



# 2025년 서산시 노인요양시설 환기 실태 및 SARS-CoV-2 공기전파 위험도 평가

한대희<sup>1</sup> , 임지애<sup>1</sup> , 이상욱<sup>1</sup> , 강혜진<sup>1</sup> , 김수진<sup>1</sup> , 최유호<sup>2</sup> , 김보람<sup>2</sup> , 최동권<sup>3</sup> , 조오현<sup>1\*</sup>

<sup>1</sup>충청남도감염병관리지원단, <sup>2</sup>서산시보건소 감염병관리과, <sup>3</sup>서울특별시청 감염병관리과

## 초 록

**목적:** 서산시 장기요양기관 중 노인요양시설과 노인요양공동생활가정을 대상으로 자연·기계 환기 실태를 정량적으로 평가하고, 환기 수준에 따른 severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) Delta 변이의 예상 감염위험도를 추정하여 감염취약시설의 환기 개선 필요성을 제시하고자 하였다.

**방법:** 서산시에 소재한 노인요양시설 23개소와 노인요양공동생활가정 4개소(총 27개소)를 방문하여 침실의 자연환기량과 기계환기량을 실측하였다. 급·배기 풍량과 실내 체적을 이용해 시간당 환기횟수(air changes per hour, ACH)를 산출하고, 질병관리청 호흡기 감염병 공기전파 위험도 평가 프로그램을 활용하여 SARS-CoV-2 Delta 변이 1인 감염자, 3시간 노출 조건에서 침실의 예상 감염위험도를 평가하였다.

**결과:** 조사 대상 시설의 자연환기 1일 평균 빈도는  $5.5 \pm 2.3$ 회, 자연환기 1회 평균 시간은  $15.4 \pm 10.4$ 분이었다. 침실의 복합환기 시 평균 시간당 환기횟수는  $1.4 \pm 0.9$  ACH로, 자연환기만으로 2 ACH 이상 충족한 시설은 11.1%에 그쳤고, 기계환기만으로 2 ACH를 충족한 시설은 없었다. 기계환기 설비가 설치된 19개 시설 모두에서 기계환기 병행 시 예상 감염위험도가 자연환기 단독 대비 평균  $11.4 \pm 6.9\%$  감소하였다(95% confidence interval: 7.9-14.7).

**결론:** 자연환기 중심의 현 환기 방식으로는 호흡기 감염병 전파 위험을 충분히 줄이기 어려우며, 기계환기 설비의 적정 용량 산정과 운전 조건 개선이 필요하다. 또한, 장기요양기관 평가관리 지표에 시간당 환기횟수와 기계환기 의무화를 포함하는 제도적 보완이 필요하다.

**주요 검색어:** 노인요양시설; 노인요양공동생활가정; 환기; 코로나바이러스감염증-19; 공기전파

## 서 론

우리나라는 초고령사회로 진입하면서 장기요양기관에 대한 수요가 급증하고 있다[1]. 이들 시설의 입소자는 대부분 고

령자이며, 기저질환과 면역 기능 저하로 인해 인플루엔자, 코로나바이러스감염증-19(코로나19) 등 호흡기 감염병에 특히 취약하다[2,3]. 밀폐된 실내공간에서 다수의 입소자가 침실, 프로그램실, 식당 등 공용 공간을 공유함에 따라 공기·비말

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\*Corresponding author: 조오현, Tel: +82-41-635-4371, E-mail: 80658@schmc.ac.kr

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### 핵심요약

#### ① 이전에 알려진 내용은?

노인요양시설과 노인요양공동생활가정은 고령자 밀집, 밀폐된 환경, 장시간 접촉으로 호흡기 감염병 집단발생 위험이 크다. 그러나 실제 환기 수준과 기계환기 설비 성능에 대한 정량적 자료는 제한적이었다.

#### ② 새로이 알게 된 내용은?

서산시 노인요양시설 23개소, 노인요양공동생활가정 4개소 침실의 복합환기 시 평균 시간당 환기횟수는  $1.4 \pm 0.9$  ACH로 병원의 입원실 환기 기준인 2 ACH보다 낮았다. 기계환기 병행 가동 시 예상 감염위험도가 평균  $11.4 \pm 6.9\%$ p 감소하였으나 전열교환기가 설치된 시설 대부분은 필요환기량에 비해 용량이 부족하거나 약한 세기로 운전되고 있었다.

#### ③ 시사점은?

장기요양기관에서 기계환기 설비를 가동하는 것이 감염위험을 줄일 수 있는 핵심 요인임을 확인하였다. 기계환기 설비의 의무화, 적정 용량 기준, 운전 단계 강화 등 환기 기준을 고도화하여 호흡기 감염병 전파 위험을 체계적으로 줄일 수 있다.

전파를 통한 집단 감염위험이 크다[2,4,5].

국토교통부 '건축물의 설비기준 등에 관한 규칙(별표 1의 6)'은 노유자 시설 중 연면적  $1,000 \text{ m}^2$  이상의 노인요양시설에 대해 환기장치 설치기준으로 1인당  $36 \text{ m}^3/\text{h}$ 의 환기량을 공급하는 환기장치를 설치하도록 규정하고 있으며[6], 보건복지부 역시 입원실·중환자실에서 환기시설을 통해 외기도 입량 기준 최소 환기횟수를 2 air changes per hour (ACH) 이상, 재순환량을 포함한 환기횟수를 6 ACH 이상으로 권고하고 있다[7]. 또한 국민건강보험공단 장기요양기관 평가에서는 일상적인 환기 시행(1일 3회 이상, 1회 10분 이상 자연환기) 및 점검표 비치를 요구하지만, 실제 환기량( $\text{m}^3/\text{h}$ )이나 환기횟수(ACH)에 대한 평가는 포함되어 있지 않다[8]. 세계보건기구(World Health Organization, WHO)의 자연환기 지침 또한 의료시설 내 감염관리 차원에서 적정 환기량 확보의 중요성을

강조하고 있다[9].

코로나19 유행 기간 중 장기요양기관 내 대규모 집단감염 사례가 반복됨에 따라 실내 공기질 관리 및 환기의 중요성이 크게 주목받았다. 그러나 국내 장기요양기관을 대상으로 자연·기계환기량을 실측하고, 감염위험도를 정량적으로 제시한 연구는 제한적이다. 이에 본 연구는 서산시 노인요양시설과 노인요양공동생활가정을 대상으로 환기량을 실측하여 환기 실태를 평가하고, Korean-virus emission & airborne transmission assessment program (K-VENT 3.1)을 활용하여 severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) 공기전파 위험을 추정함으로써 감염취약시설의 환기 기준 개선의 근거를 마련하고자 하였다[10].

## 방 법

### 1. 조사 대상

본 연구는 2025년 4월 23일부터 5월 21일까지 충청남도 서산시에 소재한 장기요양기관 대상으로 시행하였다. 「노인복지법」상 노인의료복지시설에 해당하는 노인요양시설 23개소와 노인요양공동생활가정 4개소를 포함한 총 27개소였으며, 서산시 보건소의 협조와 시설장의 동의를 얻어 현장 방문 조사하였다.

각 시설에서 입소자가 상시 사용하는 침실 1개를 선정하였고, 전열교환기가 설치되었을 때는 해당 침실을 추가로 조사하였다. 건물 연식(신축·일반·노후), 기계환기 설비 유무 및 종류, 침실 환기 방법(자연·기계·복합) 등의 일반 특성을 구조화하여 수집하였다.

### 2. 환기 방식 정의

대상공간의 환기량은 건물의 틈새를 통한 침기량(infiltration)과 자연환기량(natural ventilation), 그리고 기계환기량(mechanical ventilation) 등에 의해 결정되며, 침기량과 자연

환기량은 건물의 노후 정도, 평면 및 창호 형태, 창호 면적, 실내외 온도차, 외부풍속 등에 따라 달라진다[10].

