

Healthcare Technical Group

Healthcare White Papers

2026

Practical Guidance for
Safer, Healthier, more resilient Healthcare Environment

October 2026



ISHRAE

Indian Society of Heating, Refrigerating and Air Conditioning Engineers

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Healthcare Technical Group Healthcare White Papers 2026

**Practical Guidance for
Safer, Healthier, more resilient Healthcare Environment**

Released at

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“AIR WITH CARE”

**SATURDAY, 10TH OCTOBER 2026
HOTEL SAHARA STAR, MUMBAI**

ISHRAE

Indian Society of Heating, Refrigerating and Air Conditioning Engineers

HVAC Design, Installation, Commissioning, Operations and Service Requirements for Isolation Room

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Room Air Distribution Strategies for Infection Control in Hospital General Wards

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Indoor Air Quality Monitoring and Smart Control in Hospitals

Authors: **Nitin Naik, Abhay Santoshwar & Sameer Srivastava**

Climate-Specific Building Envelope Strategies for Healthcare Facilities: A Passive-First Active Next approach to IAQ, Moisture Control and HVAC Energy Optimisation.

Author: **Dr. Sachin Gupte**

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Disclaimer: This publication is intended to provide technical guidance based on current knowledge, accepted engineering practice and relevant standards at the time of publication. It is not intended to replace applicable statutory requirements, codes, standards, regulatory provisions or project-specific professional judgement. Users should verify the requirements applicable to the particular healthcare facility, jurisdiction and application.

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Foreword

Healthcare HVAC: From Building Envelope to Verified Indoor Air Quality

Healthcare buildings are the most demanding environments that the HVAC profession is asked to serve. Within a single facility, the air must protect immunocompromised patients, contain airborne pathogens, keep conditions stable for clinical work, and remain comfortable for patients and staff. It must do all of this around the clock, across five climatic zones and against outdoor air that routinely exceeds the WHO PM_{2.5} guideline of 5 µg/m³ by an order of magnitude. The four white papers in this compendium approach that challenge from the building shell inward and bring the discussion together as one engineering chain: load, distribution, containment and verification.



The white paper *Climate-Specific Building Envelope Strategies for Healthcare Facilities: A Passive-First, Active-Next Approach to IAQ, Moisture Control and HVAC Energy Optimisation* argues that thermal continuity, airtightness and vapour control should reduce avoidable solar, conductive, infiltration and latent loads before HVAC plant is sized. EIFS, spray-applied PU insulation and high-SRI roof coatings are presented as representative measures, aligned with ECSBC assembly U-factor limits and the IGBC and GRIHA frameworks. A tighter, drier envelope makes every downstream control objective easier to hold.

The white paper *Room Air Distribution Strategies for Infection Control in Hospital General Wards* addresses spaces where 2 to 10 or more patients share both a room and its air. It establishes the ASHRAE 170 baseline of 6 total and 2 outdoor ACH with MERV 7 pre-filtration and MERV 14 final filtration, then examines diffuser selection, bed-wise return placement to avoid short-circuiting, and the emerging options of stratum and personalised ventilation. It cautions that the high sensible heat ratio of stratum ventilation requires a DOAS to carry the full ventilation latent load, with humidity-override logic above 55% RH, and proposes a nurse-activated, bed-specific dedicated exhaust that isolates the AHU return path during aerosol-generating events.

The white paper *HVAC Design Requirements for Isolation Rooms* sets out requirements for the Indian context: negative pressure of at least 2.5 Pa for AII rooms and positive pressure of at least 8 Pa for PE rooms, with a minimum of 12 total and 2 outdoor ACH in both. PE supply air is HEPA-filtered to H13/H14 (EN 1822), while AII supply requires a minimum of MERV 14. It clarifies anteroom pressure cascades for combined AII/PE rooms, and treats environmental aerosols such as Aspergillus, HEPA integrity testing, BIBO housings, redundancy and service-personnel competency as core design issues rather than afterthoughts.

The white paper *Indoor Air Quality Monitoring and Smart Control in Hospitals* closes the loop by moving from design assumptions to continuous verification. It treats CO₂ as a surrogate for ventilation adequacy rather than as a contaminant, confines demand-controlled ventilation to wards and outpatient areas, and respects clinical floors such as the NABH provision for a 25% OT airflow setback, permitted only with positive pressure preserved. Its central insight is that dew point can be derived in software from existing temperature and RH sensors and alarmed as a first-class parameter, which matters because at 24°C and 60% RH the dew point is already about 16°C.

A single thread runs through all four papers: **moisture and pressure are the two variables on which clinical safety most depends**. The envelope limits moisture at the source, air distribution and filtration manage it in the room, isolation design holds the pressure boundary, and smart monitoring confirms continuously that all of this is actually happening. Together, these papers give designers, owners and facility managers in India a coherent, standards-aligned path from passive design to verified clinical performance, so that the building which cares for patients is itself cared for.

I commend the ISHRAE Technical Group on Health Care lead by Mr. Gautham Baliga and his team members for this comprehensive effort and hope this document will serve as a valuable reference to all.

Prof. R. Saravanan
Society President (2026-27)

Message from the Chair

In its fifth decade of exemplary service, ISHRAE remains steadfast in its mission to **Engineer a Greener Global Built Environment**. Drawing upon the collective expertise of 37 specialized Technical Groups – comprising distinguished consultants, manufacturers, contractors, end-users, and academia – the ISHRAE Technical Committee (ITC) continues to harness and disseminate our HVACR industry knowledge for the broader benefit of society.



Historically, healthcare facilities were designed around natural principles, leveraging expansive land footprints, open-to-sky corridors, and cross-ventilated spaces to manage airflow and promote healing. In recent decades, however, rapid economic growth, rising standards of living, and escalating real estate costs have driven a shift toward tightly enclosed, sealed environments. While these modern facilities offer localized thermal comfort, they also introduce significant challenges: high energy penalties, compromised Indoor Air Quality (IAQ), and an elevated risk of hospital-acquired infections.

Faced with these modern spatial and architectural constraints, our imperative is clear: we must leverage advancing technologies to design intelligent, high-efficiency HVAC systems. By mitigating risks and optimizing environmental controls, we can transform sealed healthcare facilities into safer, faster-track patient recovery centres.

Under the leadership of Mr. Gautham Baliga, ISHRAE's Healthcare Technical Group established dedicated sub-committees – notably featuring practicing medical professionals alongside engineering experts. Through this collaborative synergy, the group has developed four comprehensive white papers addressing critical pain points, design strategies, and actionable solutions across the four key domains:

1. HVAC Design Requirements for Isolation Rooms
2. Room Air Distribution Strategies for Infection Control in Hospital General Wards
3. Indoor Air Quality Monitoring and Smart Control in Hospitals
4. Climate-Specific Building Envelope Strategies for Healthcare Facilities: A Passive-First Approach

The ITC extends its sincere appreciation to the Healthcare Technical Group members, the contributing medical professionals, and all ISHRAE coordinators for their tireless dedication and collaborative effort in bringing these vital white papers to publication.

We are confident that healthcare HVAC design professionals, facility managers, and industry stakeholders will find these papers to be an indispensable resource.

Raghavan Krishnan

Chair – ISHRAE Technical Committee

Message from the Chair

The release of these four White Papers marks another step in the continuing journey of the ISHRAE Healthcare Technical Group to develop practical guidance for HVAC in healthcare facilities.

Over the past few years, the Technical Group has brought out three publications – the *ISHRAE Guide Book for Healthcare Facilities*, the *Air Conditioning and Ventilation Guide for Infection Control in Small Clinics*, and the *Guide to Operation Theatre HVAC Validation*. Each addressed a specific need that we felt was important to healthcare professionals in India.



The four White Papers in this volume continue that effort. They address **Isolation Rooms, Air Distribution for Infection Control in General Wards, Indoor Air Quality Monitoring and Smart Control, and Climate-Specific Building Envelope Strategies**. Together, they extend the discussion beyond specialised areas such as operating theatres to the wider hospital environment.

A conscious effort has been made to keep these papers relevant to Indian conditions – our climate, outdoor air quality, healthcare infrastructure, operating practices, resource constraints and the realities of maintaining systems over their entire life. At the same time, the recommendations draw upon established national and international standards and current engineering knowledge. This complements the President's emphasis on providing Indian designers, owners and facility managers a standards-aligned path towards verified clinical performance.

These papers are the outcome of a collaborative effort involving HVAC professionals, healthcare specialists and other contributors who have generously shared their knowledge and practical experience. I sincerely thank all of them.

We hope these White Papers will not merely be read, but used in – **design offices, hospitals, project meetings and plant rooms – wherever better engineering can contribute to safer and healthier healthcare environments.**

B. Gautham Baliga

Chair – ISHRAE Healthcare Technical Group

About ISHRAE

The Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE) was founded in 1981 at New Delhi by a distinguished group of HVAC&R professionals. Today, ISHRAE represents a strong network of over 25,000 members, including student members, and functions through 57 chapters and sub-chapters across the globe, with its headquarters located in New Delhi. It is led by a team of elected officers who are members of the Society working on a voluntary basis, collectively called the Board of Governors. In pursuance of its objectives, ISHRAE works in the areas of Research, Standards, Education and Training, and Publication of Technical Books and a Journal. It also organizes world-class annual exhibitions ACREX and REFCOLD, besides hosting technical seminars and conferences. ISHRAE is a responsible and socially-conscious Technical Society.

Purpose

- Nurturing the built environment

Vision

- Enabling climate positive built environment

Mission

- Global leadership & trusted knowledge partner for planet centric HVAC&R solutions, unifying professionals across industry, academia & government by setting standards, enabling policy, creating capacity and building resilience

Activities

Knowledge Dissemination: ISHRAE conducts conferences, seminars, exhibitions, workshops, panel discussions and product presentations throughout the country with both national and international participants to discuss, promote and display the state-of-the-art technologies, systems, products and services.

Books and Publications: ISHRAE publications help its members and the industry to keep up with technical developments, latest trends and sunrise technologies. ISHRAE publishes Standards, books on fundamentals of various topics, HVAC&R Handbooks and the extremely popular and informative ISHRAE Journal. The latest publication is on Insulation

Exhibitions cum Conferences: ISHRAE organises ACREX India, the largest international exposition in South Asia on the Air Conditioning, Refrigeration, Ventilation and Building Services industry. Held annually, ACREX showcases the latest technologies and innovations, and provides a platform for buyer-seller meets for technical and commercial personnel in the HVAC&R field. To serve the interests of the Refrigeration and Cold-chain sector, ISHRAE organises REFCOLD annually. ISHRAE is a member and active supporter of the National Centre for Cold-chain Development (NCCD).

Education: ISHRAE is actively engaged in Education and Training, and offers several courses for technical professionals, some with post-examination certification. This helps to bring trained manpower into the HVACR industry.

Research: ISHRAE promotes research in the field of HVAC&R technologies. It offers financial support to graduate and post-graduate students to carry out innovative R&D work in technology, systems and processes. ISHRAE partners with the industry, academia and the government to carry out scientific research at Institutes of Excellence associated with ISHRAE.

Standards: ISHRAE works in the national interest with various government ministries and departments; for example, in the development of Standards and drafting of the National Building Code for the Bureau of Indian Standards, working on Energy Conservation Building Code with the Bureau of Energy Efficiency, and with the Ozone Cell of the Ministry of Environment, Forest and Climate Change on refrigerant gases. ISHRAE has also developed a pioneering Standard on Indoor Environmental Quality.

Student Activities: ISHRAE student chapters in more than 150 engineering colleges encourage students to opt for careers in the HVAC&R industry with industry exposure including factory visits. The K-12 initiative of ISHRAE reaches out to young school children to make them aware of subjects like energy conservation and environmental concerns through drawing competitions, poster designs, quizzes and more, with emphasis on STEM education to inculcate scientific fervour and help them to grow up as responsible citizens.

Global Reach: ISHRAE works in close co-operation with other similar societies and organisations, both at national and international levels, for the promotion and development of concepts like health and safety, sustainability, Green buildings, energy efficiency and environmental responsibility, often interacting with UN bodies like UNDP and UNEP.

ISHRAE is indeed looked upon as a repository of technical knowledge in the HVAC&R and Building Services Industry globally by peer organizations and the Government.

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White Paper

HVAC Design, Installation, Commissioning, Operations and Service Requirements for Isolation Room

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Indian Society of Heating, Refrigerating and Air Conditioning Engineers

Preface

Healthcare facilities accommodate patients with widely differing infection risks. Infectious respiratory aerosols generated by infected patients through breathing, talking, coughing and aerosol-generating medical procedures can remain airborne and contribute to transmission within healthcare environments. Healthy individuals generally tolerate inhalation of environmental fungal spores without adverse effects. However, immunocompromised patients, including transplant recipients, oncology patients, burn patients and those receiving immunosuppressive therapy, are highly susceptible to invasive aspergillosis, a serious infection associated with significant morbidity and mortality. Environmental bioaerosols also present a major concern in positive-pressure protective isolation rooms, where preventing the ingress of contaminated air is essential.

Appropriate patient isolation is therefore an important component of infection prevention and control. From an HVAC perspective, two important specialised environments are **Airborne Infection Isolation (AII) rooms**, maintained at negative pressure to reduce the migration of potentially infectious airborne contaminants to adjacent areas, and **Protective Environment (PE) rooms**, maintained at positive pressure to protect selected severely immunocompromised patients from airborne contaminants.

The effectiveness of these environments depends on the appropriate integration of ventilation, filtration, temperature, room-pressure relationships, air distribution and exhaust-air management, together with architectural and operational infection control measures.

This white paper examines the HVAC design requirements for **AII** and **PE** rooms, including their application in fully air-conditioned as well as resource-constrained or partially conditioned healthcare facilities. It is intended to provide practical guidance to HVAC designers, architects, healthcare planners, facility managers and medical professionals involved in the planning, operation and maintenance of isolation environments.

Executive Summary

With advances in healthcare treatment and a better understanding of the transmission and acquisition of infections in hospital settings, the need for appropriately designed isolation environments has become increasingly important. Patients who are infected and may potentially transmit infections will require controlled environments to prevent the spread of infection. At the same time, immunocompromised patients, including organ-transplant recipients, are highly susceptible to acquiring infections and therefore require a protected environment. Isolation rooms and other specialised controlled environments have consequently become an integral part of modern healthcare facilities and treatment practices.

This white paper takes a holistic approach to the classification, design, installation, testing, and commissioning of isolation rooms. Equally important, it addresses the monitoring, operation, maintenance, and servicing of these environments, with particular emphasis on the skills and competencies required of service technicians working in healthcare facilities. Consistent performance of the HVAC and associated systems is critical to maintaining the required pressure relationships, airflow patterns, filtration, and infection-control conditions throughout the operational life of an isolation room.

This paper is intended to serve as a practical reference for hospital facility managers, HVAC designers, consultants, contractors, commissioning professionals, and service providers involved in planning, installing, operating, monitoring, maintaining, and servicing isolation rooms.

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HVAC Design, Installation, Commissioning, Operations and Service Requirements for Isolation Room

A. Scope

This white paper addresses the HVAC design and operational requirements of healthcare isolation rooms in India, covering both large and small healthcare facilities and considering the constraints of urban, rural and resource-constrained healthcare facilities. It focuses primarily on **Airborne Infection Isolation (All) rooms** for patients requiring airborne precautions and **Protective Environment (PE) rooms** for identified severely immunocompromised patients.

The scope is limited to isolation rooms, wards and specialised isolation environments and does not cover operating theatres, ICUs, OPDs or general hospital areas.

B. Indian Perspective

The availability of purpose-designed isolation facilities varies considerably across India, with dedicated **All** and **PE** rooms more commonly available in larger hospitals than in smaller or resource-constrained healthcare facilities.

The requirement for isolation should be determined by the mode of disease transmission and individual patient risk, rather than by diagnosis alone. All rooms are intended for patients with known or suspected airborne infections; PE rooms are intended primarily for selected severely immunocompromised patients, particularly allogeneic hematopoietic stem cell transplant recipients and patients with severe and prolonged neutropenia.

Conditions such as burns, solid-organ transplantation, post-surgical recovery and pre-term neonates do not, by themselves, establish a requirement for an HVAC-engineered isolation room; however, such isolation may be provided where indicated by the treating clinician or the hospital's infection-control team based on the individual patient's clinical and infection-control risk assessment.

C. Sources of Environmental Aerosols

While isolation rooms are primarily intended to control airborne transmission of infectious pathogens, HVAC designers must also consider environmental aerosols, such as *Legionella*, *Aspergillus*, *Pseudomonas*, non-tuberculosis mycobacteria, etc. Unlike infectious aerosols, which originate from infected patients through breathing, talking, coughing and aerosol-generating medical procedures, environmental aerosols arise from the surrounding environment. Common sources include outdoor air, soil, dust, damp building materials, HVAC components, water-aerosol-generating sources such as cooling towers, faucets, aerators, showers, etc., and construction or renovation activities within the healthcare facility.

From an HVAC perspective, moisture control is the most effective strategy for limiting fungal proliferation. Fungal growth requires a viable spore, suitable temperature, an organic nutrient

source and, most importantly, moisture. Preventing condensation through effective humidity control, adequate drainage, and elimination of moisture sources is one of the most effective engineering measures for preventing fungal colonisation and subsequent airborne dissemination of spores.

Any renovation activity in an operational hospital will require special attention to ensure that the isolation rooms are not contaminated. The activity can release large quantities of *Aspergillus* spores into the air. During such activities, work areas should be isolated using airtight barriers, maintained under negative pressure using HEPA-filtered exhaust systems, and monitored continuously to prevent airborne contaminants from reaching patient-care areas.

