were covered with solid metal sheets. Although only the front face and floor were wire-mesh surfaces, both wire-mesh cages (multiple and single) had high ventilation rates. The wire-mesh double cage had ventilation rates of 4.4 to 19 cfm (2.1 to 9 L/s) and the wire-mesh single cage had rates of 2 to 16 cfm (1 to 7.2 L/s). In fact, the ammonia concentration levels within wire-mesh cages were much

lower than those of micro-isolator and shoebox cages according to a survey of laboratory rat facilities (Zhang et al. 1991a).

The effects of room air velocity on cage ventilation rate were:

- Micro-isolator cage: The cage ventilation rate increases about 50% when the room air velocity at the cage front changes from 0 to 40 fpm (0.2 m/s). However, this effect declines when the room air velocity is higher than 40 fpm (0.2 m/s) for the micro-isolator cage (Figure 2). The main driving force for the cage air exchange is the buoyancy due to the temperature difference between the outside and inside air of an isolator cage. Apparently, the filters on top of the micro-isolator cages do not allow much air exchange even with high room ventilation rates and high room air velocities.
- Shoe-box cage: The ventilation rates of a shoebox cage vary largely with room air velocity. Room ventilation systems that cause a 100-fpm (0.5-m/s) cage face air velocity can result in three times as much cage ventilation as when the air velocity at the cage front is less than 50 fpm (0.25 m/s). A shoebox cage that houses two 0.66-lb (300-g) or larger rats will have a ventilation rate of 0.67 cfm (0.32 L/s) per rat and result in a poor microenvironment with still room air. The ventilation rate requirement (0.8 cfm per rat) can be satisfied by increasing the room air velocity at the cage face to 12 fpm (0.06 m/s) or more. However, high air velocity can cause discomfort to animals. The physiological responses of rats to air velocity need to be studied.
- Wire-mesh cage: Because of large open areas, room air velocity has a large effect on the ventilation of wire-mesh cages. Generally, the cage ventilation rate increases with room air velocity when it is more than 20 fpm (0.1 m/s). When the room air velocity is less than 20 fpm, cage ventilation is mainly due to buoyancy driving mass transfer rather than to forced convection. Smoke tests under the same room air velocity showed that most air exhausted from the front mesh surfaces in wire-mesh cages.

Effect of Room Airflow Direction on Cage Ventilation Rate

Room airflow direction has little effect on the micro-isolator and shoebox cages (Figures 2 and 3), and ventilation rate variations are within 25% for all room airflow directions. These variations are due to the slight difference in airflow patterns across the cage and the error of measurement. Measurement errors include ±10% of room air velocity during fan adjustment and room air temperature fluctuations (5°F [2.8°C]).

The room airflow direction has a large effect on ventilation rates for wire-mesh cages (Figures 4 and 5). The cage ventilation rates depend on the airflow patterns across and within the cage. Apparently, the airflow direction influences the airflow pattern across the cage.

When room air velocity is less than 20 fpm (0.1 m/s), 0° airflow direction toward a wire-mesh cage did not increase the cage ventilation rate because the wind pressure balanced the buoyancy force within the cage so that the mass transfer rate was decreased. Smoke tracer tests showed that the air within a wire-mesh cage stagnated (especially for the wire-mesh single cage), while 45° and 90° airflows increased the cage ventilation rate because of increased turbulence at the wire-mesh front. Backward flows (135° and 180°) decrease the cage ventilation rates for both double and single wire-mesh cages.

Comments on Concepts of Air Changes Per Hour and Air Ventilation Rate

Common practice has been to specify the ventilation requirement of a laboratory animal airspace in air changes per hour (ach). However, the concept of volumetric ventilation rate per animal is preferable to air changes per hour because the latter does not account for the sizes of the airspace or animal densities. Further, expressing ventilation rates as volumetric changes per animal allows for the evaluation of cage ventilation rates, which is a clearer definition of the ventilation requirement regardless of the enclosure size and cage types.

The following example shows that the application of the ach concept to cage ventilation rate is very misleading. The previously mentioned rat room has a volume of 4,240 ft^3 (120 m^3) and houses 700 rats. Each micro-isolator cage has a volume of 0.9 ft^3 (0.0253 m^3) and houses two rats. The room is ventilated at a rate of 15 ach, which allows 1.5 cfm (0.7 L/s) per rat. The measured ventilation rates are 0.21 cfm (0.1 L/s) per cage and 0.11 cfm (0.05 L/s) per rat (Table 2), which is much lower than the ventilation requirement of 0.8 cfm (0.385 L/s) per rat. However, this 0.21 cfm (0.1 L/s) per cage equals 14 ach, which appears to be an excellent air exchange rate but really represents a very low ventilation rate and a poor microenvironment.

CONCLUSIONS

1. The ventilation rates of cages largely depend on cage type. Micro-isolator cages without independent air supply systems did not meet the 0.8 cfm (0.385 L/s) per rat ventilation requirement even at high room air velocities and ventilation rates.
2. The ventilation rates of shoebox cages were affected by room air velocity more than by room ventilation rate. Room air velocities of 12 fpm (0.06 m/s) and higher ensured the ventilation requirement of 0.8 cfm (0.385 L/s) per rat. However, high air velocities may cause discomfort to the rats in the cage and the animal caretakers. The physiological responses of rats to various air velocities need to be studied.

3. The ventilation rates of wire-mesh cages were sufficient for all room air velocities. The effects of room air velocity and airflow direction on the cage ventilation rate were large when the room air velocity was more than 20 fpm (0.1 m/s).
4. Room airflow direction had little effect on cage ventilation rates for micro-isolator and shoebox cages. When room air velocity was less than 20 fpm (0.1 m/s), 0° room airflow direction did not increase the cage ventilation rate because of the balance of wind pressure and buoyancy force. A 45° direction improved cage ventilation rates for wire-mesh cages when the room air velocity was less than 50 fpm (0.5 m/s).
5. Basing laboratory animal ventilation rates on room air changes per hour resulted in variations of 0.1 to 15 cfm/rat (14 to 3,300 ach for cages) in fresh air supply to the rats when applied to the cage ventilation rate. Therefore, we recommend using volumetric ventilation rate per animal in the cages—a parameter by which to design ventilation systems and to evaluate the microenvironmental conditions of an animal facility.

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