건물 노후도에 따른 침기량 분석을 위해 건축 후 3년 미만은 신축 건물, 3년 이상 10년 미만은 일반 건물, 10년 이상 경과한 경우는 노후 건물로 각각 분류하였다. 자연환기는 창문, 틈새, 환기구 등을 통해 바람, 실내·외 온도차, 압력 차에 의해 공기가 자발적으로 유입·배출되는 방식으로 정의하였고, 기계환기는 팬, 덕트, 전열교환기 등을 이용하여 일정한 풍량과 공기 교환율을 유지하는 것으로 정의하였다. 또한 침실 환기 방법은 자연환기만 시행하는 경우 '자연환기', 기계환기만 사용하는 경우 '기계환기', 두 방식을 병행하는 경우 '복합환기'로 분류하였다.

### 3. 환기량(m<sup>3</sup>/h) 측정 및 시간당 환기횟수(ACH) 산출

환기량 측정에는 레이저 거리측정기(MAGPIE SABER X), 열선 풍속계(Testo 405-V1; Testo), 베인 풍속계 및 사각 퓨넬(Testo 417, Testo 4170; Testo)을 사용하였다. 각 침실의 체적(m<sup>3</sup>)은 레이저 거리측정기를 이용해 길이, 너비, 높이를 측정하여 계산하였다.

자연환기량 측정 시 각 침실의 창문의 가로 크기와 세로 크기를 레이저 거리측정기를 이용하여 측정하였고 동일한 위치에 여러 개의 창문이 있는 경우, 창문의 길이를 합산하였다.

창문 유형은 K-VENT 3.1에서 제시하고 있는 '고정창(fixed)', '여닫이창(awning)', '여닫이창(casement)', '미서기창(sliding)' 4가지 유형으로 분류하였고, 침실의 평면 유형은 K-VENT 3.1에서 제시하고 있는 '1면 개방형', '복합 개방형', '양면 개방형', '편복도형', '중복도형(1면 개방)', '중복도형(양면 개방)' 6가지 유형으로 분류하였다. 개폐가 가능한 창문은 모두 개방하여 열선 풍속계로 평균 외부 풍속(m/s)을 측정하였다.

기계환기량 측정 시 침실 내 모든 급·배기구에서 베인 풍속 측정계 및 사각 퓨넬을 이용하여 시간당 풍량을 측정하였

고, 전열교환기가 설치되었을 때는 열선 풍속계를 이용하여 평균 풍속(m/s)을 측정 후 시간당 환기량은 다음 공식을 사용하여 계산하였다.

$$\text{시간당 환기량(m}^3\text{/h)} = \text{풍속(m/s)} \times \text{급기 또는 배기 면적(m}^2\text{)} \times 3,600 \text{ (s/h)}$$

시간당 환기횟수는 K-VENT 3.1을 이용하여 자연환기, 기계환기 각각의 ACH를 산출하였다.

### 4. 환기 기준 및 평가지표

국토교통부 규정에 따라 연면적 1,000 m<sup>2</sup> 이상 노인요양 시설의 필요환기량은 1인당 36 m<sup>3</sup>/h로 설정하였다. 의료기관 입원실·중환자실 관련 지침에서 제시하는 외기도입량 기준 2 ACH 이상을 침실의 최소 권고기준으로 참고하였다. 또한 국민건강보험공단 장기요양기관 평가관리 시행세칙의 환기관리 수칙(1일 3회 이상, 1회 10분 이상 자연환기)을 조사 대상 시설의 일상적 환기 실천 수준 평가에 활용하였다.

### 5. 감염위험도 평가(K-VENT 3.1)

호흡기 감염병 공기전파 위험도는 질병관리청 K-VENT 3.1을 사용하여 추정하였다. 바이러스는 SARS-CoV-2 Delta 변이를 선택하고, 감염자 수는 1명, 활동 수준은 휴식(resting, oral breathing), 노출 시간은 3시간으로 설정하였다. 노출자 수는 각 침실의 최대 수용 인원에서 감염자 1명을 제외한 인원수를 시설별로 다르게 입력하였고(4인실은 노출자 3명, 3인실은 노출자 2명, 2인실은 노출자 1명), 활동 수준은 휴식(resting)으로 입력하였다.

외부 환경 변수인 외부 풍속과 외부 온도는 서산시 5년간 5월(2020-2024년 5월 1일-31일)의 평균 풍속 2.26 m/s, 평균 기온 17.1℃를 적용하였다. 자연환기 했을 때와 복합환기 했을 때의 각각에 대해 예상 감염위험도(%)를 산출하여 비교

하였다.

## 6. 통계 분석

노인요양시설 23개소는 알파벳 A-W를 부여하였고, 노인요양공동생활가정 4개소는 알파벳 AA, BB, CC, DD를 부여하였다. 자연환기와 복합환기 조건별 예상 감염위험도 차

이에 대한 정규성은 Shapiro-Wilk 검정을 통해 확인하였다. 정규성이 충족되면 대응 표본 t-검정하여 두 조건 간 평균 차이와 95% 신뢰구간을 추정하였다. 자연환기와 복합환기의 평균 차이의 효과 크기를 검증하기 위해 코헨의 d 효과 크기(Cohens' d effect size)를 사용하였다. 코헨의 d 효과 크기는 값에 따라  $d \leq 0.2$  작은 효과 크기(small),  $d=0.5$  중간 효

표 1. 조사 대상 시설의 일반적 특성

특성	노인요양시설(n=23)	노인요양공동생활가정(n=4)	전체(n=27)	
건물 연식(년)	<3 (신축)	2 (8.7)	0 (0.0)	2 (7.4)
	3-10 (일반)	17 (73.9)	3 (75.0)	20 (74.0)
	≥10 (노후)	4 (17.4)	1 (25.0)	5 (18.6)
침실의 평균 시간당 환기횟수	1.6±1.0	0.8±0.6	1.4±0.9	
침실의 시간당 환기횟수(ACH)	<2	18 (78.3)	4 (100.0)	22 (81.5)
	2-6	5 (21.7)	0 (0.0)	5 (18.5)
	≥6	0 (0.0)	0 (0.0)	0 (0.0)
침실의 환기 유형	자연환기	5 (21.7)	3 (75.0)	8 (29.6)
	기계환기	1 (4.3)	0 (0.0)	1 (3.7)
	복합환기 <sup>a)</sup>	17 (73.9)	1 (25.0)	18 (66.7)
자연환기 1일 평균 빈도(회)	5.7±2.6	5.3±1.1	5.5±2.3	
자연환기 1일 빈도(회)	<3	6 (26.1)	0 (0.0)	6 (22.2)
	3-6	7 (30.4)	3 (75.0)	10 (37.0)
	≥6	10 (43.5)	1 (25.0)	11 (40.8)
자연환기 1회 평균 시간(분)	16.5±11.2	12.5±4.3	15.4±10.4	
자연환기 1회 시간(분)	<10	1 (4.3)	0 (0.0)	1 (3.7)
	10-30	19 (82.6)	4 (100.0)	23 (85.2)
	≥30	3 (13.0)	0 (0.0)	3 (11.1)
자연환기 시 평균 시간당 환기횟수(ACH)	1.0±1.0	0.8±0.7	0.9±1.0	
자연환기 시간당 환기횟수(ACH)	<2	20 (87.0)	4 (100.0)	24 (88.9)
	2-6	3 (13.0)	0 (0.0)	3 (11.1)
	≥6	0 (0.0)	0 (0.0)	0 (0.0)
기계환기 시 평균 시간당 환기횟수(ACH)	0.4±0.2	0.1±0	0.4±0.2	
기계환기 시간당 환기횟수(ACH)	<2	18 (100.0)	1 (100.0)	19 (100.0)
	2-6	0 (0.0)	0 (0.0)	0 (0.0)
	≥6	0 (0.0)	0 (0.0)	0 (0.0)
기계환기 유형	공조설비	4 (17.4)	1 (25.0)	5 (18.6)
	전열교환기	10 (43.5)	0 (0.0)	10 (37.0)
	공조+전열	3 (13.0)	0 (0.0)	3 (11.1)
	단순배기(팬)	1 (4.3)	0 (0.0)	1 (3.7)
	미설치	5 (21.7)	3 (75.0)	8 (29.6)

단위: 개소(%) 혹은 평균±표준편차. ACH=air changes per hour: 공조+전열=공조설비, 전열교환기 병행. <sup>a)</sup>자연환기와 기계환기를 병행하여 환기하는 방법.