D. Isolation Room Classification

From an HVAC and infection-control perspective, isolation rooms may be classified as:

- a. **Airborne Infection Isolation (AII) Rooms:** Designed for patients with known or suspected airborne infectious diseases. The room is maintained at negative pressure relative to adjoining areas to reduce the migration of potentially infectious airborne contaminants to external space.
- b. **Protective Environment (PE) Rooms:** Designed for identified severely immunocompromised patients requiring protection from airborne environmental contaminants. The room is maintained at positive pressure relative to adjoining areas and supplied with appropriately filtered air.
- c. **Combined AII/PE Rooms:** Intended for severely immunocompromised patients who require a protective environment and simultaneous airborne infection isolation. The HVAC system should provide both patient protection and containment of infectious airborne contaminants.
- d. **Contact Isolation Rooms:** Intended for patients requiring contact precautions. These do not normally require the specialised pressure-control measures associated with **AII** or **PE** rooms unless otherwise indicated by the clinical/infection-control risk assessment.

E. Air-Conditioned and Non-Air-Conditioned Isolation Rooms

Air-conditioned isolation rooms use mechanical HVAC systems to control ventilation, airflow direction, filtration, room pressure, temperature and humidity. The specific requirements depend on whether the room functions as an **AII**, **PE** or combined **AII/PE** room.

Non-air-conditioned isolation rooms may be used in resource-constrained, temporary or climatically suitable settings, relying on natural ventilation, operable openings and/or mechanical exhaust. Since airflow direction, ventilation rate, filtration and environmental conditions are more difficult to control and verify, their application should be based on clinical and infection-control requirements and applicable healthcare guidance. Such rooms should not be considered equivalent to engineered **AII** or **PE** rooms unless the required performance criteria are demonstrated. In resource-constrained hospitals, the systems can be designed only for ventilation; however, such systems will not be able to control humidity

F. Airborne Infection Isolation (AII) Rooms – Design Considerations

Airborne Infection Isolation (**AII**) rooms are intended to contain airborne contaminants generated by a patient with a known or suspected airborne infectious disease and reduce their migration to adjoining areas. The room is therefore maintained at **negative pressure relative to adjacent spaces**, so that airflow is directed into the patient room.

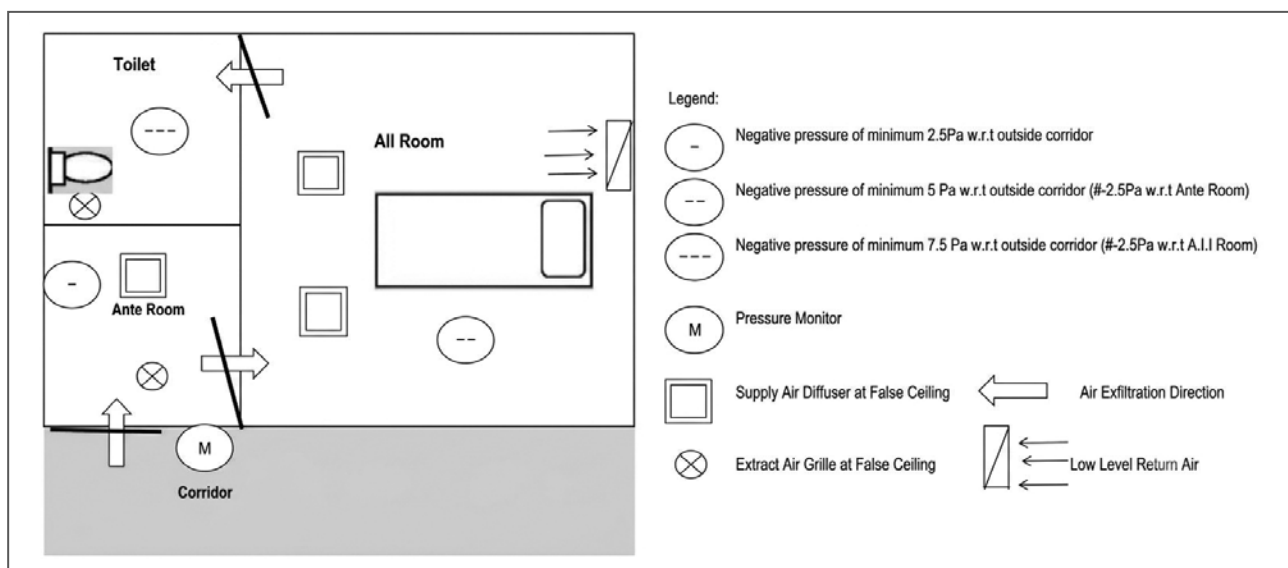
The ventilation system should provide the required outdoor and total air-change rates while continuously maintaining the specified pressure relationship. Supply air should enter from the cleaner side of the room and move towards the patient and exhaust, without creating airflow patterns that could carry contaminants towards the room entrance.

Exhaust air should preferably be discharged directly outdoors at a location that prevents re-entrainment into outdoor-air intakes or exposure of occupied areas. Where direct discharge is impractical, HEPA-filtered recirculation may be permitted, complying with the applicable standard.

Room pressure should be continuously monitored with local indication and alarm. Where an anteroom is provided, its pressure relationship should be appropriate to the intended containment strategy.

Table F-1: Key HVAC Requirements for AII Rooms

Parameter	Requirement
Purpose	Containment of patient-generated infectious airborne contaminants
Room pressure	Negative to adjoining areas; minimum differential 2.5 Pa
Ventilation	Minimum 12 total ACH and 2 outdoor ACH
Airflow direction	From cleaner adjoining areas → patient room → exhaust
Air distribution	Supply from clean side; exhaust near patient/head of bed and arranged to minimise contaminant movement towards room entrance
Exhaust	Preferably directly outdoors; HEPA-filtered recirculation only where permitted
Monitoring	Continuous room-pressure indication with alarm



Layout of Airborne Infection Isolation (AII) Room

G. Protective Environment (PE) Rooms – Design Considerations

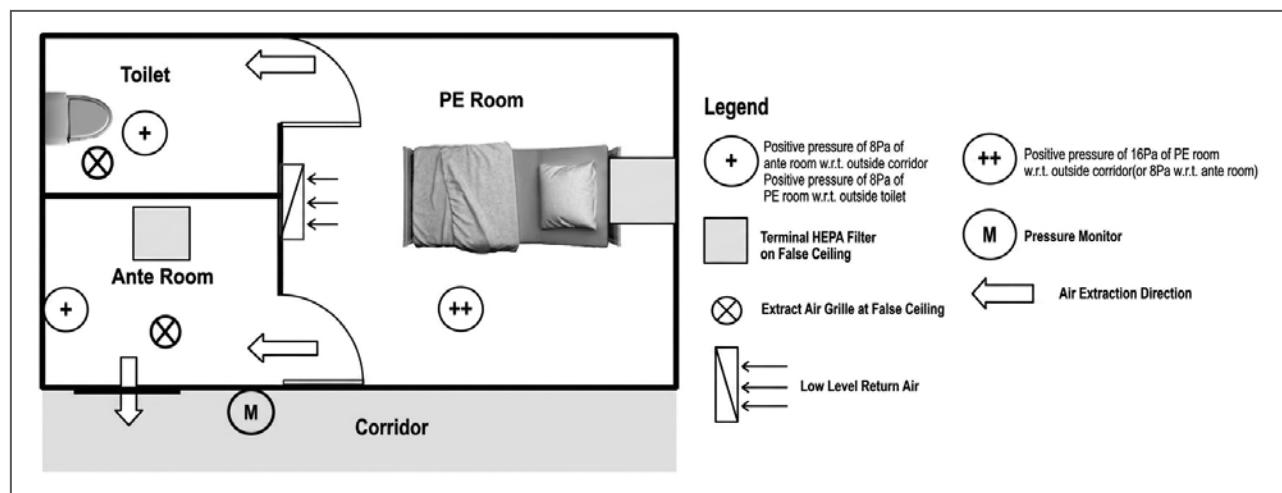
Protective Environment (PE) rooms are intended for identified severely immunocompromised patients, particularly those at high risk from airborne environmental contaminants such as fungal spores. Unlike an AII room, the PE room is maintained at **positive pressure relative to adjoining spaces**, to ensure that the potential ingress of contaminated air is minimised.

Supply air to the PE room should be **HEPA filtered**. Air distribution should deliver clean filtered air to the patient zone and then move it towards the room perimeter and return-air openings. Ceiling supply above or near the patient zone, together with appropriately located return air, can promote this clean-to-less-clean airflow pattern. Excessive turbulence and drafts around the patient should be avoided.

Room pressure should be continuously monitored with local indication and alarm. Door openings can temporarily disturb the pressure relationship and should therefore be minimised through appropriate architectural and operational practices.

Table G-1: Key HVAC Requirements for PE Rooms

Parameter	Requirement
Purpose	Protection of selected severely immunocompromised patients from airborne environmental contaminants
Room pressure	Positive to adjoining areas; minimum differential 8 Pa
Ventilation	Minimum 12 total ACH and 2 outdoor ACH
Filtration	HEPA-filtered supply air
Airflow direction	From protected patient zone → room perimeter → adjoining area
Air distribution	Clean filtered air supplied to patient zone with return arranged to carry air away from the protected zone
Monitoring	Continuous room-pressure indication with alarm



Layout of PE room

H. Common Principles of Airborne Contaminant Control

The effectiveness of both **All** and **PE** rooms depends on controlling the **concentration and movement of airborne particles**. Respiratory activities generate particles of varying sizes; particles > 5 microns generally settle more rapidly, while particles < 5 microns may remain suspended and be transported by room air currents.

Three HVAC mechanisms are particularly important:

Dilution: Ventilation reduces airborne contaminant concentration by replacing or mixing room air with clean air. Increasing the effective clean-air delivery rate generally increases the rate of contaminant removal.

Filtration: Appropriate filtration removes airborne particles from the supplied or recirculated air. PE rooms require HEPA-filtered supply air, while filtration and exhaust arrangements for **All** rooms should comply with the applicable healthcare standard.

Air distribution: ACH alone does not determine isolation-room performance. The location and characteristics of supply and exhaust/return terminals influence how effectively clean air reaches the occupied zone and how contaminants are removed. The required airflow pattern differs between **All** and **PE** rooms and should therefore be considered as an integral part of their respective designs.

HVAC measures are only one component of infection prevention and should operate together with appropriate architectural, clinical and operational controls

H.1. Conversion Between All and PE Rooms – Reversible Airflow Not Permitted

An All room should not be designed for conversion into a PE room, or vice versa, merely by reversing the room pressure or direction of airflow. ASHRAE does not permit reversible airflow provisions for switching between PE and All functions.

The reason is that All and PE rooms have fundamentally different airflow patterns and air-distribution objectives. In an All room, the airflow arrangement is designed to contain infectious aerosols generated within the patient room and prevent their migration to adjoining spaces. In a PE room, clean HEPA-filtered supply air is introduced to protect the susceptible patient, with the airflow pattern designed to carry contaminants away from the patient towards the return/exhaust and exit side of the room.

Simply reversing the room pressure therefore does not convert an All room into a PE room, or vice versa. Any proposed conversion requires review of the complete air-distribution arrangement, including supply and return/exhaust locations, filtration, airflow direction and pressure relationships.

I. Air-Handling Unit Hygiene

The Air-Handling Unit (AHU) serving isolation rooms should be designed to minimise accumulation of dust and moisture, microbial contamination, and to facilitate good servicing practices.

- **Casing:** Double-wall construction with smooth, cleanable internal metal surfaces should be used, avoiding exposed fibrous insulation within the airstream.
- **Coils and Drain Pans:** Cooling-coil sections should prevent water stagnation. Drain pans should be corrosion-resistant, adequately sloped and arranged for complete condensate drainage.
- **Filtration and Internal Surfaces:** Filters should protect downstream components and ductwork from particulate contamination. Where terminal HEPA filtration is provided, it forms the final filtration barrier before the protected space. Materials downstream of the final AHU filtration stage should not retain moisture, support microbial growth or shed fibres.
- The HVAC system should also maintain these protective functions during equipment or power failure, as addressed in the following section on system reliability
- The coils may have a growth of fungus, and the use of UV lights helps reduce the microbial growth.

J Reliability, Redundancy and Emergency Management

In isolation environments, interruption of the HVAC system can result in loss of the required pressure relationship and compromise patient or staff protection. The systems serving Protective Environment (**PE**) and Airborne Infection Isolation (**All**) rooms should therefore be designed for appropriate reliability and continuity of operation.

Of particular importance is maintaining the airflow that establishes the required room-pressure relationship during a power failure:

- **PE Rooms:** The supply-air fan serving the PE room should be connected to the hospital's essential/emergency electrical power system so that the positive pressure relationship can be maintained during interruption of normal power.
- **All Rooms:** The exhaust fan serving the All room should be connected to the essential/emergency electrical power system so that the negative pressure relationship can be maintained and potentially contaminated air does not migrate to adjacent areas.

Where supply and exhaust systems operate together to establish the required pressure relationship, their operation and controls should be appropriately interlocked so that transfer to emergency power does not inadvertently reverse the intended direction of airflow.

Other critical components, including controls, room-pressure monitoring and alarm systems, should also be provided with suitable emergency power or uninterrupted power, as appropriate, to permit continuous monitoring of the isolation-room pressure relationship. Redundancy of fans, pumps, and cooling equipment may be considered based on the facility's criticality, risk assessment, and applicable codes. N+1 redundancy should therefore be regarded as a design consideration rather than a universal requirement for every isolation room.

K. Combined AII/PE Isolation Rooms

A combined Airborne Infection Isolation/Protective Environment (AII/PE) room is intended for a severely immunocompromised patient with a known or suspected airborne infectious disease. Examples include a patient requiring a Protective Environment, such as an allogeneic haematopoietic stem-cell transplant recipient or a patient with severe prolonged neutropenia, who concurrently develops an airborne infection such as pulmonary or laryngeal tuberculosis, measles or varicella.

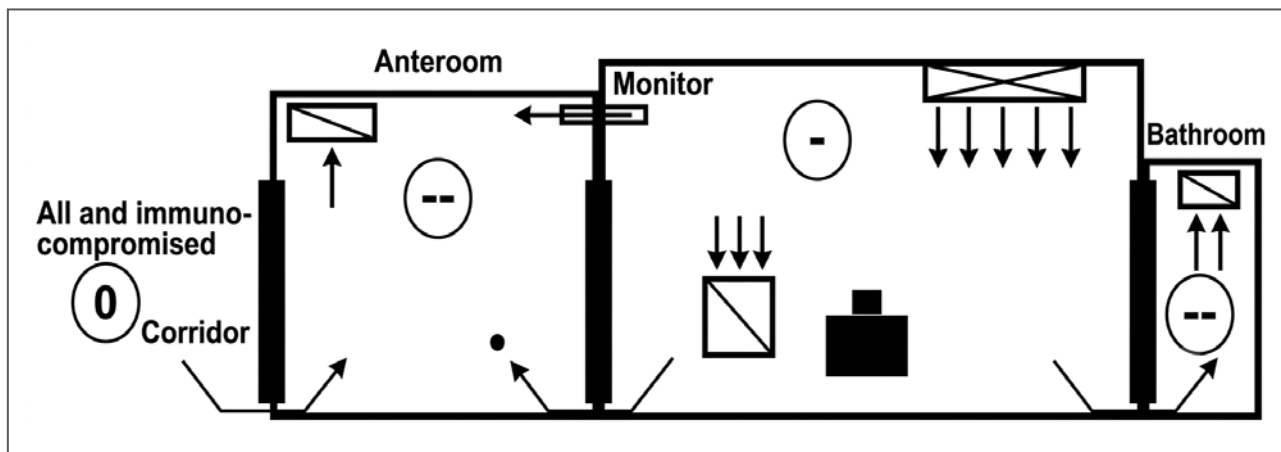
Such a patient presents two simultaneous but opposing HVAC requirements:

- Protect the patient: HEPA-filtered supply air and positive room pressure are required to minimise the ingress of environmental airborne contaminants into the patient environment.
- Protect the hospital: Patient-generated infectious aerosols must be prevented from migrating to the corridor and other hospital areas.

The patient room is therefore maintained as a positive-pressure Protective Environment, supplied with HEPA-filtered air, while air from the patient room is exhausted directly outdoors to provide airborne-infection containment. An anteroom provides the pressure-controlled transition between the patient room and the hospital corridor.

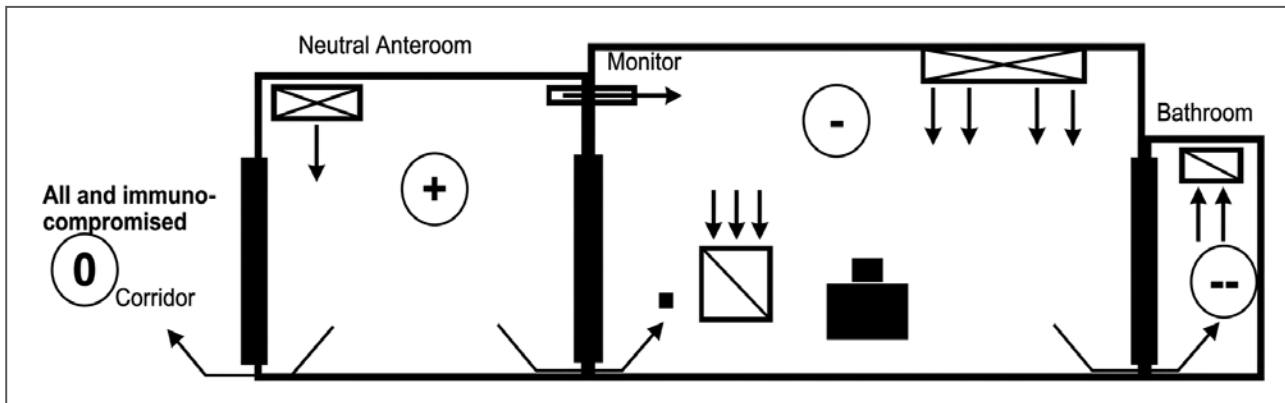
Anteroom Pressure Relationships: Two alternative pressure-control arrangements may be adopted. They are not intended for different categories of patients. Both arrangements apply to the same clinical situation - a severely immunocompromised patient who simultaneously requires airborne infection isolation. The choice is an engineering and infection-control design decision based on the facility's adopted pressure-control strategy and applicable requirements.

Combination AII/PE room - Alternative 1



The anteroom is maintained at negative pressure relative to both the patient room and the corridor. Air therefore flows from both adjoining spaces into the anteroom. The negative anteroom acts as a containment buffer between the patient room and corridor. Air removed from the anteroom should be exhausted appropriately to prevent the transfer of potentially contaminated air to other hospital areas.

Combination All/PE room - Alternative 2



The anteroom is maintained at positive pressure relative to both the patient room and the corridor. Air therefore flows out of the anteroom in both directions. The positive anteroom acts as a clean-air buffer separating the patient room from the corridor. Since air from the anteroom enters the patient room, the air supplied to the anteroom should be appropriately filtered consistent with the protective strategy.

In both alternatives, the patient room remains a HEPA-supplied Protective Environment and patient-room air is exhausted directly outdoors. The pressure arrangement should therefore be understood as two alternative anteroom strategies for achieving the same dual objective of patient protection and infection containment, rather than as arrangements for different categories of patients.

Pressure Monitoring and Alarms: Two differential-pressure monitors should continuously monitor the patient room-anteroom and anteroom-corridor pressure relationships. Both should provide local indication and alarm on loss of the required pressure differential, with displays readily visible to staff from the corridor.

Ventilation and Filtration: The ventilation system should simultaneously provide the clean-air protection required for a Protective Environment and the containment required for Airborne Infection Isolation. Key requirements include:

- **Ventilation:** Minimum 12 total ACH, including minimum 2 outdoor ACH.
- **Filtration:** Patient-room supply air shall be HEPA-filtered, with appropriate upstream prefiltration. Where a positive anteroom is used, air supplied to the anteroom should receive appropriate filtration consistent with the protective strategy.
- **Air Distribution:** Clean air should be supplied from the ceiling above or near the patient zone, with exhaust located to promote airflow from the patient zone towards the room exhaust. Unidirectional airflow is not normally required.
- **Exhaust:** Patient-room air shall be exhausted directly outdoors, with the discharge located to prevent re-entrainment into outdoor-air intakes or exposure of occupied areas.
- **Temperature and RH:** Maintain within the requirements of the applicable healthcare standard and the clinical needs of the patient.

Pressure monitoring, alarms, controls and emergency-power provisions should support maintenance of the required pressure relationships and containment/protective functions during operation.

Important: It is to be noted that Isolation rooms shall be equipped with a constant airflow system to maintain consistent ventilation parameters.

L. Operational Integrity and Life Safety Safeguards

- **Operational Integrity and Life-Safety Safeguards**

Isolation rooms are important components of a healthcare facility's infection-control and emergency preparedness strategy. Loss of ventilation or the required pressure relationship can compromise patient protection and infection containment; the associated HVAC systems should therefore be designed for appropriate reliability and continuity of operation.

- **Building-Envelope Considerations**

The building envelope should be designed and maintained to minimise uncontrolled air and moisture infiltration. In humid climates, air leakage through exterior walls and other envelope penetrations can introduce moisture into concealed building cavities, potentially leading to condensation and microbial growth.

The interaction between building pressurisation, isolation-room pressure control and the exterior envelope should therefore be considered during design. Particular care is required to avoid pressure relationships that promote uncontrolled infiltration of warm, humid outdoor air into conditioned wall or ceiling cavities, where condensation and mold growth may occur.

M. Contact Isolation Rooms

Contact and Droplet Precaution Rooms: Intended for patients requiring contact and/or droplet precautions. These are preferably single-patient rooms and generally do not require the specialised pressure control and air filtration used for **All** or **PE** rooms, unless otherwise indicated by the clinical or infection-control risk assessment.

N. Supplementary Air Cleaning

Portable air cleaners may be used as a supplementary measure to reduce airborne contaminant concentrations, particularly where existing ventilation or filtration is inadequate or cannot readily be upgraded. They do not replace the ventilation, filtration, pressure relationships or airflow requirements specified for **All**, **PE** or combined **All/PE** rooms, nor do they protect against contact or direct droplet exposure.

HEPA-filtered portable air cleaners provide an effective means of removing airborne particles, including respiratory aerosols. Units should be selected based on room volume and the required Clean Air Delivery Rate (**CADR**) or equivalent clean-air changes per hour. The **CADR** at the actual operating speed should be considered, since higher fan speeds may result in unacceptable noise levels.

Other air-cleaning technologies should be used only where their effectiveness and safety have been adequately validated, including consideration of potentially harmful by-products. Ozone-generating devices should not be used in occupied healthcare spaces.

Appropriately designed germicidal ultraviolet (GUV/UVGI) may also be used as a supplementary means of inactivating airborne microorganisms

O. Disposal of Exhaust Air

Exhaust air from an **All** room may contain infectious aerosols and should preferably be discharged directly outdoors, with the discharge located to prevent re-entrainment through outdoor-air intakes, openable windows or doors, or exposure of occupied areas. **ASHRAE 170** has given the following guidelines;

- A discharge termination shall be a minimum of 10 ft (3 m) above service access level.

- Discharge termination shall be higher than any roof surface within 4 ft (1* 2 m)*
- Discharge termination shall be a minimum of 6 ft (1.8 m) from exterior walls,
- Discharge termination shall be a minimum of 30 ft (10 m) from outdoor air intakes, openable windows/doors, and areas that are normally accessible to the public.

In case there are residential buildings in the close vicinity, a chimney with a height of at least 10 feet above the tallest building should be used to disperse the air.

Where direct outdoor discharge is not practicable, HEPA-filtered exhaust arrangements may be used where permitted by the applicable standard. The HEPA filter should be installed as close as practicable to the point of extraction, in a housing suitable for integrity testing, pressure-drop monitoring and safe filter replacement.

The exhaust fan should preferably be located downstream of the HEPA filter and contaminated exhaust ductwork, so that the upstream exhaust system remains under negative pressure, thereby reducing the risk of contaminated-air leakage into surrounding spaces.

Exhaust HEPA filters should be maintained and replaced using appropriate containment procedures and PPE to protect personnel and prevent environmental contamination

P. Air Filtration and Filter Management for Isolation Rooms

General Principles: Air filtration is an important engineering control in hospital isolation facilities. The filtration strategy depends on the purpose of the isolation room: protecting a susceptible patient from airborne contaminants in a Protective Environment (PE), or containing infectious aerosols generated within an Airborne Infection Isolation (AII) room.

Effective filtration requires appropriate filter efficiency and location, staged AHU filtration, safe management of potentially contaminated filters and maintenance of filtration performance throughout the HVAC system's service life.

Supply Air Filtration PE Rooms: Supply air to the PE room should be HEPA filtered. Where terminal HEPA filtration is provided, filters should be H13 or H14 in accordance with EN 1822, installed in housings suitable for integrity testing and differential-pressure monitoring. Air distribution should deliver clean filtered air to the patient zone and then move it towards the room perimeter and return-air openings. Ceiling supply above or near the patient zone, together with appropriately located return air, can promote this clean-to-less-clean airflow pattern. As the supply air outlet is placed above the patient, the supply velocity should be low to avoid patient discomfort, excessive turbulence and drafts.

Where an anteroom is provided, its filtration should be selected considering the required pressure relationship and airflow direction between the anteroom, patient room and corridor. Return air from a PE room may be recirculated through the HVAC system.

Air distribution: ACH alone does not determine isolation-room performance. The location and characteristics of supply and exhaust/return terminals influence how effectively clean air reaches the occupied zone and how contaminants are removed. The required airflow pattern differs between AII and PE rooms and should therefore be considered as an integral part of their respective designs.

Airborne Infection Isolation AII Rooms: Terminal HEPA filtration of supply air is not normally required for an AII room. Supply air should receive final filtration of minimum MERV 14 in accordance with ASHRAE Standard 52.2, unless a higher level is required by the governing healthcare standard or facility risk assessment.

Air from an AII room should preferably be exhausted directly outdoors. Where recirculation is permitted, the air shall be HEPA filtered before entering the return-air system, with the HEPA filter located as close as practicable to the room extract so that contaminated return ductwork is minimised.

Table P.1: Recommended Filtration Strategy

Parameter	Protective Environment (PE)	Airborne Infection Isolation (AII)
Primary objective	Protect susceptible patient	Contain infectious aerosols
Supply filtration	HEPA, H13/H14 (EN 1822)	Minimum MERV 14 (ASHRAE 52.2)
Terminal HEPA	Required/preferred at terminal supply*	Not normally required
Return/exhaust	Recirculation permitted	Direct outdoor exhaust preferred
All recirculation	—	Only where permitted and after HEPA filtration
HEPA integrity testing	Required after installation/replacement and as specified	Required where exhaust/return HEPA is provided
*Final location and configuration should comply with the applicable healthcare standard.		

AHU Filtration: AHUs serving isolation rooms should employ progressive staged filtration. A typical arrangement comprises a MERV 8 pre-filter followed by a MERV 13 or MERV 14 final AHU filter, depending on the room served and whether terminal HEPA filtration is provided. Progressive filtration improves air cleanliness, protects downstream components and extends the service life of the final filter.

HEPA Filter Integrity Testing: HEPA filters should be installed in housings that permit in-situ integrity testing and differential-pressure monitoring. Terminal HEPA filters should be integrity tested after installation or replacement and periodically thereafter, using an appropriate aerosol challenge method in accordance with the applicable test standard/protocol. A failed HEPA filter or defective seal should be rectified and successfully retested before the room is returned to service.

Filter Replacement and Disposal: Filter replacement should be based on the specified final pressure drop, monitored filter condition and manufacturer's recommendations, rather than on predetermined time intervals alone.

Filters serving **AII** exhaust or recirculation systems should be treated as potentially contaminated. Appropriate PPE and procedures that minimise disturbance of accumulated particulate matter should be used during removal. Removed filters should be immediately contained and disposed of in accordance with the hospital's biomedical-waste procedures and applicable regulations.

Where justified by infection-risk assessment, Bag-In/Bag-Out (BIBO) housings may be used for contaminated HEPA filters to provide additional protection to maintenance personnel and the surrounding environment.

Following replacement of a **PE**-room terminal HEPA filter, HEPA integrity, airflow and room pressurisation should be verified before the room is returned to clinical service.

Q. Instrumentation and Monitoring

Reliable monitoring is necessary to verify that isolation rooms maintain the required ventilation, pressure relationships and environmental conditions. Instrumentation should therefore be provided for the following critical parameters.

Airflow and Ventilation: Supply, return and/or exhaust airflow, as applicable, should be measured or monitored to verify the required air-change rate and room-pressure relationship.

Airflow may be determined using calibrated plug-fan inlet-cone measurement, Airflow Measuring Stations (AFMS), or other suitable methods. Instrumentation should be appropriately selected, installed and calibrated in accordance with the manufacturer's recommendations.

Room Differential Pressure: The differential pressure between the isolation room and adjoining spaces should be continuously monitored, with local indication and alarm on loss of the required pressure relationship.

Where an anteroom forms part of the pressure-control strategy, the patient room–anteroom and anteroom–corridor pressure relationships should be monitored. Other pressure relationships, such as with an attached toilet, should be monitored where required by the design.

Differential-pressure instruments should be appropriately ranged for the relatively low pressure differentials encountered in isolation rooms.

Temperature and Relative Humidity: Room temperature and relative humidity should be monitored to verify the required environmental and clinical conditions. Where a BMS is provided, these parameters may be continuously monitored and alarmed as appropriate.

Filter Differential Pressure: Differential pressure across filter banks, particularly final and HEPA filters, should be monitored to indicate increasing filter resistance and the need for maintenance or replacement.

The instrument range and alarm/set point should be selected with reference to the filter manufacturer's specified operating and final pressure drops. Monitoring may be local or through the BMS.

Calibration: Instruments monitoring critical isolation-room parameters should have valid calibration and be recalibrated at intervals consistent with the manufacturer's recommendations, hospital quality system and applicable regulatory requirements.

R. Commissioning and Maintenance

Commissioning: Commissioning of isolation-room HVAC systems should follow the ISHRAE HVAC Commissioning Guidebook, with particular attention to ventilation rates, room-pressure relationships, airflow direction, filtration, controls and alarms. Instruments used for commissioning should have valid calibration.

For **All** rooms, the exhaust system should be balanced to establish and maintain the specified negative pressure relative to adjoining areas. For **PE** rooms, supply, return and/or exhaust airflow should be balanced to maintain the specified positive-pressure relationship. Where automatic pressure control is provided, the control response during door opening should be suitably limited to avoid unnecessary fan or damper response to the temporary loss of pressure differential.

Fan interlocks and start-up/shutdown sequences should ensure that failure or operation of one fan does not reverse the required airflow direction. **All** exhaust should establish containment before normal supply operation; **PE** systems should similarly establish and maintain the required positive-pressure relationship. Pressure monitors, alarms, door-status inputs and associated controls should be functionally verified.

Isolation-room performance should be verified, as applicable, for:

- Supply, return and exhaust airflow and resultant ACH
- Room differential pressure and airflow direction
- Temperature and relative humidity
- HEPA-filter integrity, where HEPA filtration is provided
- Air velocity/distribution, where relevant
- Particle concentration and recovery, where applicable
- Functional operation of alarms, controls, door inputs and fan interlocks

Where applicable, HEPA-filter integrity, airflow, particle-concentration and recovery tests may follow ISO 14644-3:2019. Other tests should follow the applicable healthcare standard and approved commissioning/validation protocol.

Maintenance: HVAC systems serving isolation rooms should be maintained using preventive and, where practicable, predictive maintenance practices, with particular attention to components affecting airflow, filtration, pressure relationships and infection control.

The maintenance programme should be based on manufacturers' recommendations, operating conditions, hospital maintenance policy, infection-control requirements and condition monitoring. Particular attention should be given to:

AHU internal surfaces and fan blades: Inspect regularly and clean as required using hospital-approved methods. Monthly inspection/cleaning may be considered in critical applications.

Condensate drains and traps: Inspect regularly and clean as required to ensure free drainage and prevent water stagnation.

Ductwork: Inspect periodically for contamination. Internal cleaning, including robotic cleaning where appropriate, may be undertaken when inspection indicates the need. The frequency should be condition- and risk-based rather than solely time-based.

Filter Maintenance: Filter differential pressure should be monitored, and filters should be cleaned, where specifically designed to be cleanable, or replaced before reaching the manufacturer's specified final pressure drop.

Fine filters and HEPA filters not designed for cleaning or washing should be replaced rather than cleaned.

Filters in the exhaust stream of **All** systems should not be reused. Similarly, where **All** room air is recirculated through HEPA filtration, potentially contaminated filters should be replaced rather than cleaned and reused.

For **PE** recirculation systems, cleanable filters may be cleaned where specifically designed for this purpose. Replacement intervals should be based on filter type, pressure drop, operating conditions, manufacturer's recommendations and hospital maintenance policy, rather than time alone.

Handling and Disposal of Contaminated Filters: Filters removed from **All** exhaust or recirculation systems should be regarded as potentially contaminated. They should be removed with minimum disturbance, immediately contained and handled and disposed of in accordance with the hospital's biomedical-waste procedures and applicable regulations. Where Bag-In-Bag-Out (**BIBO**) housings are provided, the prescribed safe-change procedure should be followed.

Following replacement of a **PE**-room terminal HEPA filter, filter integrity, airflow and the required room-pressure relationship should be verified before the room is returned to clinical service.

Personnel Protection: Personnel maintaining isolation-room HVAC systems should use appropriate PPE and follow the hospital's infection-control procedures. Depending on the activity and exposure risk, this may include protective clothing, gloves, eye protection and appropriate respiratory protection, such as N95 or higher where indicated by the infection-risk assessment.

S. Competency of HVAC Service Personnel

Maintenance of isolation-room HVAC systems requires personnel who understand not only the equipment but also the infection-control implications of their work. Incorrect servicing can compromise room pressure, airflow direction, filtration and containment.

Service personnel should therefore be trained in the relevant pressure-control systems, HEPA filtration, alarms and controls, safe filter handling and appropriate PPE/infection-control precautions.

Healthcare facilities should establish minimum competency requirements for such personnel, with site-specific infection-control orientation by the Hospital Infection Control (HIC) team before they undertake work in isolation areas.

Conclusion

Effective isolation-room HVAC requires the integration of clinical needs, infection-control principles and sound engineering. **All** and **PE** rooms serve different purposes, and their ventilation, pressure relationships, filtration and air-distribution strategies must be designed accordingly.

Isolation performance depends not on any single parameter such as ACH or room pressure, but on the combined performance of ventilation, filtration, airflow direction, exhaust management, environmental control and system reliability. This performance must be demonstrated through commissioning and sustained through effective monitoring and maintenance.

Isolation-room HVAC should therefore be regarded as an integral component of the healthcare facility's infection-prevention strategy, requiring close coordination between clinicians, infection-control teams, HVAC professionals and facility managers.

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FGI, *Guidelines for Design and Construction of Hospitals*, Facilities Guidelines Institute (FGI). The applicable edition should be selected according to the project jurisdiction and year of construction.

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White Paper
Room Air Distribution Strategies
for Infection Control in
Hospital General Wards

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Executive Summary

General wards are places where patients, healthcare workers and visitors are present. Due to airborne transmission of infectious aerosols, Healthcare-Associated Infections (HAIs) remain a significant risk in such environments unless appropriate infection-control measures are implemented. A general ward is a shared inpatient area that serves non-critical patients.

General wards can have 2/4/6 and maybe up to 8-10 beds or more in a room with shared bathroom and notably shared air conditioning.

Proper ventilation with control on the path of infectious aerosols and particulate contaminants along with various air-cleaning technologies is essential to prevent nosocomial infection. This is to be done without compromising on thermal comfort of patients and healthcare workers.

This white paper discusses the various ventilation strategies that can be used to achieve the above mentioned goals, viz. (i) Traditional mixing air systems or the strategy of dilution of pathogens by using high volume of clean air, (ii) Stratum Ventilation, (iii) Personalized Ventilation. It will also discuss filtration and air cleaning strategies like UVGI and in room air cleaners

Room Air Distribution Strategies for Infection Control in Hospital General Wards

1. Introduction

Hospital General Wards see a flow of diverse patients, health care workers and visitor population, often with varying levels of susceptibility to infection. In such shared environments, despite strict universal precautions – such as rigorous hygiene measures and personal protective equipment (PPE) – a high risk of nosocomial (hospital-acquired) infections remains due to airborne transmission of pathogens and remains a critical challenge to patient safety and healthcare quality. These challenges are compounded in general wards, which often accommodate patients at various stages of illness and allow bystanders, visitors to introduce external pathogens during designated hours. Furthermore, general wards are commonly cooled and ventilated as a single, collective space using mixing ventilation systems. While these systems are economical and easy to operate, they can inadvertently contribute to the transmission of infectious bioaerosols.