과 크기(medium),  $d \geq 0.8$  큰 효과 크기(large)로 나타낼 수 있다. 통계 분석에는 R 4.2.2 버전을 사용하였으며, 유의수준은  $p < 0.05$ 로 하였다.

## 결 과

### 1. 조사 대상 시설의 일반적 특성

조사 대상 27개 시설 중 건물 유형은 사용 연수 기준 3-10년 일반 건물이 20개소(74.0%)로 가장 많았고, 10년 이상 노후 건물 5개소(18.6%), 3년 미만 신축 2개소(7.4%) 순이었다. 자연환기 빈도는 1일 6회 이상이 11개소(40.8%), 3

표 2. 시설별 환기량 및 시간당 환기횟수

침실	체적 (m <sup>3</sup> )	측정 환기				인증 환기			
		침기량(m <sup>3</sup> /h)	자연환기량 (m <sup>3</sup> /h)	기계환기량 (m <sup>3</sup> /h)	총 환기량 (m <sup>3</sup> /h)	측정값의 전체 환기횟수 (ACH)	전열교환기 인증환기량 <sup>a)</sup> (CMH)	인증값의 전체 환기횟수 (ACH)	
4인실	A	75.0	18.8	6.6	6.2	31.5	0.4	100	1.7
	B	67.0	23.4	9.2	6.5	39.1	0.6	단순배기(팬)	-
	C	77.2	19.3	0.0	38.9	58.2	0.8	100	1.6
	D	96.4	24.1	13.5	36.1	73.7	0.8	70	1.1
	G	64.4	16.1	12.2	33.7	62.0	1.0	100	2.0
	H	79.1	19.8	70.4	0.0	90.2	1.1	미설치	-
	I	97.5	14.6	25.9	66.2	106.7	1.1	공조설비	-
	K	85.2	21.3	60.4	15.9	97.6	1.1	80	1.9
	L	82.7	20.7	35.3	39.8	95.8	1.2	100	1.9
	M	62.2	15.6	28.0	40.0	83.6	1.3	70	1.8
	N	85.1	29.8	89.3	0.0	119.1	1.4	미설치	-
	O	59.1	14.8	36.5	33.1	84.4	1.4	100	2.6
	P	69.2	24.2	75.5	0.0	99.7	1.4	미설치	-
	Q	72.0	18.0	89.6	11.7	119.3	1.7	공조설비	-
R	75.4	18.9	74.6	40.0	133.3	1.8	70	2.2	
V	66.0	16.5	213.3	0.0	229.8	3.5	미설치	-	
AA	66.4	16.6	8.1	0.0	24.7	0.4	미설치	-	
CC	64.9	16.2	22.6	0.0	38.8	0.6	미설치	-	
DD	71.3	17.8	106.8	5.9	130.5	1.8	공조설비	-	
3인실	E	65.7	9.9	19.9	24.6	54.3	0.8	공조설비	-
	F	100.1	25.0	14.5	46.7	86.2	0.9	70	1.1
	J	57.7	14.4	31.1	19.0	64.5	1.1	공조설비	-
	S	60.9	15.2	61.6	43.4	120.2	2.0	100	2.9
	U	59.9	15.0	129.3	0.0	144.3	2.4	미설치	-
	W	39.9	10.0	164.2	18.3	192.5	4.8	100	6.9
	BB	58.6	14.7	8.6	0.0	24.3	0.4	미설치	-
2인실	T	34.1	8.5	60.1	6.1	74.7	2.2	80	4.4

총 환기량=침기량+자연환기량+기계환기량; 측정값의 전체 환기횟수=총 환기량÷체적; 인증값의 전체 환기횟수=(침기량+자연환기량+전열교환기 인증환기량)÷체적; ACH=air changes per hour; CMH=cubic meter per hour, m<sup>3</sup>/h와 같은 단위. <sup>a)</sup>전열교환기 각 제품의 '중간'세기를 기준으로 함('중간'세기 정보가 없는 제품은 '강'세기 기준으로 함).

회 이상 6회 미만 10개소(37.0%), 3회 미만 6개소(22.2%)였으며, 27개소 중 21개소(77.8%)가 장기요양기관 평가에서 요구하는 1일 3회 이상 환기 기준을 충족하였다. 자연환기 시 1회 시간은 10분 이상 30분 미만이 23개소(85.2%), 30분 이상 3개소(11.1%)였고, 26개소(96.3%)가 1회 10분 이상 기준을 만족하였다(표 1).

기계환기 설비는 19개소(70.4%)에 설치되어 있었으며, 이 중 전열교환기 10개소(37.0%), 공조설비 5개소(18.6%), 공조설비와 전열교환기 병행 3개소(11.1%), 단순배기(팬) 1개소(3.7%)였다. 나머지 8개소(29.6%)는 기계환기 설비가 없었다. 환기 방법으로는 복합환기가 18개소(66.7%)로 가장 많았고, 자연환기만 시행하는 시설이 8개소(29.6%)였으며 1개소(3.7%)는 자연환기가 불가능하여 기계환기만으로 하고 있었다(표 1).

## 2. 시설별 침실의 자연환기, 기계환기 현황 및 시간당 환기횟수

자연환기 1일 평균 빈도는 노인요양시설  $5.7 \pm 2.6$ 회, 노인요양공동생활가정  $5.3 \pm 1.1$ 회였으며, 자연환기 1회 평균 시간은 노인요양시설  $16.5 \pm 11.2$ 분, 노인요양공동생활가정  $12.5 \pm 4.3$ 분이었다(표 1). 자연환기 시 평균 시간당 환기횟수는 26개소에서  $0.9 \pm 1.0$  ACH였고, 기계환기 설비가 설치된 19개 시설의 기계환기 시 평균 시간당 환기횟수는  $0.4 \pm 0.2$  ACH였다. 침실의 평균 시간당 환기횟수는 27개 시설에서  $1.4 \pm 0.9$  ACH였으며, 노인요양시설 23개소는 평균 시간당 환기횟수  $1.6 \pm 1.0$  ACH, 노인요양공동생활가정 4개소는 평균 시간당 환기횟수  $0.8 \pm 0.6$  ACH였다(표 1).

노인요양시설 23개소 중 1개소는 창문 개방이 불가능하여 자연환기를 할 수 없었다.

자연환기만으로 2 ACH 이상 충족한 시설은 3개소(11.1%)로 해당 시설들은 창문을 상시 개방하여 환기하고 있었다(표 1). 기계환기만으로 2 ACH 이상 충족한 시설은 없었다.

침실의 시간당 환기횟수가 2 ACH 이상인 시설은 전체 27개소 중 노인요양시설 5개소(18.5%)였으며, 노인요양공동생활가정 중에서는 없었다(표 1).

## 3. 전열교환기의 설치된 공간대비 시간당 환기횟수

전열교환기가 설치된 노인요양시설 13개소(A, C, D, F, G, K, L, M, O, R, S, T, W)에서 측정된 기계환기량을 기준으로 복합환기 시 평균 시간당 환기횟수는  $1.5 \pm 1.1$  ACH이며, 인증 환기량(cubic meter per hour, CMH)을 기준으로 복합환기 시 평균 시간당 환기횟수는  $2.5 \pm 1.5$  ACH였다(표 2).

전열교환기 세기가 '낮음' 또는 '약'일 때 복합환기 시 2 ACH 이상 만족하는 시설은 2개소(S, T)였으며, 전열교환기 세기를 '중' 이상으로 가동한다고 가정했을 때 복합환기 시 2 ACH 이상 만족하는 시설은 6개소(G, O, R, S, T, W)였다(표 2).