Thus, room air distribution plays a pivotal role in mitigating this risk by influencing the movement and dilution within the general ward. Unlike specialized Isolation and operating rooms, general wards are typically not designed with strict containment systems, making effective ventilation and airflow design all the more important.

This white paper examines the principles and practical considerations of room air distribution strategies aimed at infection control in hospital general wards. It highlights how airflow patterns, supply and return configurations, ventilation rates, interact to influence airborne contaminant transport. Drawing upon established standards and emerging research, the paper seeks to bridge the gap between engineering design and clinical outcomes.

By focusing on scalable and evidence-based solutions, this white paper aims to support healthcare planners, engineers, and facility managers in creating safer indoor environments – ultimately contributing to reduced transmission risks and improved patient and staff well-being.

2. Ward layout and bed positioning

Before getting into the strategies for air distribution, it is important to have a look at the bed positioning configurations in general wards.

The bed layout in a general ward plays an important role in air distribution. As per the Indian Health Facility Guidelines 2014¹, each inpatient unit may contain maximum of 32 patients with beds arranged on either side of a common corridor in what is termed as the Nightingale pattern with a central nursing station. However these configurations may be more common in public hospitals but as per IPHS² (Revised 2022) and TAHPI Draft 1.2³ (2014) it is recommended that maximum beds per room should be 8, in possibly Riggs pattern. The strategies discussed apply to all these configurations.

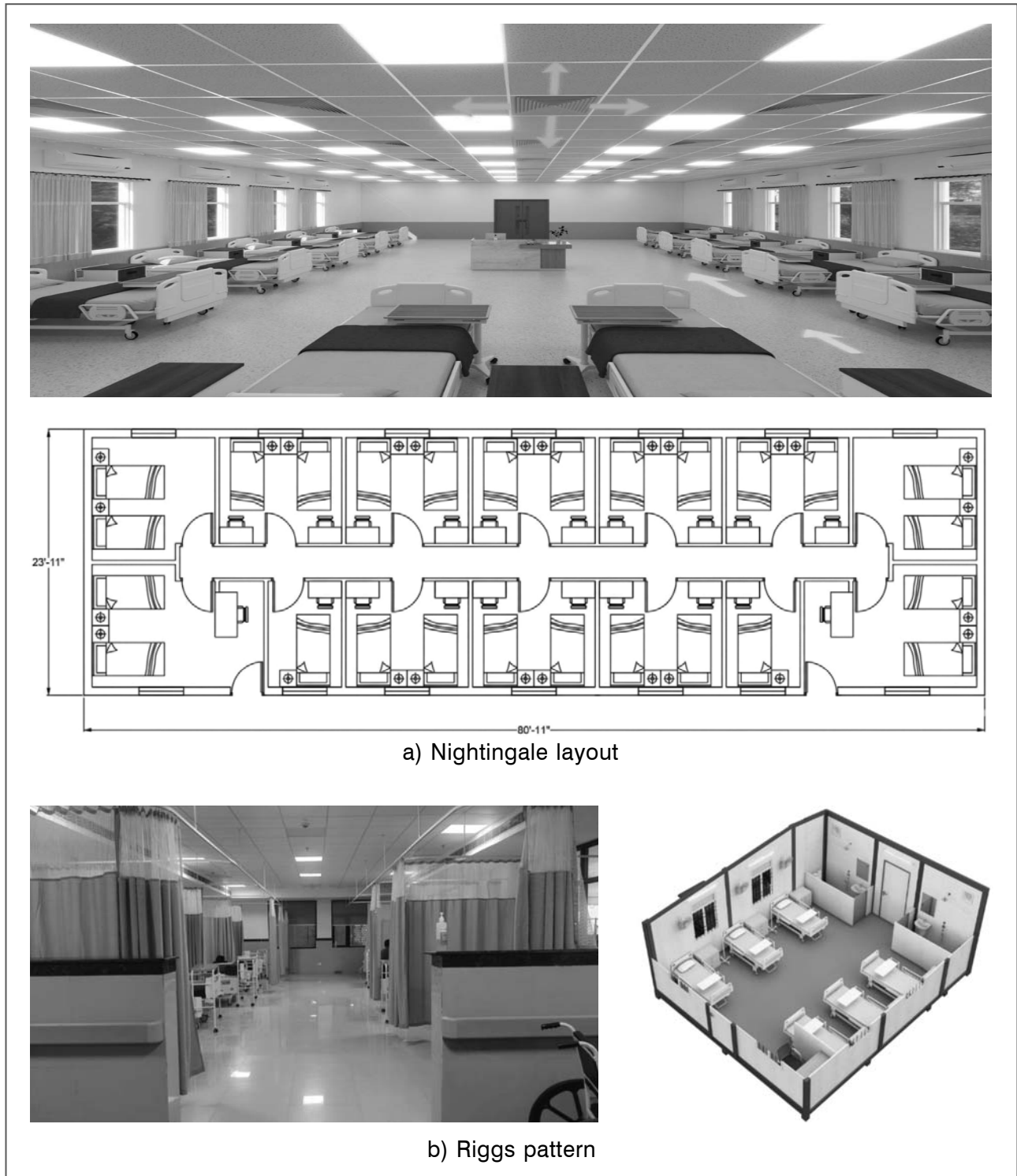


Figure 2.1: Ward layouts in a General Wards

3. Mixing Air Systems

In general hospital wards, mixing air systems are the most common method of ventilation. The fundamental principle of this system is to dilute the concentration of airborne contaminants by supplying filtered, conditioned air through appropriately selected air inlets that provide sufficient throw and induction to entrain and mix with room air.

It dilutes airborne contaminant concentration and facilitates their removal through return air outlets.

3.1 The Principle of Distribution & Dilution

Mixing air ventilation would generally rely on an overhead air distribution system which would have supply air ducts running over-head (above false ceiling) utilizing four-way, three-way or two-way supply air diffusers (Shown in Fig 3.1) installed on the false ceiling. These diffusers are designed to create a high-induction air flow, meaning they entrain the room air to mix with the incoming filtered, conditioned air.

3.2 Air Distribution

Depending on the space geometry, the overhead air distribution may be replaced by a supply air duct installed high along the side walls, concealed by a bulk head created to conceal the ductwork and also serve as a passage for the exhaust air duct. In such designs, the clean, conditioned primary air is admitted to the space by suitable side wall grilles. It is advisable that these grilles are of the adjustable type, equipped with individually adjustable horizontal and vertical vanes which will help to control the spread and direction of the air flow to ensure good mixing.

Surfaces of all air distribution outlets and Inlets should be suitable for cleaning. All supply air outlets will generally be in accordance with Table 6-2 of ASHRAE Std 170⁴. For general wards, it recommends the use of Group A outlet types (outlets mounted in or near the ceiling) that discharge air horizontally or discharging air horizontally that are not affected by adjacent surfaces.

3.3 Contaminant Dilution

By increasing the effective clean-air change rate (ACH, Air Changes per Hour), the concentration of droplet nuclei and aerosols is reduced. According to ASHRAE Standard 170 (Table 7-1), general patient rooms typically require a minimum of 2 Outdoor ACH and a minimum of 6 total ACH. The goal is to create a uniform environment where temperature, humidity, and pollutant levels are consistent throughout the space, preventing “dead zones” where stagnant air could allow pathogens to accumulate.

Use of Recirculating Room Units (with heating and or cooling coils) to maintain air changes are not recommended because of cleaning and maintenance issues which may have potential for build up of contaminants.

3.4 Air Filtration and Pathogen Removal

In a mixing system, the quality of the “diluting” air (conditioned, primary air) is paramount. ASHRAE Standard 170 (Table 6.1) recommends a two stage filtration system. The first stage (Pre-Filter Stage), Minimum MERV 7 followed by a second stage final filter of minimum MERV 14. The MERV 7 pre-filter captures larger particles such as dust, lint, and debris, protecting downstream equipment and extending the life of the final filter. The MERV 14 final filter provides higher-efficiency filtration, removing a significant portion of smaller airborne particles, including those that may carry infectious agents (e.g., droplet nuclei, bacteria). Using MERV 14 as the final filter significantly enhances the removal of fine particulate matter that supports airborne infection. This is the basic control strategy in shared patient environments where strict isolation is not implemented.

Higher Filtration Levels (Like HEPA Filters) are not typically required in general wards. Proper installation, sealing and regular maintenance / replacement of filters are essential to achieve intended performance levels.

The newer ASHRAE Standard 241⁵ emphasizes “Equivalent Clean Airflow,” which considers the combined effect of outdoor air, filtered re-circulated air and additional technologies like UV-C or Upper-Room Ultraviolet Germicidal Irradiation (UVGI) systems to neutralize pathogens that standard mixing air systems may not catch.

3.5 Airflow Patterns and Outlet / Inlet Placements^{6,7}

The placement of supply air outlets and return air inlets is a critical design factor towards reducing the potential for airflow to transport infectious aerosols from an infected patient towards healthcare workers, other patients or visitors

While mixing systems are effective for general wards, in reality, perfect mixing is rarely achieved. Obstructions like privacy curtains, medical equipment, and monitors can create “short-circuiting,” where supply air goes straight to the exhaust without diluting the air around the patient or can form stagnant air pockets where contaminants can accumulate.

Even in a general ward, maintaining a slightly positive pressure relative to the corridor is important to prevent the ingress of air from the adjacent corridor

In a general ward with eight to ten beds, the primary objective of the HVAC layout is to achieve uniform dilution while establishing a “clean-to-dirty” airflow path that protects both the health care workers and the patients.

For mixing air systems in hospital general wards, the goal of supply air outlets is to promote uniform air mixing, avoid stagnation zones, and dilute contaminants effectively

3.6 Common Types of Supply Air Outlets for Mixing Systems

3.6.1 Ceiling Diffusers (Most Common)

These are designed to discharge air horizontally along the ceiling (Coanda effect), allowing it to mix with room air before gently descending into the occupied zone.

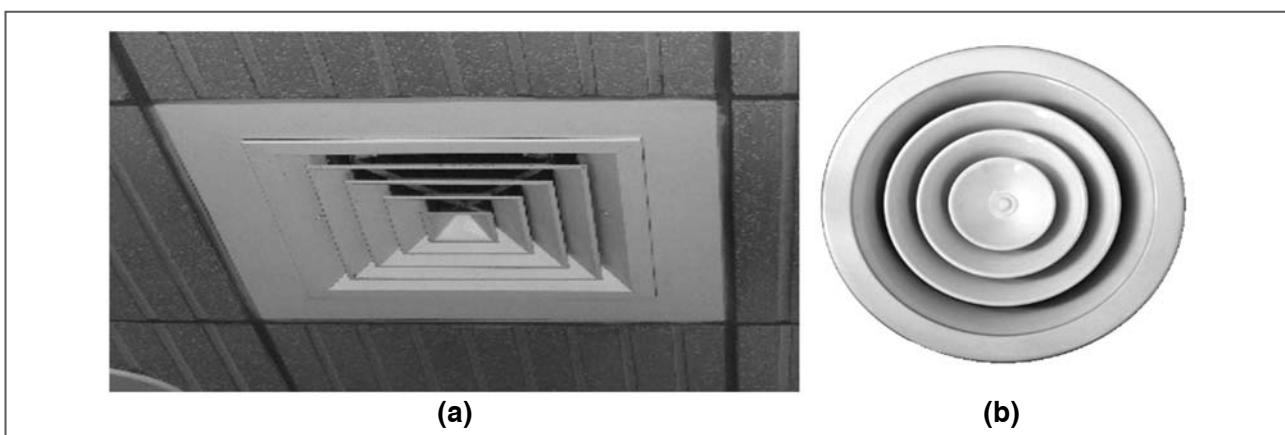


Figure 3.1: (a) Four-Way, Three-Way or Two-Way Supply Air Diffusers (b) Circular Diffuser

3.6.2 High Induction Radial / Perforated Ceiling Diffusers

Perforated diffusers MUST be equipped with pattern deflectors behind the perforated distribution plate to deliver air across a broad area. It helps to reduce drafts while maintaining uniform mixing.



Figure 3.2: High Induction Radial / Perforated Ceiling Diffusers

A radial diffuser is designed to discharge air in a 180 / 360-degree pattern, typically flush with the ceiling. In healthcare environments, they are valued for their ability to provide high entrainment - mixing the supply air rapidly with room air – while maintaining a horizontal air throw that prevents cold air from “dumping” directly onto a patient.

In a general ward, these would be placed in the central ceiling area to distribute air outward toward the patient beds. The design helps maintain the uniform dilution necessary for effective infection control.

3.6.3 Swirl Diffusers

These diffusers create a swirling air pattern to enhance entrainment and mixing. They are effective in rapidly diluting contaminants. Often used in spaces requiring improved air distribution performance



Figure 3.3: Swirl Diffuser



Figure 3.4: Plaque Diffuser

3.6.4 Slot Diffusers (Linear Diffusers)

These are installed in ceilings or high sidewalls and provide controlled directional airflow with good entrainment. They are suitable for perimeter zones or along corridors of ward layouts.

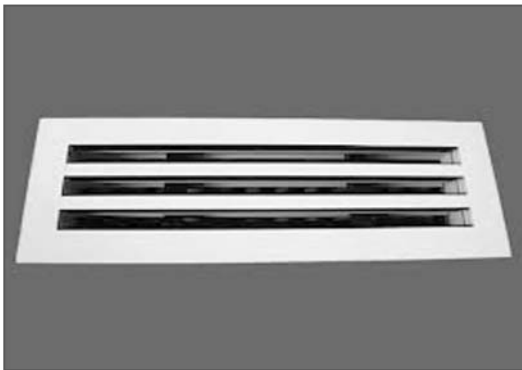


Figure 3.5: Slot Diffuser

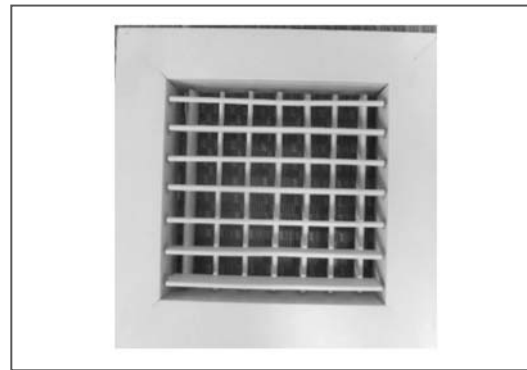


Figure 3.6: Sidewall register

3.6.5 High Sidewall Grilles/Registers

As shown in *Figure 3.6*, these are mounted near ceiling level on side walls. It discharges air horizontally across the room to promote mixing. It is useful where ceiling installation is constrained. Always BEST to use grilles with adjustable vanes to provide better control on spread and velocity.

3.7 Key Design Considerations for Mixing Systems

- Supply air should be delivered at sufficient velocity to ensure mixing without causing drafts in the occupied zone.

- Direct airflow from one patient to another is to be avoided by implementing proper directional air flow.
- Supply air diffuser placements must be co-ordinated with location of return air diffusers.
- Proper air movement to maintain thermal comfort. ASHRAE recommends 21 to 24 °C with RH of 40 to 60%, however temperatures more suitable to the Indian environment with adaptive comfort considerations may be chosen. It is important to check the dew point temperature for the conditions chosen to avoid condensation
- In hospital general wards, ceiling-mounted diffusers (especially square, plaque or swirl types, (*Figure 3.1, 3.3 & 3.4*) are most commonly recommended for mixing systems because they promote good mixing, are easy to integrate with standard HVAC designs and provide balanced comfort and infection risk reduction because it provides a clear pathway for air.

These outlet types align with the general design philosophy in non-isolation spaces where dilution (mixing) is the primary infection control strategy.

- To achieve the required mixing without creating uncomfortable drafts or stagnant zones, a distributed grid is superior to a centralized supply.
- Supply diffusers should be located in the ceiling above the central circulation zone (the aisle between the foot-ends of the beds). This ensures that the cleanest, filtered air is introduced where healthcare workers spend most of their time moving between patients.
- Diffusers should be spaced to provide overlapping “throw” patterns. This prevents “dead spots” between beds where airborne pathogens could accumulate.
- The placement of return air inlets is the most critical factor for controlling the direction of contaminant transport. For optimal infection control, return air (or exhaust) Inlets should be located low on the side walls
- The return air inlets, which could be simple linear fixed bar grille sized suitably for the air loading, should be positioned on the wall behind the patient’s head (the headwall), typically the top of the return air inlet should not be more than 1m from the finished floor level
- Locating supply-air outlets towards the central zone and return air inlets near the patient zones encourages airflow from the central circulation area towards the bed areas and facilitates removal of airborne contaminants closer to their source. The effectiveness of this arrangement depends on diffuser characteristics, return air locations, patient thermal plumes, privacy curtains and other room airflow disturbances, and should therefore be evaluated for the specific ward configuration
- Ideally, there should be one return air grille for every one to two beds to ensure that the airflow remains localized to each patient station.
- The resulting airflow follows a “centre-to-perimeter” and “high-to-low” trajectory:
 1. Clean air enters via the ceiling diffusers in the central aisle.
 2. The air moves outward toward the bed areas, diluting any airborne contaminants.
 3. The air is pulled downward and backward toward the headwall.
 4. Contaminated air is removed through the low-level return grilles, preventing it from recirculation back into the breathing zone of other occupants.
- Ceiling returns need to be avoided . while easier to install, placing return air inlets in the ceiling (especially near supply outlets) can cause “short-circuiting,” where the clean air is sucked out before it ever reaches the patient’s breathing zone.
- Privacy curtains should either made of mesh at the top or are accounted for in the airflow modelling, as they can act as physical barriers that disrupt the mixing and return paths. Typically, the privacy curtains should be drawn only at the time of examination or when local procedures are being conducted. They should remain retracted at other times.



Figure 3.7: Return Air (or Exhaust) Inlets located low on the Side Walls

4. Stratum Ventilation⁸

This is an emerging air distribution strategy that can be used in general hospital wards, though it is currently more common in research and high-efficiency office designs. While traditional mixing systems aim to dilute the entire room, stratum ventilation works by introducing clean, conditioned supply air horizontally into the occupied/breathing zone at an appropriate height determined by the occupant and patient configuration

4.1 Potential Benefits in General Wards

Studies suggest several advantages for using stratum ventilation in healthcare settings:

Reduced infection risk - Studies on specific two-bed ward configurations have reported faster dilution of cough-generated contaminants and reduced high-concentration exposure zones compared with mixing and displacement ventilation.

Rapid Dilution - Research on two-bed hospital wards shows that coughed contaminants are diluted faster under Stratum Ventilation as compared to mixing systems, significantly reducing high-concentration spots.

Energy Efficiency - Because the system focuses on cooling and ventilating only the occupied zone where people are located, it can save energy compared to a mixing ventilation system.

Lower Exposure for Staff - By establishing a clear horizontal flow, it can minimize the exposure risk for healthcare workers attending to the patients by their bedside.

4.2 Implementation Challenges

Despite its benefits, there are several practical hurdles to using it in a general ward:

Thermal Comfort (Drafts) - Because the air is supplied directly at head level with sufficient velocity to reach occupants, it can lead to drafts near the patient's head. The supply air outlet velocity will need to be controlled to avoid uncomfortable drafts.

Temperature Gradients - It may create a large temperature difference between the head and feet, which might not be ideal for patients who are sedentary and supine in bed for long periods.

Layout Constraints - Supply air outlets must be located along the side walls just behind the patient's head (or slightly above). In a crowded 8–10 bed ward, medical equipment, monitors, and privacy curtains can easily obstruct the horizontal air path towards return air inlet.

While ASHRAE Standard 170 provides the baseline for healthcare ventilation, traditional overhead mixing systems remain the standard room air distribution method. If using Stratum Ventilation, it would be prudent to undertake a detailed Computational Fluid Dynamics (CFD) analysis and modelling during the design phase to prove it will work in a specific room layout.

4.3 Handling of Moisture Loads

A word of caution here, before implementing Stratum Ventilation, managing moisture (latent) loads requires specific advisory and design considerations.

Because Stratum Ventilation operates at an elevated supply air temperature the system's inherent Sensible Heat Ratio (SHR) is high. This reduces the primary cooling coil's natural dehumidification capability.

One would need to address the requirements for handling moisture:

1. Primary Load Decoupling & DOAS Integration

Decouple latent and sensible loads: A Dedicated Outdoor Air System (DOAS) with deep-cooling / dehumidification or a desiccant wheel must handle 100% of the ventilation latent load.

Outdoor air introduced into the room must be sub-cooled below its dew point before being re-heated or blended to the Stratum Ventilation supply temperature viz. 19-21°C. One cannot rely on re-circulated Stratum Ventilation air terminal units alone for moisture removal.

The indoor relative humidity has to be maintained between 30% and 60% RH (preferably 40% to 50%) at all load conditions. RH greater than 60% increases survival rates of some viral pathogens, promotes bacterial and viral proliferation on surfaces and creates mold growth risks. RH less than 30% desiccates patient mucous membranes compromising natural immune defences and also increases airborne suspension time of pathogen droplets.

2. High internal latent load accounting

Patient wards carry unique, variable latent heat sources that must be explicitly estimated:

Eg. Patient respiration / perspiration along with that from visiting family members, bystanders and healthcare staff.

Moisture loads are added from bed-baths, frequent floor washing / disinfection

3. Jet trajectory & condensation prevention

In stratum ventilation, conditioned air is supplied horizontally at or near the occupants' breathing zone. The supply-air temperature and velocity must be carefully selected to ensure that the air jet reaches the intended occupied zone. If the supply air is too cold relative to the room air, it becomes more negatively buoyant and may drop prematurely towards the bed instead of travelling horizontally through the breathing zone. High indoor humidity can further complicate the design by requiring sufficiently dry supply air to maintain the desired room humidity.

Since stratum ventilation outlets are located on side walls close to the occupied zone, condensation is another important consideration. If the surface temperature of the outlet falls below the room-air dew-point temperature, moisture will condense on the outlet. This can result in sweating or dripping and create an undesirable hygiene and microbial-growth risk in a healthcare environment.

4. Part-Load & Seasonal Control

Variable occupancy & off-peak monitoring: During night hours or milder seasons (when sensible cooling loads drop sharply but outdoor / ambient humidity remains high), the Stratum Ventilation terminal cooling coils may throttle down.

Humidity-override control logic needs to be implemented. When ward relative humidity exceeds 55%, the DOAS coil must override the temperature setpoint to prioritize dehumidification, utilizing secondary reheat loops to prevent overcooling the patient.

Table 4.1: Comparison - Stratum vs. Mixing Ventilation

Feature	Mixing Ventilation	Stratum Ventilation
Air Delivery	Overhead or high side wall	Side wall in the occupied zone
Mechanism	Dilution in entire room	Dilution in occupied zone
Primary Risk	Short cycling to return	Uncomfortable drafts, HCW will get exposed to the air off the patient
Energy Use	High (Treats whole volume)	Lower since elevated supply air temperature is used 19-21 °C as compared to 12-14 °C in conventional mixing systems

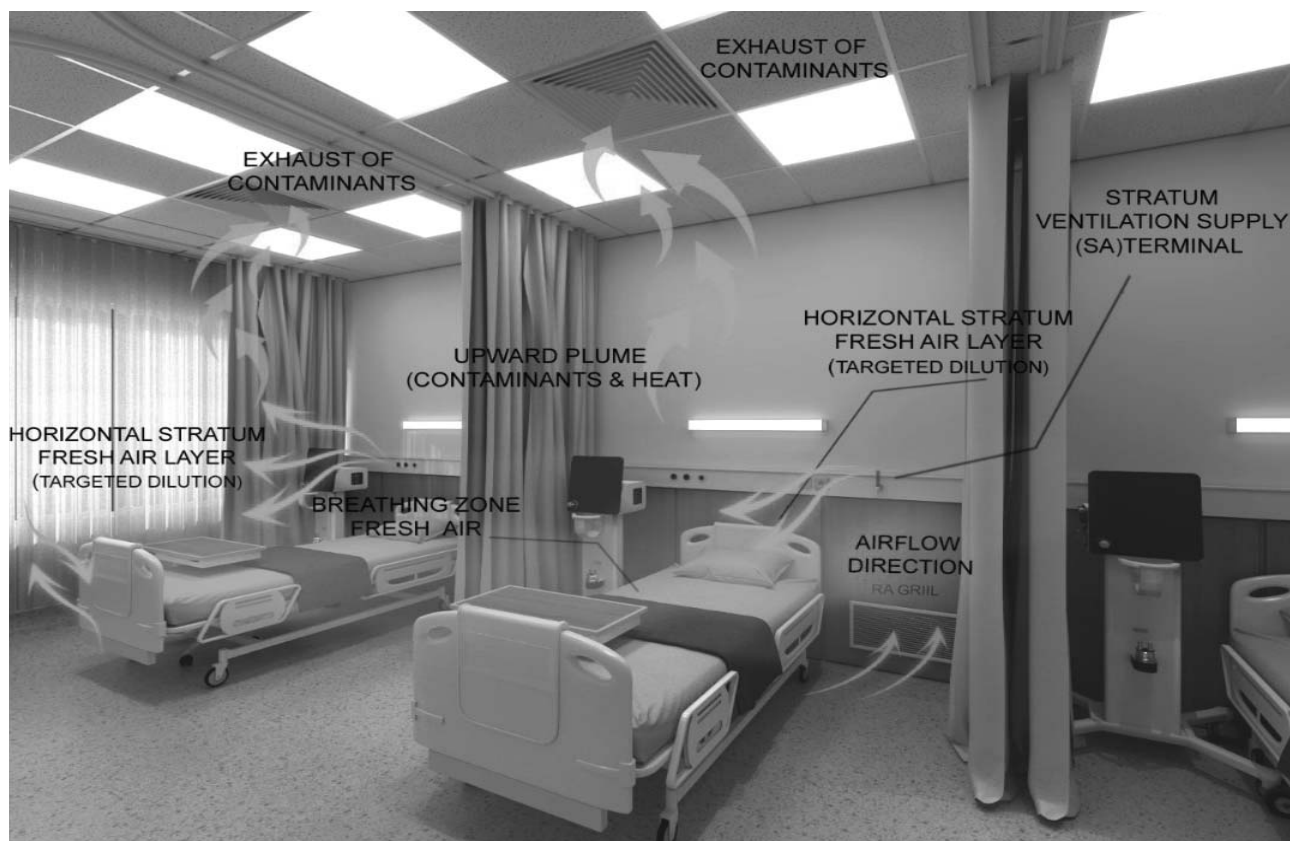


Figure 4.1: Stratum ventilation system

5. Personalized Ventilation⁹

Personalized Ventilation systems act as a micro-environment control strategy, providing high-quality, filtered and conditioned air directly to the individual patient's breathing zone. While the primary HVAC system (like a mixing system) handles the general ward's thermal load and basic air changes, The personalized ventilation system creates a localized filtered-air microenvironment around the patient's breathing zone

A Personalized Ventilation system typically uses a localized air terminal device located near the patient's head or at times could be through a pillow. The clean air jet creates a localized clean zone

in the patient's breathing zone, pushing away the ambient ward air which may contain pathogens, CO₂ and other contaminants from other sources or occupants. In some configurations, the air flow rate or temperature can be adjusted to meet the specific comfort needs of a febrile or sensitive patient.

5.1 Potential Benefits in General Wards

Inhalation protection - It significantly reduces the intake fraction – the proportion of room air inhaled by the patient (re-breathed air) lowering the risk of cross-infection from neighbouring beds or staff.

Exhalation Entrainment - When designed correctly, the Personalized Ventilation jet can also help capture the patient's own exhaled breath and direct it toward the return air inlets more efficiently thus protecting healthcare workers and other patients.

Supplementary Resilience -It allows for high-level protection even if the main HVAC System is operating at lower Air Change Rates for energy-saving purposes.

5.2 Implementation Challenges

Integrating Personalized Ventilation Systems into an 8–10 bed Ward will require specific hardware adjustments.

Terminal Types - Common designs include movable arms (similar to a dental lamp), headboard-mounted slats, or pillow-integrated nozzles.

Table 5.1: Comparison - PV vs. Mixing Ventilation

Feature	Mixing Ventilation	Personalized Ventilation
Focus	Entire room volume	Individual breathing zone
Air Quality	Uniform dilution	Highest at the breathing zone
Energy Use	High (Treats whole volume)	Lower (Treats only breathing zone)
Protection	General	Specific / maximum for Patient

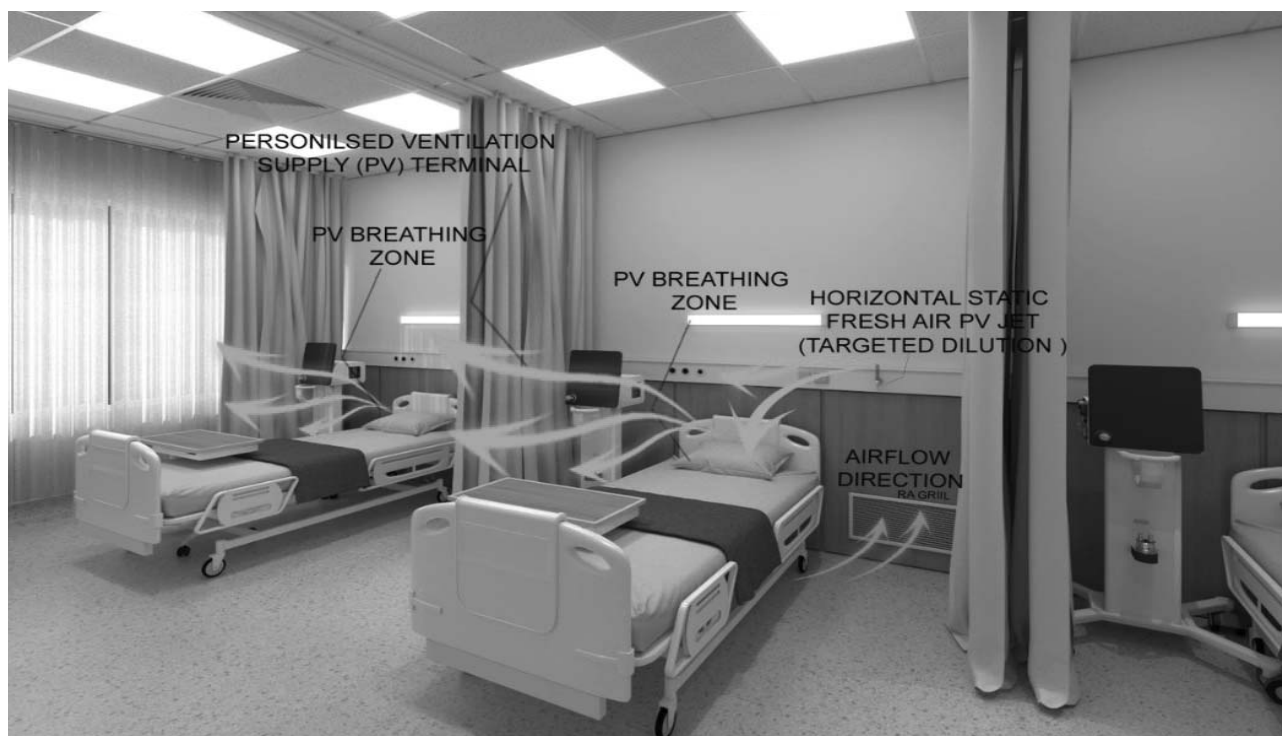


Figure 5.1: Personalised ventilation Systems

Air Source - The system must be fed by a dedicated clean air duct or by a local unit that draws clean and conditioned room air and re-circulates it locally.

Interaction with main air distribution - In a mixing system for example, the overhead diffusers must not have an outlet velocity so strong that they disrupt the delicate personalized ventilation air jet before it reaches the patient.

Patient Mobility - Fixed personalized ventilation terminals can be restrictive for patients who move frequently or need to be transferred out of bed.

Maintenance - The additional localized air terminals increases the maintenance load, particularly for filter replacements and cleaning of the flexible ducting etc.

Noise - The localized air terminals near the patient's head must be extremely quiet (typically <35 dB) to avoid disrupting sleep and recovery.

6. Other Additional Strategies

Applying Ultraviolet Germicidal Irradiation (UVGI), also known as Upper Room Ultraviolet Germicidal Irradiation in a general ward is a highly effective strategy for neutralizing airborne pathogens that mixing air ventilation might not immediately capture.

When integrating UVGI into a healthcare environment, there are three primary application methods

6.1 Upper-Room UVGI

This is the most common and effective method for general wards. UV-C fixtures are mounted on walls or ceilings much above the occupied zone. The fixtures create a disinfection zone in the upper portion of the room. As the mixing air system naturally moves air upward due to thermal plumes from patients and equipment, the pathogens are inactivated by the UV-C light. The light is shielded and directed horizontally upward as shown in *Figure 6* and preferably above the false ceiling in return air path to ensure that occupants in the lower occupied zone are not exposed to direct UV radiation

Good mixing air system helps to ensure proper disinfection. Safety is a concern because lamps are in the occupied space. Care must be taken to ensure that suitable tests are carried out for occupied zone exposure. These systems are approved by the US CDC and National Institute for

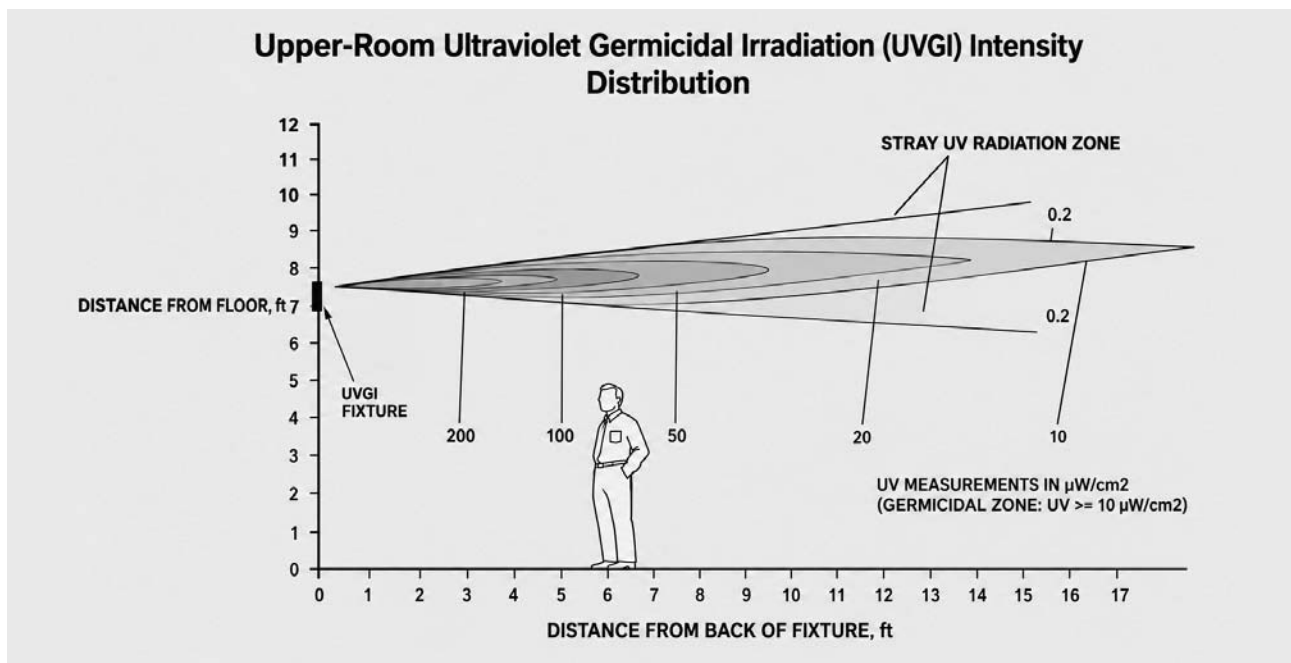


Figure 6.1: Zone of UV exposure Ref, 2019 ASHRAE Handbook, HVAC Applications Ch 62

Occupational Safety and Health for Control of TB. For more information, please consult CDC and NIOSH Guidelines.