## 4. 기계환기 병행에 따른 감염위험 감소 효과

기계환기 설비가 설치된 19개소(노인요양시설 18개소, 노인요양공동생활가정 1개소)를 대상으로 자연환기 단독과 자연환기와 기계환기 병행 조건의 예상 감염위험도를 비교한 결과, 모든 시설에서 기계환기 병행 시 예상 감염위험도가 감소하였다. 가장 큰 감소 폭을 보인 시설은 '노인요양시설 I'로 자연환기 시 97.1%에서 기계환기 병행 시 73.9%로 예상 감염위험도가 23.2%p 감소하였다(그림 1). 자연환기 대비 복합환기 조건에서의 예상 감염위험도 차이는 정규성을 만족하였고(Shapiro-Wilk test,  $p=0.101$ ), 대응 표본 t-검정 결과 평균 차이는  $11.4 \pm 6.9\%$ ,  $p=0.001$  (95% confidence interval [CI]: 7.9-14.7), Cohen's  $d=0.57$ 로 통계적으로 유의하였다.

전열교환기를 설치한 노인요양시설 13개소(A, C, D, F, G, K, L, M, O, R, S, T, W)에서 각 설비의 최대 환기량('강' 세기)을 반영하여 예상 감염위험도를 확인하였을 때 13개소 모두 자연환기 대비 예상 감염위험도가 감소하였다(그림 1).

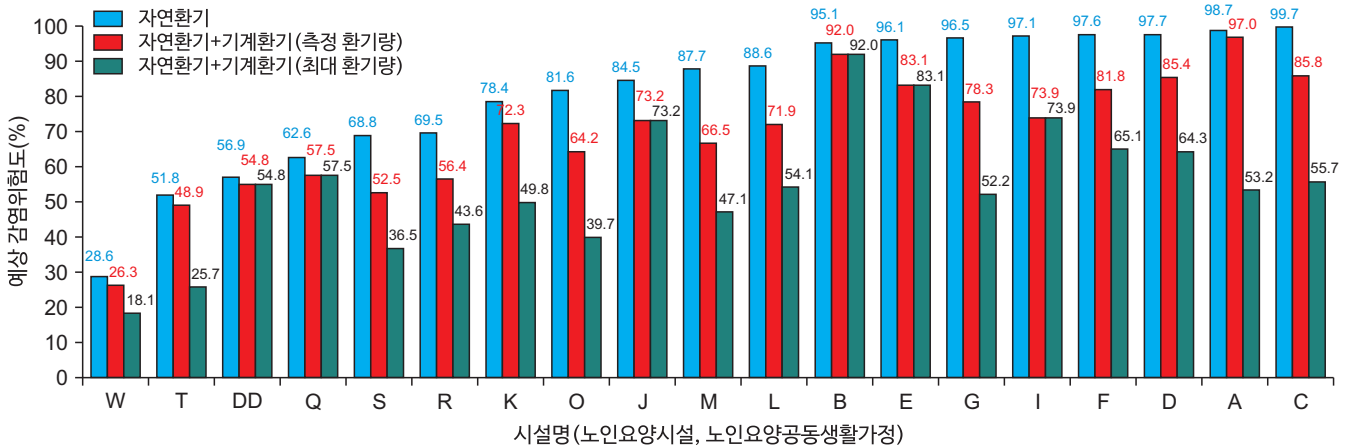


그림 1. 시설별 침실의 기계환기 유무에 따른 호흡기 감염병 예상 감염위험도

최대 환기량 반영 시 예상 감염위험도의 가장 큰 감소 폭을 보인 시설은 '노인요양시설 A'로 자연환기 시 98.7%에서 기계환기 병행 예상 감염위험도 53.2%로 예상 감염위험도가 45.5%p 감소하였다(그림 1). 전열교환기를 설치한 노인요양 시설 13개소의 자연환기 대비 복합환기(전열교환기 최대 환기량) 조건에서의 예상 감염위험도 차이는 정규성을 만족하였고(p=0.184), 대응 표본 t-검정 결과 평균 차이는  $33.8 \pm 9.8\%$ ,  $p=0.001$  (95% CI: 28.0-32.6), Cohen's  $d=1.28$ 로 통계적으로 유의하였다.

## 논 의

본 연구는 서산시 노인의료복지시설을 대상으로 자연·기계 환기량을 실측하고, K-VENT 3.1을 활용하여 SARS-CoV-2 공기전파 위험을 정량적으로 제시한 조사·감시 보고이다. 조사 결과, 장기요양기관 평가에서 요구하는 '1일 3회, 1회 10분 이상 자연환기'와 같은 행위 중심의 환기관리 수칙은 상당수 시설에서 충족되고 있었으나, 실제 27개소의 침실 중 24개소(88.9%)가 자연환기 시 평균 시간당 환기횟수 2 ACH 미만이었다. 호흡기 감염병 예상 감염위험도 평가에 적용한 평균 외부 풍속이 바닷가 인근인 지리적 특성으로 WHO의 자연환기 지침에서 제시하는 1 m/s보다 상대적으로 높음

에도 불구하고, 환기 빈도와 시간만으로는 충분한 공기 교환을 확보하기 어려웠다[9]. 이는 창문 크기, 개방 정도, 외부 풍속·온도 등 자연환기를 좌우하는 요인이 시설마다 상이하다는 점을 반영한다.

침실의 평균 시간당 환기횟수는  $1.4 \pm 0.9$  ACH로 기계환기 설비는 감염위험을 줄이는 중요한 수단임이 확인되었다. 자연환기만 시행할 때와 비교하여, 기계환기를 병행하였을 때 예상 감염위험도가 평균  $11.4 \pm 6.9\%$  감소하였으며, 일부 시설에서 최대 23.2%p 감소하였다.

전열교환기의 최대 환기량을 반영하였을 때 노인요양시설 13개소의 예상 감염위험도는 자연환기 대비 평균  $33.8 \pm 9.8\%$  감소하였으며, 일부 시설에서 최대 45.5%p 감소하였다.

자연환기와 복합환기 간 예상 감염위험도 차이에 대한 효과 크기는 측정 환기량일 시 Cohen's  $d=0.57$ 였으며, 최대 환기량일 시 Cohen's  $d=1.28$ 로 산출되었다. 이는 감염위험 감소 효과가 통계적으로 유의할 뿐만 아니라 실질적으로도 의미 있는 수준임을 확인할 수 있다.

평상시에는 지금과 같이 전열교환기의 세기를 '약'으로 가동하는 것을 유지하되, 호흡기 감염병이 유행할 때는 전열교환기의 세기를 '중' 또는 '강'으로 가동하여 감염위험도를 최대한 낮출 수 있도록 감염관리를 하는 것이 중요한 것으로 판

단된다.

본 조사에서 전열교환기의 세기를 '중' (인증 환기량)으로 가동한다고 가정했을 때 전열교환기가 설치된 13개소 중 6개소는 2 ACH 이상이었고, 7개소는 2 ACH 미만이었다. 이는 장기요양기관에서 기계환기 설비 설치 시 실내 체적을 충분히 고려하지 않고 일률적인 용량의 제품을 적용한 결과로 해석할 수 있으며, K-VENT와 같은 도구를 활용해 설계 단계에서부터 외기 도입량을 검토하여 전열교환기를 설치하는 곳의 필요한 시간당 환기횟수를 확인하는 절차가 필요함을 시사한다.

본 연구의 제한점은 첫째, K-VENT 3.1은 바이러스의 종류, 감염자의 활동 수준에 따른 바이러스 방출량, 노출자의 호흡량과 노출 시간 등 가정 값에 민감하므로 실제 감염률과 차이가 있을 수 있다. 둘째, 2024년에 조사한 「요양병원의 환기 상태 및 오염도 측정을 통한 개선방안 연구」에서 활용되었던 실시간 CO<sub>2</sub> 농도 측정 등을 병행하지 못해 공기질 변화와 환기량을 직접 연계하여 분석하지는 못했다[11]. 셋째, 전열교환기의 세기를 '중' 또는 '강'으로 가동했을 때 환기량을 측정하여 CMH 값과의 실질적인 비교는 하지 못했다. 한계점이 있음에도 상당수 시설에서 자연환기만으로는 충분한 환기가 이루어지지 않음을 알 수 있었으며, 전열교환기를 병행해야 안정적인 환기횟수를 확보할 수 있는 점을 확인할 수 있었다.

정책적 시사점은 다음과 같다. 장기요양기관 평가지표에 시간당 환기횟수(ACH) 기준과 기계환기 설비 의무화를 단계적으로 도입하고, 자연환기·배기팬 설치·전열교환기 등 환기방식에 따라 등급을 세분화할 필요가 있다. 또한, 지방자치단체 차원에서 정기적인 환기량 실측과 모니터링을 제도화하고, 기계환기 개선 및 설비 교체에 대한 재정 지원·인센티브를 마련해야 한다. 마지막으로 시설 관리자를 대상으로 기계환기 설비의 적정 용량 산정, 운전 세기 설정, 유지관리 방법에 대한 교육을 강화해야 한다.

K-VENT 기반의 감염위험 추정 방법은 학교, 어린이집,

장애인복지시설 등 다른 다중이용시설로 확대 적용한다면 지역사회 감염병 대응을 위한 표준 환기관리 지침 수립에 활용할 수 있을 것이다.

## Declarations

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**Conflict of Interest:** The authors have no conflicts of interest to declare.

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## Surveillance Report

# Ventilation Assessment and Airborne Transmission Risk of SARS-CoV-2 in Nursing Homes in Seosan, the Republic of Korea, 2025

Dae-Hui Han<sup>1</sup> , Ji-Ae Lim<sup>1</sup> , Sang-Ouk Woo<sup>1</sup> , Hye-Jin Kang<sup>1</sup> , Su-Jin Kim<sup>1</sup> , Yoo-Ho Choi<sup>2</sup> , Bo-Ram Kim<sup>2</sup> ,  
Dong-Kwon Choi<sup>3</sup> , Oh-Hyun Cho<sup>1\*</sup> 

<sup>1</sup>Chungnam Center for Infectious Disease Control and Prevention, Hongseong, Korea, <sup>2</sup>Division of Infectious Disease Control, Seosan-si Public Health Center, Seosan, Korea, <sup>3</sup>Division of Infectious Disease Control, Seoul Metropolitan Government, Seoul, Korea

## ABSTRACT

**Objectives:** This study quantitatively evaluated the levels of natural and mechanical ventilation in nursing homes and group homes in Seosan, the Republic of Korea, and estimated the airborne transmission risk of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (Delta variant) according to ventilation conditions, with the aim of emphasizing the need for improved ventilation in infection-vulnerable facilities.

**Methods:** On-site investigations were conducted in 23 nursing homes and four group homes. Bedroom ventilation rates were directly measured, and air changes per hour (ACH) were calculated by using supply and exhaust airflow data and room volume. The Korea Disease Control and Prevention Agency airborne transmission risk assessment tool was also applied to estimate infection risk under a scenario involving one infectious SARS-CoV-2 Delta variant case and a 3-hour exposure period.

**Results:** The average frequency of natural ventilation was  $5.5 \pm 2.3$  events per day, with a mean duration of  $15.4 \pm 10.4$  minutes per event. The mean total ventilation rate in bedrooms was  $1.4 \pm 0.9$  ACH. Only 11.1% of the facilities achieved  $\geq 2$  ACH through natural ventilation alone, while none achieved  $\geq 2$  ACH through mechanical ventilation alone. In the 19 facilities equipped with mechanical ventilation systems, combined operation with natural ventilation reduced the estimated infection risk by an average of  $11.4 \pm 6.9\%$  relative to natural ventilation alone (95% confidence interval: 7.9–14.7).

**Conclusions:** Reliance on natural ventilation alone is insufficient for mitigating airborne infection risk. Thus, enhanced design and operation of mechanical ventilation systems, together with the adoption of ACH-based standards and mandatory mechanical ventilation requirements, should be incorporated into evaluation criteria for long-term care facilities.

**Key words:** Nursing homes; Group homes; Ventilation; COVID-19; Disease transmission, infectious

\*Corresponding author: Oh-Hyun Cho, Tel: +82-41-635-4371, E-mail: 80658@schmc.ac.kr

## Introduction

As the Republic of Korea (ROK) transitions into a

super-aged society, the demand for long-term care facilities is increasing rapidly [1]. Residents of these facilities are predominantly elderly and are particularly vulnerable to respiratory

### Key messages

#### ① What is previously known?

Nursing homes and group homes are at high risk for outbreaks of respiratory infectious disease outbreaks because older adults reside in crowded, enclosed environments with prolonged close contact. However, quantitative evidence on actual ventilation levels and the performance of mechanical ventilation systems in these facilities remains limited.

#### ② What new information is presented?

Across 23 nursing homes and four group homes in Seosan, the mean combined ventilation rate in bedrooms was  $1.4 \pm 0.9$  ACH, which is below the 2 ACH standard recommended for hospital inpatient rooms. Operating mechanical ventilation in addition to natural ventilation reduced the estimated infection risk by an average of  $11.4 \pm 6.9\%$ . However, in most facilities equipped with energy recovery ventilators, system capacity was insufficient for providing the required airflow, or the units were operated at low fan settings.

#### ③ What are the implications?

Operation of mechanical ventilation systems in long-term care facilities is a key factor in reducing infection risk. Strengthening ventilation standards, such as mandating mechanical ventilation, establishing minimum capacity requirements, and promoting higher operational levels, can systematically reduce the transmission risk of respiratory infectious diseases.

infectious diseases, such as influenza and coronavirus disease 2019 (COVID-19), owing to underlying medical conditions and age-related immune decline [2,3]. The shared use of communal spaces, including bedrooms, activity rooms, and dining areas, by large numbers of residents within enclosed indoor environments substantially increases the risk of cluster infections through airborne and droplet transmission [2,4,5].

The Ministry of Land, Infrastructure and Transport's Rules

on Facility Standards for Buildings [Attached Table 1-6] require nursing homes, classified under facilities for the elderly and young with a total floor area of  $\geq 1,000$  m<sup>2</sup>, to install ventilation systems providing 36 m<sup>3</sup>/h of outdoor air per person [6]. The Ministry of Health and Welfare additionally recommends a minimum outdoor air ventilation rate of at least 2 air changes per hour (ACH) and a total ventilation rate of at least 6 ACH, including recirculated air, for wards and intensive care units [7]. Furthermore, the National Health Insurance Service's evaluation criteria for long-term care facilities mandate routine ventilation practices (at least three times per day, with a minimum of 10 minutes of natural ventilation per session) and maintenance of a ventilation checklist; however, they do not include assessment of actual ventilation rates expressed as volumetric flow (m<sup>3</sup>/h) or ACH [8]. The World Health Organization (WHO) guidelines on natural ventilation likewise emphasize the importance of ensuring adequate ventilation in healthcare facilities for infection prevention and control [9].

The recurrence of large outbreaks in long-term care facilities during the COVID-19 pandemic has underscored the critical importance of indoor air quality management and adequate ventilation. However, studies that directly measure natural and mechanical ventilation rates and quantitatively assess infection risk in Korean long-term care facilities remain limited. Accordingly, this study aimed to evaluate the ventilation status of nursing homes and group homes in Seosan City by measuring ventilation rates and to provide evidence to inform improved ventilation standards for infection-vulnerable facilities through estimation of airborne transmission risk of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) using Korean-virus emission & airborne transmission assessment program (K-VENT 3.1) [10].

## Methods

### 1. Study Sites

This study was conducted between April 23 and May 21, 2025, and targeted long-term care facilities in Seosan City, Chungcheongnam-do Province, ROK. A total of 27 facilities were included, comprising 23 nursing homes and 4 group homes, all of which are classified as medical welfare facilities for the elderly under the Welfare of Senior Citizens Act. On-site surveys were performed with the cooperation of the Seosan Health Center and with informed consent obtained from facility directors.