6.2 In-Duct UVGI Systems

This application focuses on disinfecting the air within the HVAC system itself before it is admitted into the occupied space. The UV-C lamps are installed within the Air Handling Unit (AHU) or inside the supply air ductwork. While filters like MERV 14 physically trap particles, UVGI inactivates viruses and bacteria that might be small enough to pass through or that accumulate on filter and coil surfaces. This method helps meet ASHRAE Standard 241 requirements for Equivalent Clean Airflow by providing a non-mechanical means of air cleaning.

6.3 In-Room Recirculation Units

For General Wards where it is not possible to install the UV-C Lamps in the AHU or where it is not possible to mount them within the supply air ducts, stand-alone units can be used. These are mobile or fixed floor units that draw room air through a HEPA Filter and a chamber equipped with UV-C Lights, before exhausting it back into the ward. These are particularly useful as supplementary technology during infectious disease outbreaks to boost the local air cleaning capacity.

Table 6.1: Design Considerations for General Wards

Feature	Best Practice for UVGI
Wavelength	254 nm (Standard) or 222 nm (Far-UVC, which is safer for direct exposure).
Maintenance	Regular cleaning of lamps and monitoring of UV output intensity is required.
Humidity Impact	UVGI is most effective when Relative Humidity (RH) is maintained between 40% and 60%.
Integration	Must be used as a supplement to, not a replacement for, high air change rates (ACH) and proper filtration.

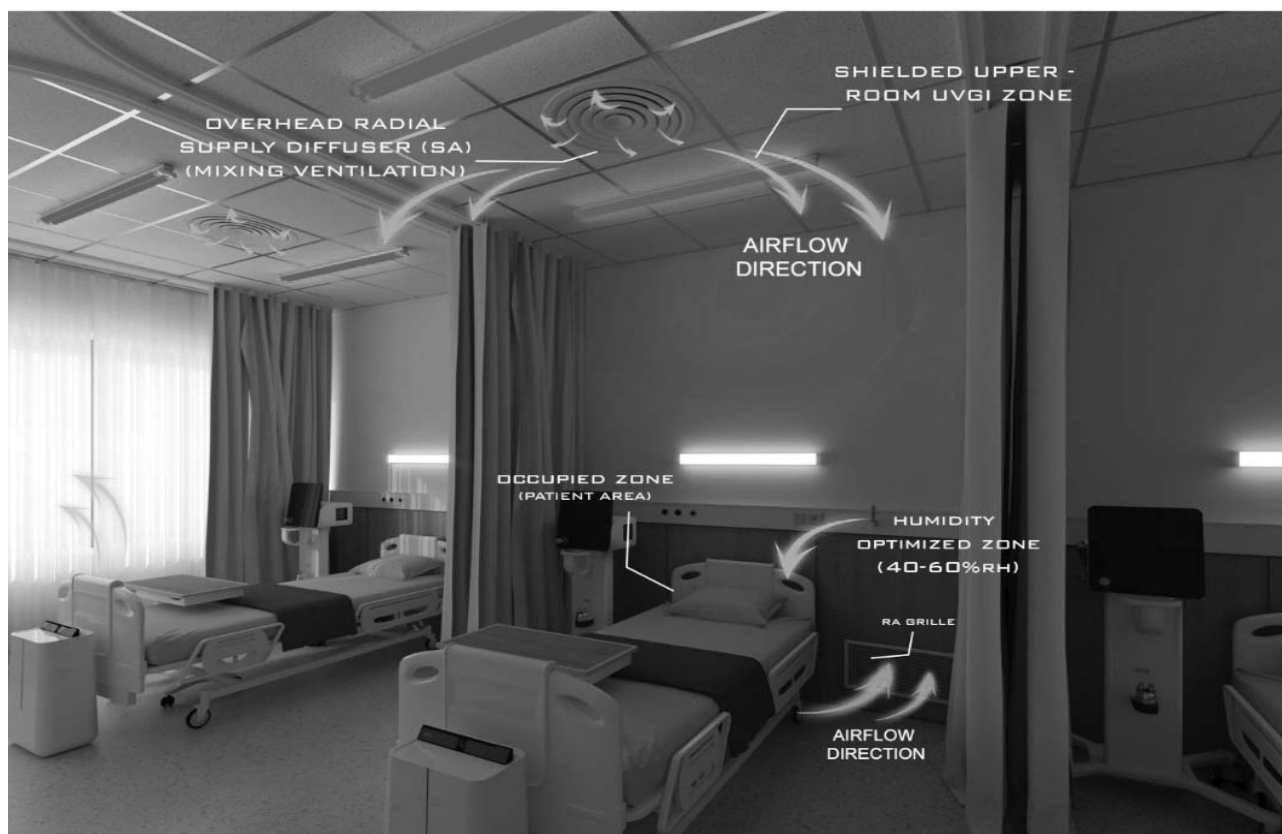


Figure 6.2: Upper Room UVGI

Incorporating In-Room air cleaners or purifiers are a highly effective way to supplement the main HVAC system, especially in high-occupancy areas like an 8–10 bed general ward. These units are often referred to as HEPA-Filtered Recirculating Units or Portable Air Cleaners (PACs).

In-room purifiers help facilities meet ASHRAE Standard 241 by providing “Equivalent Clean Airflow.” If the central system only provides 4 Air Changes per Hour, adding a purifier with a high Clean Air Delivery Rate (CADR) can effectively boost the ward to the recommended 6 Air Changes per Hour without the need for expensive ductwork upgrades.

Unlike a Central System, purifiers can be moved to where they are needed most:

Near High-Risk Patients - Placing a Unit between two Beds can help in arresting by interception of the aerosols from one patient before they reach the next.

Near the Entry - Placing a unit near the ward entrance can help create a Clean Air Curtain to protect air ingress from the corridor.

Modern Medical-Grade Air Purifiers often combine several technologies:

HEPA Filters - Capture 99.95% of particles down to 0.3 microns, including bacteria and most viral-carrying droplets.

Activated Carbon - Helps remove odours and Volatile Organic Compounds (VOCs) which are common in hospital environments.

Integrated UVC - Some units include internal UVC lamps to kill pathogens trapped on the filter surfaces, preventing bio-nesting or live viruses from remaining in the unit.

Care needs to be taken with respect to the following to ensure that the strategy is successful:

Acoustics - In a general ward, units must be quiet enough to allow patients to sleep. The unit selected has to maintain a high Clean Air Delivery Rate whilst maintaining a noise level between 40 – 45 dB.

Airflow Path - It is vital that while locating the purifier, the purifier’s discharge does not blow across a patient’s face, which could inadvertently transport pathogens. The exhaust should ideally point toward the ceiling to assist the mixing flow.



Figure 6.3: Integrated Infection Control Mixing Ventilation with Upper room UVGI and In room HEPA purifier

Maintenance - Filters must be replaced in strict accordance with the manufacturer's recommendation. Using units with pressure sensors that raise a clogged filter alarm is recommended for healthcare compliance.

6.4 Humidity and Temperature Control

Infection control is not just about moving air - it is about the viability of the pathogen itself.

Relative Humidity (RH): Maintaining RH between 40% and 60% is considered the optimum zone. If the air is too dry, respiratory droplets evaporate quickly into smaller droplet nuclei which stay airborne for longer periods. If the air is too humid, mold and fungal growth become a risk.

Temperature: Consistent cooling helps maintain the comfort of febrile patients (patients with fever) and ensures the HVAC system operates within the parameters required for effective filtration and dehumidification.

7. An Innovative Dedicated Exhaust System for removal of Airborne Bio-contaminants at source

The air distribution system in hospital wards is generally designed in accordance with ASHRAE Standard 170 and other applicable healthcare ventilation guidelines to achieve the required Air Changes per Hour (ACH), temperature, relative humidity (RH), filtration efficiency, airflow patterns, and dilution ventilation to support infection-control objectives and occupant comfort.

However, conventional ventilation systems are primarily intended to maintain acceptable indoor environmental conditions under normal operating circumstances. They are not specifically designed to address localized episodes of vomiting, regurgitation, spasms of coughing or other such events that may generate unpleasant odours, aerosolized biological contaminants, and infectious droplets in multi-bed patient care areas.

To address this limitation, healthcare facilities may consider incorporating a **Dedicated Exhaust System** in multi-bed general wards as a supplemental engineering control. The objective of this system is to rapidly remove contaminated air from the immediate vicinity of the affected patient, thereby minimizing odour nuisance, reducing the potential spread of aerosolized contaminants, and improving environmental hygiene within the occupied space.

7.1 Concept and Operation

Consider a general ward conditioned by a central Air Handling Unit (AHU). Under normal operation, conditioned air is supplied through ceiling supply diffusers, while return air is collected through return air grilles located near the head side of each patient bed and re-circulated through the AHU after appropriate filtration.

During an event such as patient vomiting, there is a risk that aerosolized particles and foul odours may be entrained into the return air stream and subsequently mixed with the room air before passing through the HVAC system. Although filtration can remove a significant proportion of particulate contaminants, immediate localized extraction of contaminated air provides a more effective means of limiting exposure to nearby patients, visitors, and healthcare workers.

To mitigate this risk, a dedicated exhaust system may be provided as an independent exhaust arrangement. The system typically consists of:

- A dedicated exhaust fan connected to a separate exhaust duct network.
- An exhaust grille installed adjacent to the head side of each patient bed.
- Individual branch ducts serving each bed, each fitted with a motorized control damper.
- A common exhaust header connected to the dedicated exhaust fan.
- A control panel located at the nurse station with appropriate interlocking logic.

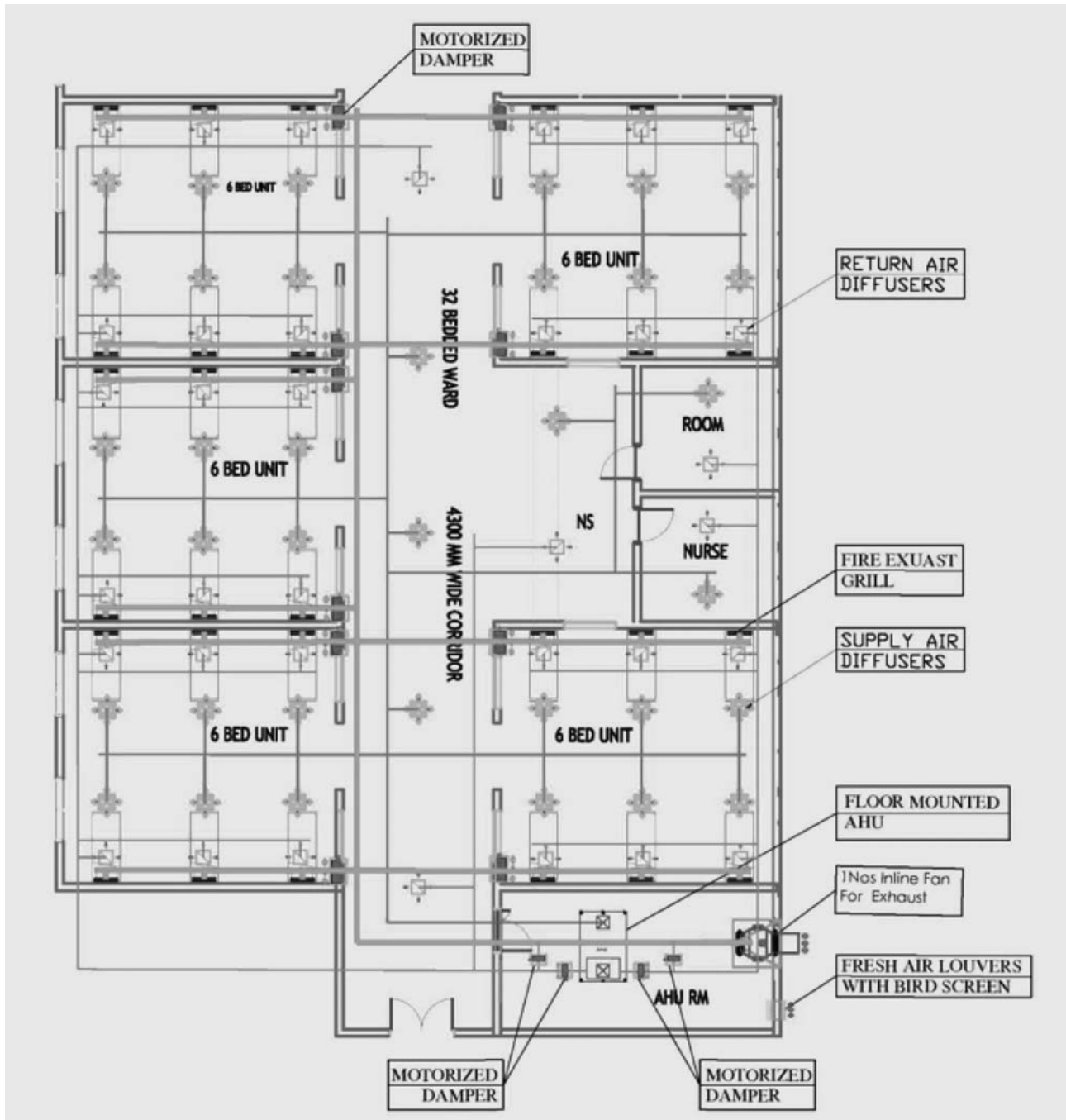


Fig 7.1 Layout of Dedicated Exhaust System

7.2 Mode of Operation

Under normal conditions, all motorized dampers remain closed and the vomit exhaust fan remains switched off.

Whenever a patient experiences vomiting or any other event requiring immediate localized extraction of contaminated air, the attending nurse activates the control corresponding to the affected bed from the nurse station. Upon activation:

- The motorized damper serving the selected bed opens.
- The dedicated vomit exhaust fan starts automatically.
- Contaminated air is extracted only from the exhaust grille associated with the selected bed.
- All remaining dampers remain closed, thereby preventing unnecessary extraction from other beds and ensuring that the full exhaust capacity is concentrated at the affected location.

- To further prevent recirculation of contaminated air through the central HVAC system, the preferred control strategy is to maintain the AHU supply in operation while temporarily isolating the return air path by closing the motorized return air damper.
- Simultaneously, the dedicated localized exhaust system shall extract contaminated air directly to the outside.
- Where the serving AHU is provided with modulating outdoor air dampers and suitable controls, the outdoor air intake shall increase as necessary to compensate for the temporary closure of the return air path and maintain the required supply airflow and near-neutral or slightly positive room pressurization.
- Once the vomiting/regurgitation/coughing event has been managed and the affected area has been cleaned and disinfected in accordance with the hospital infection prevention protocol, the dedicated exhaust fan shall stop, the exhaust isolation damper shall close, the return air damper shall reopen, the outdoor air damper shall revert to its normal operating position, and the AHU shall resume its normal operation

7.3 Advantages of the Dedicated Exhaust System

The proposed system offers several operational and infection-control benefits:

- Rapid removal of foul odours from the patient zone.
- Localized extraction of aerosolized biological contaminants generated during vomiting.
- Reduced potential for cross-contamination between adjacent patient beds.
- Prevention of contaminated air from entering the central return air system during nuisance events.
- Improved indoor air quality and patient comfort.
- Enhanced environmental hygiene for patients, healthcare workers, and visitors.
- Simple operation through centralized nurse station controls.
- Minimal energy consumption, as the system operates only when required.

7.4 Design Considerations

While a dedicated vomit exhaust system is not presently mandated by ASHRAE Standard 170 or other international healthcare ventilation standards, it represents an effective supplementary engineering control that complements conventional dilution ventilation strategies. The system should be carefully designed to ensure:

- Adequate localized capture velocity at the exhaust grille.
- Proper balancing of exhaust airflow.
- Appropriate pressure relationships within the ward.
- Safe discharge of exhaust air in accordance with applicable ventilation and environmental regulations. Local guidelines need to be checked beforehand
- Reliable interlocking with the central HVAC system and Building Management System (BMS), where provided.

As hospitals increasingly focus on infection prevention, patient safety, and enhanced indoor environmental quality, the incorporation of a dedicated exhaust system in multi-bed general wards offers a practical and innovative solution for managing episodic contamination events while supporting a cleaner and safer healthcare environment

8. Summary

Managing airborne transmission risks in hospital general wards requires a careful balance between engineering precision and clinical necessity. While specialized isolation rooms leverage strict containment, general wards depend heavily on scalable, evidence-based room air distribution strategies to maintain patient safety. Maximizing the efficiency and effectiveness of traditional mixing air systems through proper air change rates, a two-stage MERV 7 and MERV 14 Filtration

layout, and Strategic “High Level-Supply, Low Level-Return” configurations ensures effective contaminant dilution and pathogen removal. In addition, integrating advanced auxiliary methods – such as Stratum or Personalized Ventilation, UVGI Disinfection Systems, localized medical-grade air purifiers – provides critical layers of supplementary resilience without requiring cost-prohibitive ductwork overhauls. A dedicated system for removing airborne contaminants at source to be used only when such events happen is an added measure to reduce nosocomial infections. Ultimately, maintaining strict adherence to regulatory guidelines, alongside consistent system maintenance and precise humidity control, enables healthcare planners and facility managers to cultivate a safer indoor ecosystem that safeguards both vulnerable patients and frontline healthcare workers.

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White Paper
**Indoor Air Quality Monitoring and
Smart Control in Hospitals**

Chair: Nitin Naik, Managing Partner, Dew Point
Sameer Srivastava, Partner, Ambience Solutions
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Indian Society of Heating, Refrigerating and Air Conditioning Engineers

Executive Summary

Hospital air protects patients from infection, supports their recovery and affects the health and performance of the staff who work in it. The COVID-19 pandemic brought wide recognition of airborne transmission, and with it the case for managing hospital air on measured data instead of design-stage assumptions checked only at long intervals. In most Indian hospitals that data does not exist: apart from the differential-pressure meter NABH requires in operating theatres [7], continuous IAQ monitoring is not a norm.