At each facility, one bedroom routinely occupied by residents was selected for assessment; if an energy recovery ventilator (ERV) was installed, that bedroom was additionally evaluated. General facility characteristics were systematically collected, including building age (categorized as new, general, or old), the presence and type of mechanical ventilation systems, and bedroom ventilation mode (natural, mechanical, or combined).

### 2. Definition of Ventilation Methods

The ventilation rate within the target space is determined by air infiltration through building envelope leakage, natural ventilation, and mechanical ventilation. Infiltration and natural ventilation rates vary according to building age, floor plan and window type, window area, indoor–outdoor temperature differences, and outdoor wind speed [10].

For the purpose of estimating infiltration, building age was categorized as new (<3 years since construction), general ( $\geq 3$  to <10 years), or old ( $\geq 10$  years). Natural ventilation refers to the unforced inflow and outflow of air through windows, gaps,

and vents driven by wind, indoor–outdoor temperature differences, and pressure gradients. Mechanical ventilation refers to systems that maintain controlled airflow and air exchange rates using components such as fans, ducts, and ERVs. Bedroom ventilation methods were classified as “natural ventilation” when only natural ventilation was used, “mechanical ventilation” when only mechanical ventilation was used, and “combined ventilation” when both methods operated concurrently.

### 3. Measurement of Ventilation Rate ( $\text{m}^3/\text{h}$ ) and Calculation of ACH

Ventilation rates were measured using a laser rangefinder (MAGPIE SABER X), a hot-wire anemometer (Testo 405-V1, Testo), and a vane anemometer with a square funnel (Testo 417 and testo 4170, Testo). The volume ( $\text{m}^3$ ) of each bedroom was calculated by measuring room length, width, and height with the laser rangefinder.

For natural ventilation assessment, the horizontal and vertical dimensions of windows in each bedroom were measured using the laser rangefinder. When multiple windows were located on the same wall, their lengths were summed.

Window types were classified into four categories according to K-VENT 3.1: fixed, awning, casement, and sliding. Bedroom floor plan types were categorized into six types defined in K-VENT 3.1: one-sided open, composite open, double-sided open, single-loaded corridor, double-loaded corridor (one-sided open), and double-loaded corridor (double-sided open). All operable windows were fully opened, and the average outdoor wind speed (m/s) was measured using the hot-wire anemometer.

For mechanical ventilation, the hourly airflow rate was measured at all supply and exhaust vents within each bedroom

using a vane anemometer with a square funnel. When an ERV was installed, the average air velocity (m/s) was measured using a hot-wire anemometer, and the hourly ventilation rate was calculated using the following equation:

$$\text{Ventilation rate (m}^3\text{/h)} = \text{air velocity (m/s)} \times \text{supply or exhaust area (m}^2\text{)} \times 3,600 \text{ (s/h)}.$$

ACH for both natural and mechanical ventilation were calculated using K-VENT 3.1.

#### 4. Ventilation Standards and Evaluation Criteria

According to regulations of the Ministry of Land, Infrastructure and Transport, nursing homes with a total floor area of  $\geq 1,000 \text{ m}^2$  are required to provide a ventilation rate of  $36 \text{ m}^3\text{/h}$  per person. The guideline-recommended minimum outdoor air intake rate of at least 2 ACH, specified for hospital wards and intensive care units, was adopted as the reference standard for evaluating bedroom ventilation. In addition, the ventilation management guidelines prescribed in the National Health Insurance Service's Detailed Enforcement Rules for the Evaluation and Management of Long-Term Care Facilities—which require natural ventilation at least three times per day for a minimum of 10 minutes per session—were applied to assess routine ventilation practices in the surveyed facilities.

#### 5. Infection Risk Assessment (K-VENT 3.1)

The risk of airborne transmission of respiratory infectious diseases was estimated using K-VENT 3.1, developed by the Korea Disease Control and Prevention Agency. Model parameters were defined as follows: the SARS-CoV-2 Delta variant was selected as the target virus; one infected individual

was assumed; the activity level was set to resting (oral breathing); and the exposure duration was 3 hours. The number of exposed individuals was determined by subtracting the single infected individual from the maximum occupancy of each bedroom, resulting in facility-specific exposure scenarios (e.g., three exposed individuals in a four-person room, two in a three-person room, and one in a two-person room).

External environmental parameters included outdoor wind speed and ambient temperature. Five-year (2020–2024) May averages for Seosan City— $2.26 \text{ m/s}$  for wind speed and  $17.1^\circ\text{C}$  for temperature—were applied. The estimated infection risk (%) was calculated for each scenario and compared between natural ventilation and combined ventilation conditions.

#### 6. Statistical Analysis

The 23 nursing homes were labeled A through W, and the four group homes were labeled AA, BB, CC, and DD. Normality of the differences in estimated infection risk between natural ventilation and combined ventilation conditions was assessed using the Shapiro–Wilk test. When the normality assumption was satisfied, a paired t-test was performed to estimate the mean difference and its 95% confidence interval (CI) between the two ventilation conditions. Effect size was quantified using Cohen's *d* to evaluate the magnitude of the difference between natural and combined ventilation. Cohen's *d*-values were interpreted as small ( $\leq 0.2$ ), medium (0.5), and large ( $\geq 0.8$ ). All statistical analyses were conducted using R version 4.2.2, with statistical significance defined as  $p < 0.05$ .

## Results

### 1. General Characteristics of the Study Sites

Among the 27 study sites, 20 facilities (74.0%) were classified as general buildings with 3–10 years of use, five (18.6%) as old buildings with more than 10 years of use, and two (7.4%)

as new buildings with less than 3 years of use. The frequency of natural ventilation was  $\geq 6$  times per day in 11 facilities (40.8%),  $\geq 3$  to  $< 6$  times per day in 10 facilities (37.0%), and  $< 3$  times per day in six facilities (22.2%). Overall, 21 of the 27 facilities (77.8%) met the long-term care facility evaluation requirement of natural ventilation at least three times per day. The duration

**Table 1.** General characteristics of the facilities

Characteristic		Nursing home (n=23)	Group home (n=4)	Total (n=27)
Building type (yr)	<3 (new)	2 (8.7)	0 (0.0)	2 (7.4)
	3–10 (standard)	17 (73.9)	3 (75.0)	20 (74.0)
	$\geq 10$ (old)	4 (17.4)	1 (25.0)	5 (18.6)
Mean hourly combined ventilation rate <sup>a</sup> room (ACH)		1.6 $\pm$ 1.0	0.8 $\pm$ 0.6	1.4 $\pm$ 0.9
Hourly combined ventilation rate <sup>a</sup> room (ACH)	<2	18 (78.3)	4 (100.0)	22 (81.5)
	2–6	5 (21.7)	0 (0.0)	5 (18.5)
	$\geq 6$	0 (0.0)	0 (0.0)	0 (0.0)
Ventilation method in residents' room	Natural only	5 (21.7)	3 (75.0)	8 (29.6)
	Mechanical only	1 (4.3)	0 (0.0)	1 (3.7)
	Combined <sup>a)</sup>	17 (73.9)	1 (25.0)	18 (66.7)
Mean number of natural ventilation events per day (times)		5.7 $\pm$ 2.6	5.3 $\pm$ 1.1	5.5 $\pm$ 2.3
Daily frequency of natural ventilation (times)	<3	6 (26.1)	0 (0.0)	6 (22.2)
	3–6	7 (30.4)	3 (75.0)	10 (37.0)
	$\geq 6$	10 (43.5)	1 (25.0)	11 (40.8)
Mean duration of natural ventilation per event (min)		16.5 $\pm$ 11.2	12.5 $\pm$ 4.3	15.4 $\pm$ 10.4
Duration of natural ventilation per event (min)	<10	1 (4.3)	0 (0.0)	1 (3.7)
	10–30	19 (82.6)	4 (100.0)	23 (85.2)
	$\geq 30$	3 (13.0)	0 (0.0)	3 (11.1)
Mean hourly natural ventilation rate (ACH)		1.0 $\pm$ 1.0	0.8 $\pm$ 0.7	0.9 $\pm$ 1.0
Hourly natural ventilation rate (ACH)	<2	20 (87.0)	4 (100.0)	24 (88.9)
	2–6	3 (13.0)	0 (0.0)	3 (11.1)
	$\geq 6$	0 (0.0)	0 (0.0)	0 (0.0)
Mean hourly mechanical ventilation rate (ACH)		0.4 $\pm$ 0.2	0.1 $\pm$ 0	0.4 $\pm$ 0.2
Hourly mechanical ventilation rate (ACH)	<2	18 (100.0)	1 (100.0)	19 (100.0)
	2–6	0 (0.0)	0 (0.0)	0 (0.0)
	$\geq 6$	0 (0.0)	0 (0.0)	0 (0.0)
Mechanical ventilation system	HVAC system	4 (17.4)	1 (25.0)	5 (18.6)
	Heat recovery ventilator	10 (43.5)	0 (0.0)	10 (37.0)
	HVAC+ERV	3 (13.0)	0 (0.0)	3 (11.1)
	Exhaust fan only	1 (4.3)	0 (0.0)	1 (3.7)
	Not installed	5 (21.7)	3 (75.0)	8 (29.6)

Unit: number (%) or mean $\pm$ standard deviation. ACH=air changes per hour; HVAC=heating, ventilation, and air conditioning; ERV=energy recovery ventilator. <sup>a)</sup>Combined ventilation refers to the concurrent use of natural and mechanical ventilation.

of natural ventilation per session was  $\geq 10$  to  $< 30$  minutes in 23 facilities (85.2%) and  $\geq 30$  minutes in three facilities (11.1%), with 26 facilities (96.3%) meeting the minimum criterion of 10 minutes per session (Table 1).

Mechanical ventilation systems were installed in 19 facilities (70.4%), including 10 facilities (37.0%) equipped with ERVs, five (18.6%) with heating, ventilation, and air-conditioning (HVAC) systems, three (11.1%) with both HVAC systems and ERVs, and one (3.7%) with a simple exhaust fan. The remaining eight facilities (29.6%) had no mechanical ventilation systems. Combined ventilation was the most common ventilation mode, observed in 18 facilities (66.7%), followed by natural ventilation alone in eight facilities (29.6%) and mechanical ventilation alone in one facility (3.7%), where natural ventilation was not feasible (Table 1).

## 2. Natural and Mechanical Ventilation and ACH in Bedrooms by Facility

The mean daily frequency of natural ventilation was  $5.7 \pm 2.6$  times in nursing homes and  $5.3 \pm 1.1$  times in group homes. The mean duration per natural ventilation session was  $16.5 \pm 11.2$  minutes in nursing homes and  $12.5 \pm 4.3$  minutes in group homes (Table 1). The mean ACH during natural ventilation was  $0.9 \pm 1.0$  across 26 facilities, whereas the mean ACH during mechanical ventilation was  $0.4 \pm 0.2$  across 19 facilities equipped with mechanical ventilation systems. Overall, the mean bedroom ACH was  $1.4 \pm 0.9$  across all 27 facilities; nursing homes averaged  $1.6 \pm 1.0$  ACH, while group homes averaged  $0.8 \pm 0.6$  ACH (Table 1).

One of the 23 nursing homes had no natural ventilation because the windows were non-operable.

Only three facilities (11.1%) achieved an air change rate

of at least 2 ACH through natural ventilation alone; in these facilities, windows were kept continuously open to maintain ventilation (Table 1). No facilities met the  $\geq 2$  ACH criterion through mechanical ventilation alone.

Overall, five nursing homes (18.5%) achieved at least 2 ACH in bedrooms, whereas none of the group homes met this threshold (Table 1).

## 3. ACH in Spaces with ERV Installation

Based on measured mechanical ventilation rates in 13 nursing homes equipped with ERVs (A, C, D, F, G, K, L, M, O, R, S, T, and W), the mean ACH under combined ventilation conditions was  $1.5 \pm 1.1$ . In contrast, the mean ACH calculated using the certified ventilation capacity (cubic meters per hour) was  $2.5 \pm 1.5$  (Table 2).

When ERVs were operated at a low or weak setting, only two facilities (S and T) achieved at least 2 ACH under combined ventilation. Under the assumption that ERVs were operated at a medium setting or higher, six facilities (G, O, R, S, T, and W) met the  $\geq 2$  ACH criterion during combined ventilation (Table 2).

## 4. Reduction in Infection Risk with Concurrent Mechanical Ventilation

Estimated infection risk was compared between natural ventilation alone and combined natural and mechanical ventilation in 19 facilities equipped with mechanical ventilation systems (18 nursing homes and one group home). In all facilities, the estimated infection risk decreased when mechanical ventilation was applied concurrently. The largest reduction was observed in nursing homes I, where the estimated infection risk decreased by 23.2%p, from 97.1% under natural

**Table 2.** Ventilation rates and air changes per hour by facility

Facility	Bed room	Room volume (m <sup>3</sup> )	Measured ventilation				Certified ventilation		
			Infiltration volume (m <sup>3</sup> /h)	Natural ventilation volume (m <sup>3</sup> /h)	Mechanical ventilation volume (m <sup>3</sup> /h)	Total ventilation volume (m <sup>3</sup> /h)	ACH based on measured total volume (ACH)	Certified volume <sup>a)</sup> (CMH)	ACH based on measured certified volume (ACH)
4	A	75.0	18.8	6.6	6.2	31.5	0.4	100	1.7
	B	67.0	23.4	9.2	6.5	39.1	0.6	Exhaust fan only	-
	C	77.2	19.3	0.0	38.9	58.2	0.8	100	1.6
	D	96.4	24.1	13.5	36.1	73.7	0.8	70	1.1
	G	64.4	16.1	12.2	33.7	62.0	1.0	100	2.0
	H	79.1	19.8	70.4	0.0	90.2	1.1	Not installed	-
	I	97.5	14.6	25.9	66.2	106.7	1.1	HVAC system	-
	K	85.2	21.3	60.4	15.9	97.6	1.1	80	1.9
	L	82.7	20.7	35.3	39.8	95.8	1.2	100	1.9
	M	62.2	15.6	28.0	40.0	83.6	1.3	70	1.8
	N	85.1	29.8	89.3	0.0	119.1	1.4	Not installed	-
	O	59.1	14.8	36.5	33.1	84.4	1.4	100	2.6
	P	69.2	24.2	75.5	0.0	99.7	1.4	Not installed	-
	Q	72.0	18.0	89.6	11.7	119.3	1.7	HVAC system	-
	R	75.4	18.9	74.6	40.0	133.3	1.8	70	2.2
	3	V	66.0	16.5	213.3	0.0	229.8	3.5	Not installed
AA		66.4	16.6	8.1	0.0	24.7	0.4	Not installed	-
CC		64.9	16.2	22.6	0.0	38.8	0.6	Not installed	-
DD		71.3	17.8	106.8	5.9	130.5	1.8	HVAC system	-
E		65.7	9.9	19.9	24.6	54.3	0.8	HVAC system	-
F		100.1	25.0	14.5	46.7	86.2	0.9	70	1.1
J		57.7	14.4	31.1	19.0	64.5	1.1	HVAC system	-
S		60.9	15.2	61.6	43.4	120.2	2.0	100	2.9
U		59.9	15.0	129.3	0.0	144.3	2.4	Not installed	-
W		39.9	10.0	164.2	18.3	192.5	4.8	100	6.9
2	BB	58.6	14.7	8.6	0.0	24.3	0.4	Not installed	-
	T	34.1	8.5	60.1	6.1	74.7	2.2	80	4.4

Total ventilation volume=infiltration volume+natural ventilation volume+mechanical ventilation volume; ACH based on measured total volume=total ventilation volume÷room volume; ACH based on certified volume=(infiltration volume+natural ventilation volume+certified volume)÷room volume; ACH=air changes per hour; CMH=cubic meter per hour (m<sup>3</sup>/h); HVAC=heating, ventilation, and air conditioning. <sup>a)</sup>Calculations based on the “medium” fan setting for each product; when information for the medium setting was unavailable, the “high” setting was used.

ventilation alone to 73.9% with combined ventilation (Figure 1). The difference in estimated infection risk between natural ventilation alone and combined ventilation satisfied the normality assumption (Shapiro–Wilk test, p=0.101). A paired t-test demonstrated a statistically significant mean reduction of

11.4±6.9%p (p=0.001, 95% CI: 7.9–14.7), with a moderate effect size (Cohen’s d=0.57).