This white paper shows how continuous IAQ monitoring and smart control can work together in Indian hospitals, where general wards, operating theatres and isolation rooms each have very different requirements. The core parameters are temperature, relative humidity, dew point, particulate matter, CO₂ and VOCs, with oxygen and waste anaesthetic gases added in specific areas. CO₂ is treated throughout as an indicator of ventilation, not as a contaminant [13]. The paper relates each parameter to ASHRAE, WHO, NABH and NBCS 2026 requirements [1], [3]–[7], [10], and gives practical guidance on control, sensors, calibration and sensor placement.

Two messages run through the paper. First, dew point, the parameter that best predicts condensation and mould in India's humid climate, needs no dedicated sensor: it can be calculated continuously from the temperature and RH readings hospitals already take [18], and ASHRAE 62.1 now limits it to 15 °C in mechanically cooled spaces whenever outdoor air is more humid [27]. Second, monitoring only pays off if the data is used; in the authors' experience, most buildings with sensors collect data and act on none of it.

Principal recommendations. The recommendations, set out in full in Section 11, are that hospitals: (1) optimise energy above, and never below, the clinical minimums for air changes, pressure and filtration; (2) monitor the core parameters continuously at one-minute intervals and calculate dew point in software; (3) hold dew point at or below 15 °C and alarm on every exceedance; (4) monitor oxygen where medical-gas pipelines run and waste anaesthetic gases in theatres; (5) apply demand-controlled ventilation in wards and outpatient areas at 1,000 ppm CO₂, or about 700 ppm above outdoor; (6) choose CO₂ sensors that do not depend on automatic baseline correction and maintain all sensors on a set schedule; (7) decide in advance which readings may act automatically, and assign a named owner to the data; (8) build the business case from their own data; and (9) anchor the design in the applicable standards.

Keywords: Indoor Air Quality (IAQ), Relative Humidity (RH), Dew-Point Temperature, Particulate Matter (PM), Carbon Dioxide (CO₂), Volatile Organic Compounds (VOCs), Building Management System (BMS), Demand-Controlled Ventilation (DCV)..

Indoor Air Quality Monitoring and Smart Control in Hospitals

1. Introduction

A hospital is one of the most demanding built environments for air management. Within a single facility, air must simultaneously protect immunocompromised patients from infection, prevent the escape of airborne pathogens from isolation areas, maintain sterile conditions over an operating table, and provide comfortable, healthy air to wards, waiting areas and staff. These objectives frequently conflict, and they must be met continuously, around the clock, across seasons, and during unplanned contamination events.

Historically, hospital HVAC systems in India have been engineered to fixed design set-points and verified only periodically, typically through six-monthly validation of operating theatres [7]. A limited amount of continuous monitoring is already mandated: NABH requires that the differential pressure of each operating theatre be measured and displayed using a dedicated differential-pressure meter [7]. Beyond such specific instruments, however, the prevailing approach assumes that a system commissioned correctly will continue to perform as designed. In practice, filter loading, sensor drift, changing occupancy, door movements, equipment ageing and highly variable outdoor conditions cause real performance to diverge from design intent between validation cycles. The consequence is that most IAQ parameters are effectively unmonitored for most of a facility's operating life.

Two developments have made this monitoring gap (the long stretches between validations during which air quality is neither measured nor recorded) untenable. First, the recognition that many significant pathogens (such as SARS-CoV-2 and *Mycobacterium tuberculosis*) transmit through the air has shifted ventilation from a comfort consideration to an infection-control measure [5], [6]. Second, the maturation of low-cost sensing, networked controllers and analytics now makes it economically feasible to measure IAQ continuously and to act on the data automatically through the BMS.

This paper shows how continuous IAQ monitoring and smart control can be put together in Indian hospitals. It follows the international consensus standards, principally ANSI/ASHRAE/ASHE Standard 170 and WHO guidance [1], [3]–[6], and the Indian framework of NABH, NBCS 2026 and ISHRAE's own standards [7]–[10]. It also starts from a condition that guidance written for temperate climates tends to underplay: across most of India, high ambient humidity makes moisture control, and with it dew-point management, the first engineering problem to solve.

1.1 Scope and audience

The paper is written for hospital HVAC designers, facility and biomedical engineers, infection-control teams and hospital administrators. Every numeric requirement is attributed to its source standard. Where a figure could not be verified against the primary document during preparation, the text says so.

2. Why Indoor Air Quality Matters in Healthcare

The case for managing hospital air rests on three linked outcomes: patient safety (principally protection against healthcare-associated infection), the occupational health of staff, and the operational resilience of the facility.

2.1 Infection Control

Ventilation is one of the recognised engineering controls for airborne infection. WHO guidance [6] judges infection-control ventilation on three counts: the quantity of clean air supplied, the direction it travels between zones, which must always be towards the more contaminated area, and how evenly it is distributed within the room. Each of these can degrade without anyone in the room noticing. An exhaust filter that loads up, a damper that drifts or a door that is routinely propped open can reverse the pressure of an isolation room while the space still feels perfectly comfortable. In the authors' experience, few Indian hospitals carry out any check on these conditions between the six-monthly validations; those that do are the exception. The authors therefore hold that continuous monitoring is the only practical way to detect such degradation when it happens; the next scheduled test may be months away.

2.2 Patient Recovery and Staff Wellbeing

Pathogens are not the only concern. Controlled studies of office occupants have linked higher CO₂ and VOC levels with measurably poorer decision-making [20], [21]. In a hospital, the people breathing that air are recovering patients and clinicians making high-stakes decisions, often across long shifts. Particulate matter adds respiratory irritation for patients who are already vulnerable, and temperature and humidity outside their recommended bands affect patient comfort and, in theatres, the integrity of the sterile field [1], [7].

2.3 The Indian Ambient-air Challenge

Indian hospitals draw their outdoor air from some of the most polluted cities in the world [12]. The benchmark used in this paper is the WHO air quality guideline (AQG): a health-based concentration below which a pollutant is not expected to cause significant harm. It is a reference for assessment, not a legal limit [3]. Ambient particulate concentrations across much of India routinely exceed the WHO Global Air Quality Guideline for PM_{2.5} (an annual average of just 5 µg/m³ [3]) by more than an order of magnitude. India also sets its own statutory benchmark: the Central Pollution Control Board's National Ambient Air Quality Standards (NAAQS) permit PM_{2.5} up to 40 µg/m³ (annual) and 60 µg/m³ (24-hour), themselves several times the WHO guideline [11]. Table 1 illustrates the gap using reported annual averages for major Indian cities [12].

*Table 1: Reported annual-average outdoor PM_{2.5} for major Indian cities, against the WHO AQG (5 µg/m³) [3] and the Indian NAAQS (40 µg/m³) [11]. City values are drawn from the IQAir World Air Quality Report 2024 [12] except those marked * (2022 data, latest consistent figure available). Values vary by year, station and source and are indicative.*

City	Annual PM _{2.5} (µg/m ³) [12]	× WHO AQG (5) [3]	× NAAQS (40) [11]
Delhi	107	~21×	2.7×
Kolkata *	59	~12×	1.5×
Hyderabad *	42	~8×	1.1×
Mumbai	36	~7×	0.9×
Bengaluru	33	~7×	0.8×
Chennai	30	~6×	0.7×

A cross-sectional study of hospitals in northern India found indoor PM_{2.5} as high as 149 µg/m³, and outdoor levels above 220 µg/m³ at one hospital in an industrial belt [17]. Because most indoor particulate in Indian hospitals comes in from outside, a filter specification fixed at design is not enough. Filtration has to be checked against actual indoor concentrations as pollution levels rise and fall through the year.

3. Key IAQ Parameters to Monitor

Table 2 lists the parameters proposed for monitoring. Each can be measured with sensors that are commercially available today, and each is tied to a specific clinical or engineering risk.

Table 2. Core IAQ parameters, their clinical/engineering relevance and representative reference values. Values are attributed to their source standards; see Sections 5, 8 and 9. Sources: [1], [3], [4], [7], [11], [13]–[15].

Parameter	Why it matters	Typical reference / target
Temperature	Patient and staff comfort; sterile-field conditions in theatres; equipment operation.	OR 20–24 °C (ASHRAE 170) [1]; NABH 21 ±3 °C, 18 ±2 °C for joint-replacement OTs [7].
Relative humidity (RH)	Mould and microbial growth above about 60%; static, dryness and infection risk when too low.	≤60% across most clinical spaces; OR 20–60% (ASHRAE 170) [1]; NABH ideal ~55% [7].
Dew-point temperature	Best single indicator of condensation risk; decisive in India's humid climate.	Derived from T and RH (Section 6). Target: keep below the coldest exposed surface temperature, with a safety margin; ≤15 °C in all mechanically cooled spaces whenever the outdoor dew point exceeds 15 °C (ASHRAE 62.1) [27]; lower, typically 13–14 °C, in critical zones held at 20–22 °C.
Particulate matter (PM _{2.5} /PM ₁₀)	Fine particles carry pathogens and irritants; indoor PM shows how well filtration is working.	WHO AQG: PM _{2.5} 5 µg/m ³ annual, 15 µg/m ³ 24-h; PM ₁₀ 15 / 45 µg/m ³ [3]. Indian NAAQS: 40 / 60 µg/m ³ (PM _{2.5}) [11].
Carbon dioxide (CO ₂)	An indicator of outdoor-air ventilation and occupancy, not a contaminant at indoor levels [13].	Commonly <800 ppm as an adequate-ventilation benchmark (see note in Section 3.1).
VOCs	Released by disinfectants, sterilants and furnishings; can irritate and affect health.	WHO 2010 sets limits for named compounds (e.g. formaldehyde 0.1 mg/m ³ , 30-min); no WHO TVOC limit [4].
Oxygen (O ₂) for specific areas	Detects leaks where medical-gas pipelines run; enrichment raises fire risk.	NFPA 99: >23.5% is an oxygen-enriched atmosphere (fire hazard) [14]. Monitor in ICUs, pipeline rooms, stores.
Waste anaesthetic gases for OTs	Exposure of theatre staff to N ₂ O and halogenated agents.	NIOSH REL: N ₂ O 25 ppm (TWA); halogenated agents 2 ppm ceiling (0.5 ppm if used with N ₂ O) [15].

3.1 A note on CO₂: a ventilation surrogate, not a contaminant

CO₂ monitoring is easy to misread, so it is worth being clear about what it shows. At the levels found in occupied buildings, the ASHRAE Position Document on Indoor Carbon Dioxide treats CO₂ as an indicator of outdoor-air ventilation, not as a contaminant in its own right, and warns against using it as a direct health metric or a stand-alone measure of infection risk [13]. Some controlled studies have reported effects on decision-making at moderately elevated concentrations [20], [21], but the ASHRAE document regards that evidence as not yet consistent. CO₂ earns its place because it is cheap to measure and responds quickly: outdoor air is now around 420 ppm and exhaled breath around 40,000 ppm, so the indoor level shows the balance between the people in a room and the fresh air reaching them. The familiar “below 800 ppm” benchmark for a well-ventilated space comes from pandemic-era public-health guidance issued by the UK’s SAGE-EMG,

REHVA and the US CDC, not from a WHO limit [22]–[24]. WHO's 2021 ventilation roadmap likewise accepts CO₂ as a proxy for ventilation adequacy while cautioning that it is not a proxy for infection risk [5]. ASHRAE Standard 241, Control of Infectious Aerosols, reflects the same distinction: it sets minimum equivalent clean airflow rates, which filtration and air cleaning can help meet without lowering CO₂, and sets no CO₂ limit [25]. In this paper CO₂ is therefore used as a trigger for more outdoor air, not as a pollutant to be removed.

3.2 Oxygen monitoring in medical-gas areas

Oxygen is rarely discussed as an IAQ parameter, but it matters wherever medical-gas pipelines run. A leak can build up an oxygen-enriched atmosphere, which lowers ignition temperatures and makes materials burn far more readily. NFPA 99 defines an oxygen-enriched atmosphere as one above 23.5% oxygen [14]. Continuous oxygen monitoring with alarms is therefore recommended in intensive-care units, oxygen manifold and cylinder-storage rooms, and other spaces with pipelines, as both a life-safety and a fire-safety measure. It is a targeted addition for these areas only, not a requirement for the whole facility.

3.3 Waste anaesthetic gases in operating theatres

Operating theatres carry a specific occupational exposure: waste anaesthetic gases (nitrous oxide (N₂O) and halogenated volatile agents such as sevoflurane, isoflurane and desflurane) that escape into theatre air. NIOSH sets recommended exposure limits of 25 ppm for N₂O, averaged over the period of anaesthetic administration, and a 2 ppm ceiling for any halogenated agent used alone; where a halogenated agent is given together with N₂O, the ceiling drops to 0.5 ppm [15]. Strictly, these are occupational-hygiene limits, not IAQ guidelines. They are still best handled by the same monitoring and ventilation system, and periodic or continuous measurement of anaesthetic gases, together with effective scavenging, belongs in any theatre IAQ programme.

4. Requirements Differ Sharply Across Clinical Spaces

No single IAQ target fits a hospital. The three classes of space below show how far requirements differ; Table 3 brings the numbers together.

4.1 General patient areas and wards

Wards, outpatient departments and waiting areas are managed mainly for comfort, enough fresh air and reasonable particulate levels. ASHRAE 170 requires at least 6 total air changes per hour (ACH) in general patient rooms and sets no pressure relationship [1]. The parameters that matter most here are CO₂, PM, temperature and RH. Occupancy in these spaces swings widely through the day, which is why they offer the largest savings from demand-controlled ventilation.

4.2 Operating theatres

Operating theatres are the most tightly controlled spaces, and the primary purpose of their ventilation is to minimise the risk of surgical site infection (SSI). An operating theatre (OT) is maintained at a higher pressure than its adjoining rooms/areas so that the leakage always runs outward, and is supplied with HEPA-filtered air in a unidirectional downflow over the sterile field, within the prescribed temperature and humidity limits [1], [7]. Indian practice under the NABH 2018 operating-theatre guidelines specifies a minimum of 20 total ACH (of which at least 4 are fresh air), a minimum positive differential of 2.5 Pa maintained at all times, a unidirectional downward face velocity of 25–35 feet per minute (about 0.13–0.18 m/s) within the laminar-flow field, and terminal HEPA filtration to 99.97% at 0.3 µm [7]. NABH divides theatres into Type A (super-specialty) and Type B (general), specifying air cleanliness at the supply grille of ISO Class 5 and ISO Class 6 respectively [7].

4.3 Isolation and airborne-infection wards

Airborne-infection isolation (All) rooms invert the theatre logic: they are held at negative pressure so that air flows into the room and is exhausted safely, preventing pathogens from escaping to adjoining areas. ASHRAE 170 specifies All rooms at a minimum of 12 ACH (existing rooms may be permitted lower) with negative pressure and exhaust directly to outdoors, or through HEPA if any air is recirculated [1]. Protective-environment (PE) rooms, which shield immunocompromised patients, use the opposite pressure regime, positive pressure with HEPA-filtered supply [1]. For naturally ventilated facilities, WHO guidance [6] asks for 60 L/s per patient in general wards but more than two and a half times that, 160 L/s per patient as an hourly average with a floor of 80 L/s, in rooms used for airborne precautions.

Table 3: Representative per-space requirements. ASHRAE 170 values reflect the 2017/2021 editions (current edition is 170-2025; core OR/All/PE parameters are unchanged) [1], [2]. NABH 2018 governs Indian operating theatres, and additionally requires that each OT's differential pressure be measured and displayed on a dedicated meter [7]. The 2 outdoor-ACH figure for patient/All/PE rooms and the exact filter classes should be confirmed against the current ASHRAE 170 tables for the edition applicable in a given jurisdiction.

Space	Pressure	Min total ACH	Temp / RH	Filtration
General patient room	None / neutral	6	21–24 °C; ≤60% RH	MERV 7 + MERV 14 [1]
Operating theatre	Positive	20 (ASHRAE 170 & NABH) [1], [7]	20–24 °C; 20–60% RH	MERV 16 min. [2]; HEPA for ortho/transplant/neuro
All / isolation	Negative	12	21–24 °C; ≤60% RH	Exhaust outdoors or via HEPA
Protective environment	Positive	12	21–24 °C; ≤60% RH	HEPA-filtered supply

5. Building Standards

Continuous monitoring is only as useful as the limits it is checked against, so every threshold in this paper is tied to a recognised standard. For Indian hospitals these come from international consensus documents and national instruments, which largely agree because the Indian instruments themselves draw on ASHRAE.

5.1 ANSI/ASHRAE/ASHE Standard 170

Standard 170, Ventilation of Health Care Facilities, is the main international reference [1]. It sets design temperature and humidity, minimum total and outdoor air changes, pressure relationships and filtration for more than sixty space types. The current edition is 170-2025, following the 2008, 2013, 2017 and 2021 editions. A 2020 addendum, carried into the 2021 edition, raised the minimum filtration for surgical spaces to MERV 16, with HEPA for the most demanding procedures [2]. As a US consensus standard, it takes legal force through the FGI Guidelines and NFPA 99 [14], so the edition that applies depends on the authority having jurisdiction.

5.2 WHO guidance

Four WHO documents are relevant. The Global Air Quality Guidelines (2021) supply the health-based particulate and gas benchmarks used throughout this paper [3]. The Guidelines for Indoor Air Quality: Selected Pollutants (2010) set limits for individual compounds, such as formaldehyde at 0.1 mg/m³ over 30 minutes, and deliberately set no limit for total VOCs [4]. The Roadmap to Improve and Ensure Good Indoor Ventilation (2021) and the earlier Natural Ventilation for Infection Control in Health-Care Settings (2009) provide the ward and isolation-room ventilation rates given in Section 4.3, roughly 6 and 12 ACH respectively, and accept CO₂ as a ventilation proxy [5], [6].