When infection risk was recalculated for the 13 nursing homes equipped with ERVs (A, C, D, F, G, K, L, M, O, R, S, T, and W), assuming operation at the maximum ventilation

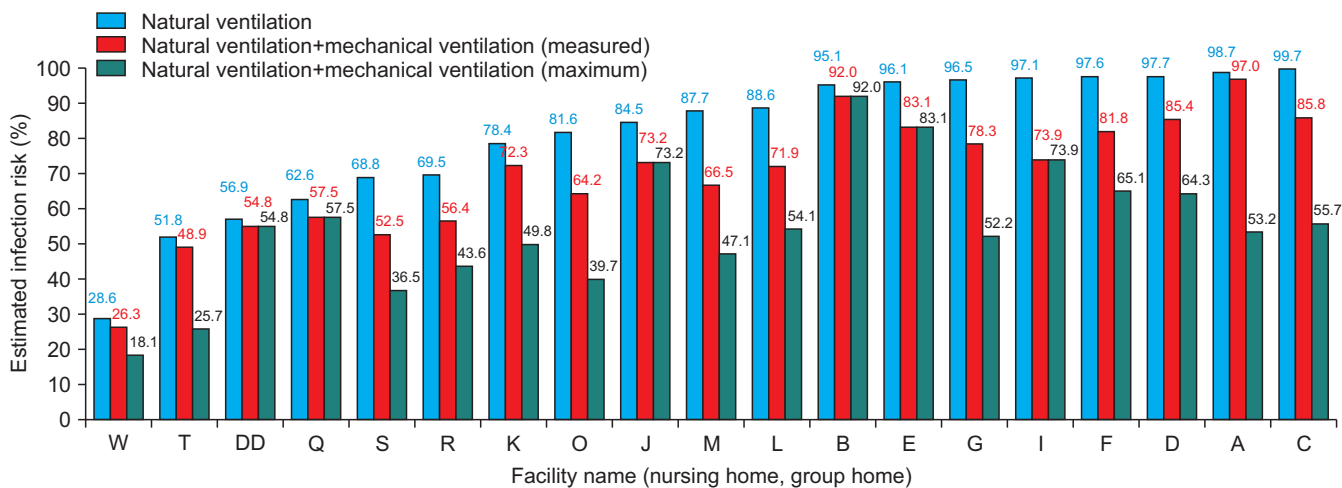


Figure 1. Estimated risk of respiratory infection in bedrooms by facility and mechanical ventilation status

capacity (high setting), the estimated infection risk decreased in all facilities compared with natural ventilation alone (Figure 1).

When the maximum ventilation capacity was applied, the largest reduction in estimated infection risk was observed in nursing homes A, where the risk decreased by 45.5%p, from 98.7% under natural ventilation alone to 53.2% with combined ventilation (Figure 1). The differences in estimated infection risk between natural ventilation alone and combined ventilation under the maximum ERV ventilation scenario satisfied the normality assumption ( $p=0.184$ ). A paired t-test demonstrated a statistically significant mean reduction of  $33.8\pm 9.8\%$ ,  $p=0.001$  (95% CI: 28.0–32.6), with a large effect size (Cohen’s  $d=1.28$ ), across the 13 nursing homes equipped with ERVs.

## Discussion

This study conducted a survey-based assessment of natural and mechanical ventilation rates in elderly medical welfare facilities in Seosan City and quantitatively evaluated the risk of

airborne transmission of SARS-CoV-2 using the K-VENT 3.1 program. The findings indicate that behavior-based ventilation management guidelines, such as natural ventilation at least three times daily for a minimum of 10 minutes per session, as required in long-term care facility evaluations, were met in many facilities. However, despite adherence to these operational criteria, 24 of the 27 facilities (88.9%) exhibited an average bedroom air change rate below 2 ACH during natural ventilation. Although the average outdoor wind speed applied in the infection risk assessment exceeded the 1 m/s value suggested in the WHO guidelines for natural ventilation, reflecting the coastal geographical characteristics of the study area, adequate air exchange could not be reliably ensured through ventilation frequency and duration alone [9]. These findings highlight the substantial variability in factors influencing natural ventilation performance across facilities, including window size, degree of window opening, and outdoor wind speed and temperature.

The mean bedroom ACH was  $1.4\pm 0.9$ , underscoring the importance of mechanical ventilation as a key measure for reducing infection risk. Compared with natural ventilation alone, the addition of mechanical ventilation reduced the estimated

infection risk by an average of  $11.4 \pm 6.9\%$ , with a maximum reduction of  $23.2\%$  observed in individual facilities.

When ERVs were assumed to operate at their maximum ventilation capacity, the estimated infection risk across the 13 nursing homes decreased by an average of  $33.8 \pm 9.8\%$  relative to natural ventilation alone, with a maximum reduction of  $45.5\%$ .

The magnitude of these reductions was supported by effect size analysis, with Cohen's d-values of 0.57 for measured ventilation rates and 1.28 for maximum ventilation rates. These effect sizes indicate that the observed reductions in estimated infection risk were not only statistically significant but also of practical relevance.

Although ERVs are typically operated at a low setting during routine conditions, it is critical to strengthen infection control by increasing operation to medium or high settings during outbreaks of respiratory infectious diseases to minimize transmission risk.

In this survey, when ERVs were assumed to operate at a medium setting corresponding to the certified ventilation rate, only six of the 13 facilities equipped with ERVs achieved a bedroom ventilation rate of at least 2 ACH, whereas the remaining seven facilities did not meet this threshold. This finding likely reflects the practice of installing mechanical ventilation systems with uniform capacities in long-term care facilities without adequate consideration of room volume. These results highlight the need for procedures to verify whether required ACH levels can be achieved by reviewing outdoor air intake at the design stage, using assessment tools such as K-VENT, when installing ERVs.

This study has several limitations. First, K-VENT 3.1 is sensitive to assumed input parameters, including virus type, virus

emission rates associated with the infected individual's activity level, and the respiratory rate and exposure duration of susceptible individuals; consequently, estimated infection risks may differ from actual transmission outcomes. Second, real-time CO<sub>2</sub> concentrations were not measured concurrently. Unlike the 2024 study Measuring Ventilation and Contamination in Long-term Care Hospitals to Study Improvements, this limitation precluded direct correlation of ventilation rates with indoor air quality indicators [11]. Third, ventilation rates were not measured under medium or high ERV operating settings, preventing direct comparison between measured ventilation performance and certified ventilation capacity. Despite these limitations, the findings consistently indicate that natural ventilation alone was insufficient in many facilities and that concurrent operation of ERVs is necessary to achieve a stable and adequate air change rate.

The policy implications of this study are as follows. First, there is a need to gradually introduce air change rate (ACH) standards and mandatory mechanical ventilation requirements into the evaluation criteria for long-term care facilities, with grading systems differentiated by ventilation approach, such as natural ventilation, exhaust fan installation, and ERVs. Second, regular measurement and monitoring of ventilation performance should be institutionalized at the local government level, accompanied by financial support and incentive mechanisms for mechanical ventilation upgrades and equipment replacement. Third, training programs for facility managers should be strengthened to improve competency in determining appropriate ventilation capacities, selecting operational settings, and implementing proper maintenance of mechanical ventilation systems.

In addition, extending K-VENT-based infection risk

estimation to other multi-use facilities, including schools, day-care centers, and welfare facilities for persons with disabilities, could support the development of standardized ventilation management guidelines for community-level infectious disease preparedness and response.

## Declarations

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