5.3 Indian References: NABH, NBCS 2026 and ISHRAE

For Indian facilities, the NABH Revised Guidelines for Air Conditioning in Operation Theatres (2018) are the governing operating-theatre reference and are explicitly derived from ASHRAE 170-2017 and the ASHRAE HVAC Design Manual for Hospitals and Clinics [7]. Alongside NABH, the ISHRAE HVAC Design Guidelines for Healthcare Facilities provide India-specific design guidance for hospital air-conditioning and ventilation and should be consulted in parallel [9]. The umbrella national instrument for building HVAC and ventilation, including healthcare occupancies, is now the National Building Construction Standards, 2026 (NBCS 2026), published by the Bureau of Indian Standards as SP 7:2026 and notified through the Gazette of India dated 30 April 2026 [10]. NBCS 2026 supersedes the earlier National Building Code (NBC) 2016; designers and specifiers should reference NBCS 2026 (SP 7:2026) instead of NBC 2016 from now on, subject to each state and municipal authority updating its own building bye-laws. ISHRAE's own IEQ Standard 10001:2019 (India's first Indoor Environmental Quality standard) is particularly relevant because, alongside threshold levels for thermal comfort, air quality, lighting and acoustics, it defines measurement protocols and monitoring-device specifications and grades performance into classes; its sensor specifications are used in Table 8 [8]. The standard is currently under revision. The monitoring guidelines in Section 9 are consistent with NBCS 2026 [10]. For per-space numeric values (air changes, pressure, temperature and humidity), Indian healthcare HVAC practice continues to rely principally on ASHRAE 170 and NABH [1], [7].

6. Dew-Point Temperature: A Critical Parameter Without a Dedicated Sensor

Dew point tells the engineer how cold a surface in a room can be before moisture starts to form on it: any duct, diffuser, wall or glazing surface below the room's dew point will sweat, however comfortable the room feels. Formally, it is the temperature at which the room air, cooled without gaining or losing moisture, reaches saturation. It is the single most direct indicator of condensation risk, and in India's humid climate it is arguably the most important humidity-related quantity to keep under control.

6.1 Why dew point matters in Indian hospitals

Along India's coast, and across much of the country during the monsoon, the outdoor dew point sits well above any acceptable indoor value; in coastal cities it typically lies between 24 and 27 °C for much of the year. The latent (moisture) load therefore dominates hospital cooling, and it is not only external: patients, staff, respiratory therapy, sterilisation and washdown all add moisture inside the building. Holding the RH ceiling of 60% [1], or the tighter 45–55% favoured in critical zones, cannot be done by removing sensible heat alone; it needs deliberate dehumidification. ASHRAE Standard 62.1 now makes this explicit for all mechanically cooled buildings: whenever the outdoor dew point is above 15 °C, indoor humidity must be held to a dew point of no more than 15 °C, in occupied and unoccupied hours alike [27]. On India's coast that condition applies almost all year.

Indian practice is far from this. Most indoor spaces, hospitals included, are controlled by thermostat alone and were never designed to hold a dew point. Many hospitals are now installing VRF systems, which cool effectively but offer limited humidity control; if RH were monitored in these spaces, keeping it within limits would prove a serious challenge. In practice it is almost never monitored. The results are visible to anyone who maintains these buildings: diffusers that sweat, false ceilings that stay damp, and walls and floors with persistent dampness and mould. Operating theatres and isolation suites, which run high outdoor-air fractions, carry both the largest energy burden and the largest moisture risk. Monitoring dew point gives operators a direct warning of condensation that RH alone cannot give, because RH changes with temperature while dew point does not.

6.2 A dedicated dew-point sensor is not necessary

The authors' view is that dew point should be tracked wherever temperature and humidity are measured, and that this needs no extra hardware. Dew point is fully determined by air temperature and relative humidity, which hospitals already measure, so a standard psychrometric formula can calculate it continuously at every sensing point. A dedicated dew-point sensor in each zone would add cost and a second calibration burden without adding information.

The Magnus–Tetens approximation (with the Sonntag/WMO coefficients) is the standard, widely validated form [18]. Defining an intermediate term $\gamma(T, RH) = \ln(RH/100) + (a \cdot T)/(b + T)$, the dew-point temperature is $T_d = (b \cdot \gamma)/(a - \gamma)$, with $a = 17.62$ and $b = 243.12$ °C, valid over the range –45 °C to +60 °C [18]. RH is entered in percent and T in degrees Celsius.

The calculation can run in the BMS or in the sensor's own firmware. It takes a few arithmetic operations per reading and needs no calibration beyond what the temperature and humidity channels already receive. Some IAQ sensor manufacturers now show a calculated dew point live on their dashboards. Table 4 shows how the numbers behave: air temperature is held at 24 °C, a typical air-conditioned set-point, and only relative humidity changes, so the rise in dew point, and in condensation risk, is easy to see.

Table 4. Dew-point temperature at a fixed air temperature of 24 °C as relative humidity rises, computed with the Magnus–Tetens (Sonntag) formula [18]. Holding temperature constant isolates the effect of humidity: at 60% RH (the usual ceiling) the dew point is already ~16 °C, so any surface below that will sweat. As a physical check, the formula returns a dew point equal to the air temperature at 100% RH. (At a cooler 21 °C set-point the corresponding dew points are about 6.9, 10.2, 12.9, 15.3 and 17.4 °C for 40–80% RH.)

Relative humidity at 24 °C (%)	Calculated dew point (°C)	Condensation risk
40	9.6	Low
50	12.9	Low–moderate
60	15.8	Moderate (RH ceiling reached)
70	18.2	High
80	20.3	Very high

6.3 Practical implications

Calculating dew point in software has three advantages. A facility with hundreds of monitored zones avoids buying and maintaining hundreds of extra sensors. There is no second instrument to calibrate. And dew point becomes available wherever temperature and RH are already measured, which gives far denser coverage than dedicated instruments could. The BMS can then alarm on dew-point margins, for example when the dew point approaches a known cold-surface temperature, and start dehumidifying before condensation forms.

7. From Monitoring to Smart Control

Monitoring produces data; the value comes from acting on it. Smart control turns IAQ readings into HVAC actions that keep each space within its clinical limits while using no more energy than necessary.

7.1 What smart control means: the closed control loop

Smart control is a closed loop that repeats continuously (Figure 1). Sensors measure the air; the readings reach the BMS over standard protocols such as BACnet or Modbus; the control logic compares them with each space's set-points and clinical minimums; and the BMS drives dampers, variable-frequency drives, valves and dehumidifiers in response. The same sensors then confirm that the space is back on target, which also leaves an auditable record. What distinguishes this from conventional control is that each decision follows the measured condition of the air, not a fixed schedule or a design-day assumption.

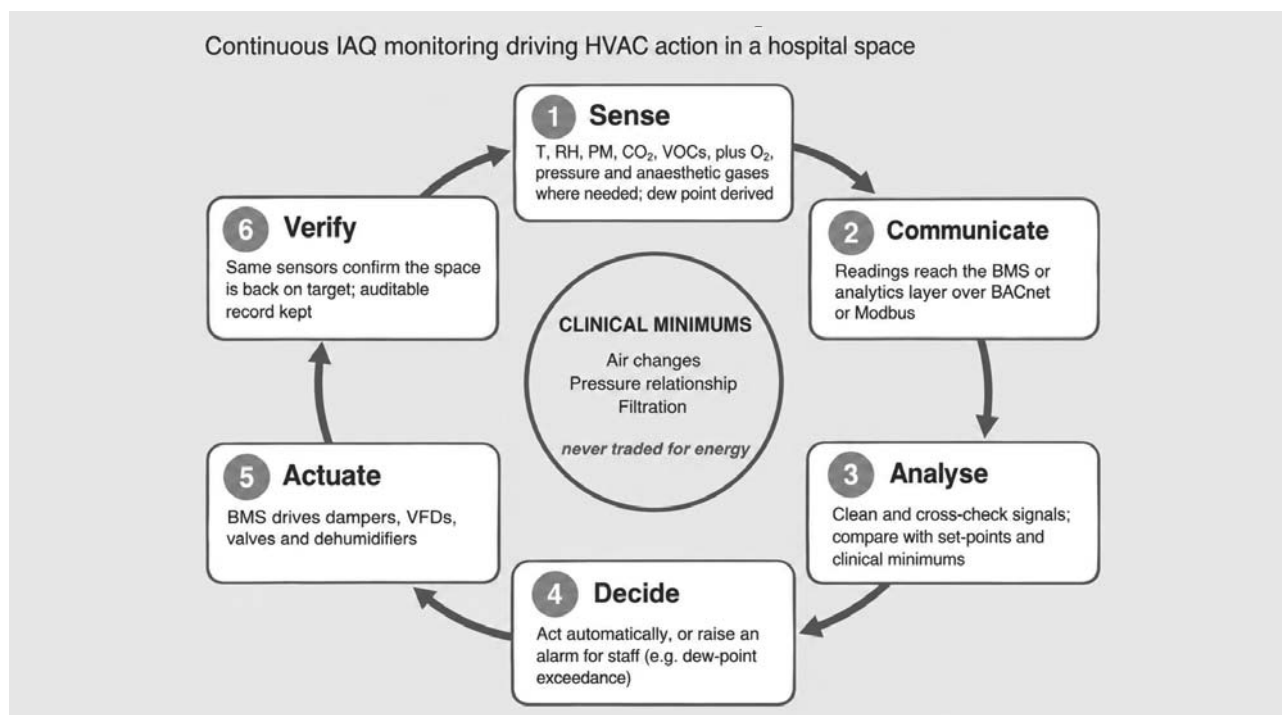


Figure 1: The smart-control loop. Every action in the loop is bounded by the space's clinical minimums for air changes, pressure relationship and filtration.

Most Indian hospitals have not yet reached the first step of this loop. With no parameter monitored, control usually rests on a room thermostat that displays temperature and RH, and any correction is made by hand, not through a BMS. A BMS is typically installed only where there is a chilled-water plant, mainly to modulate the AHU valves; even there, dew-point control is usually absent, and outdoor-air intake is often cut back to reduce energy cost. For most hospitals, therefore, smart control begins with measurement.

Two design rules govern every loop in a hospital. First, clinical minimums are never traded for energy: the loop may optimise freely above each space's minimum air changes, pressure relationship and filtration, but must never drive below them. Second, the authority to act must be settled in advance. For each action it must be decided whether a reading may move plant automatically or may only raise an alarm for a person to act on, and in critical spaces automatic action is deliberately limited. As a minimum, the authors recommend an alarm on dew-point exceedance in every monitored space.

7.2 Levels of intelligence: rule-based, analytics, predictive

Smart control does not have to be adopted all at once. Hospitals can start with simple rules and move to more advanced levels as their data and confidence grow (Table 5).

Table 5. Levels of smart control, from rule-based to predictive.

Level	What it does	Example
1. Rule-based control	Fixed if-then logic on live readings	Raise outdoor air when CO ₂ exceeds the DCV trigger; increase dehumidification when dew point rises
2. Analytics and fault detection and diagnostics (FDD)	Learns normal patterns, flags drift and developing faults, and suggests likely causes	A slow rise in theatre humidity together with falling coil performance points to a failing dehumidification valve
3. Predictive, model-based control	Anticipates load from occupancy schedules and weather and pollution forecasts, and prepares the plant in advance	Raise filtration ahead of a forecast outdoor PM episode; pre-dry a theatre before the first list

Level 1 alone delivers most of the value and is where the authors recommend every hospital begin. Levels 2 and 3 add value but also complexity and new ways to fail; each should be justified on its own merits and must respect the same clinical minimums.

7.3 Control sequences: turning readings into actions

In practice, smart control comes down to a set of sequences, each linking a measured condition to an action and a safeguard. Table 6 gives a representative set for a hospital: what the system watches, what it does, what protects the clinical minimums, and where each sequence applies. The sequences are illustrative, not set-points; each facility has to tune them and reconcile them with the applicable codes.

Table 6. Representative control-logic matrix linking monitored triggers to control actions and safeguards. Illustrative only: set-points and permitted actions must be tuned per facility and reconciled with ASHRAE 170, NABH and the authority having jurisdiction [1], [7].

Trigger (measured)	Control action	Safeguard / clinical minimum	Where it applies
CO ₂ above target (e.g. >1,000 ppm, or ~700 ppm above outdoor)	Increase outdoor-air damper / fan speed (DCV) until CO ₂ falls	Never below minimum ACH; do not disturb OT pressure	Wards, OPD, diagnostics, offices
Derived dew point approaching a cold-surface / coil temperature	Increase dehumidification (lower coil, engage dedicated dehumidifier), add reheat if needed	Hold RH ≤60% and space temperature band	All conditioned spaces; critical zones first
RH rising toward 60% ceiling	Boost dehumidification ahead of the limit	Maintain temperature set-point; avoid overcooling	OTs, ICUs, isolation, wards
Room differential pressure out of range	Alarm and trim supply/exhaust to restore cascade	Positive for OT/PE, negative for All; restore before anything else	OTs, All, PE rooms
PM rising indoors (filter loading or infiltration)	Raise filtration stage / recirculation; flag filter change	Maintain outdoor-air minimum; escalate if not corrected	All spaces; critical zones prioritised
VOC surge (e.g. disinfection)	Temporary purge with increased outdoor air, then return to normal	Respect pressure relationships; time-limit the purge	OTs, wards, labs after cleaning
Oxygen > 23.5% near pipelines	Alarm (life-safety); ventilate the area; notify staff	Treated as safety alarm, not energy optimisation	ICUs, gas manifold / store rooms
Filter ΔP / fan energy trending abnormal	Predictive-maintenance work order before failure	No automatic shutdown of critical-space AHUs	AHUs serving OTs, isolation, ICU

7.4 Demand-controlled ventilation

Demand-controlled ventilation (DCV) matches the fresh-air supply to actual need, usually judged from CO₂ and occupancy, instead of running at design maximum all day. The opportunity in hospitals is large, because occupancy in wards, outpatient areas and diagnostic suites changes sharply through the day. The NIST review of CO₂-based DCV remains the standard technical reference [16]. DCV depends directly on continuous CO₂ and occupancy data; it is the control action that puts the monitoring argued for in this paper to use. It must still be applied with clinical judgement and only where codes allow. It suits general wards, outpatient departments, and diagnostic and administrative areas. It should not be used in operating theatres: cutting outdoor air there can upset the room's positive pressure, and ASHRAE 170 does not allow operating-room ventilation to be turned down while the room is in use [1]. Indian practice allows one narrow exception. NABH permits theatre air changes to be reduced to 25% during genuinely non-operational hours, using

variable-frequency drives, provided positive pressure is kept [7]; even this should be automated cautiously. In every case the applicable Indian codes and the authority having jurisdiction decide what turndown is allowed. For general wards and outpatient areas, the authors recommend a DCV trigger of 1,000 ppm, or about 700 ppm above the measured outdoor level where outdoor CO₂ is monitored. This corresponds to roughly 7.5 L/s of outdoor air per person, the relationship long described in the informative material of ASHRAE Standard 62.1 [26]. It is a ventilation set-point, not a health limit, and in every case the space's minimum air changes under ASHRAE 170 still apply [1]. During outbreaks, or in wards adjoining isolation rooms, a lower trigger of 800 ppm is advisable [22]–[24].

7.5 Predictive maintenance

Continuous monitoring also changes how the plant is maintained. The same live data (filter pressure drop, fan energy, coil performance and airflow) show when maintenance is actually needed, instead of leaving it to fixed intervals or to failure. In most Indian hospitals, filters are cleaned or replaced on a fixed schedule, an exercise that too often amounts to ticking boxes. The better approach is to measure the differential pressure across each filter bank, which shows how far the filter has loaded and when it actually needs attention. Developing faults in the air-handling units serving theatres and isolation suites can likewise be flagged before they affect pressure or filtration. The US Federal Energy Management Program estimates that predictive maintenance saves 8–12% over a preventive programme alone, and more than 30–40% compared with purely reactive maintenance [28]. Vendor case studies claim larger gains; these should be treated as illustrative, not guaranteed. Costs and return on investment are discussed in Section 8.4.

7.6 Proactive response to contamination events

Because the system sees the air in real time, it can respond to abnormal events as they happen: a spike in particulates when a door is propped open, a loss of pressure differential in an isolation room, or a VOC surge during disinfection. The response can range from an alarm and increased ventilation to the affected zone, to escalation to facility staff. Contamination is then dealt with when it occurs, not discovered at the next periodic check.

7.7 Energy optimisation with clinical safety

Hospital HVAC is energy-intensive, and India's latent load makes it more so. As noted in Section 7.1, energy is often saved today by cutting back outdoor air, which trades away exactly the protection that ventilation is meant to provide. Smart control saves energy the other way: by ventilating and dehumidifying to measured need instead of worst-case assumptions, while holding every space above its minimum air changes, pressure relationship and filtration. That only works if the data can be trusted, which is why the instrumentation and monitoring guidelines in Sections 8 and 9 are part of the control strategy, not an add-on.

7.8 What smart control looks like, space by space

Operating theatre. During a list, the loop holds temperature, humidity and the positive-pressure cascade continuously, dehumidifying to keep dew point and RH within their limits while never reducing air changes or pressure. Pressure, anaesthetic-gas and dew-point exceedances are alarmed. Between lists, the BMS may apply the NABH setback to 25% air changes, provided positive pressure is maintained [7], and a Level 3 system can pre-dry the suite ahead of the next scheduled list.

Airborne-infection isolation room. Holding negative pressure comes before comfort or energy. The loop continuously trims supply and exhaust to maintain the pressure cascade and alarms immediately on any excursion. Pressure and fan data also show the condition of the exhaust filter, so a loading filter is flagged as a developing fault, not discovered at the next test.

General ward. Here the loop has the most freedom. Demand-controlled ventilation follows real occupancy using the CO₂ trigger in Section 7.4, dehumidification tracks dew point, and rising PM triggers a filtration boost during outdoor pollution episodes, always above the ward's minimum air changes. Most of the energy saving is realised here, without touching any clinical minimum.

8. Instrumentation, Sensors and their Limitations

A monitoring programme is only as credible as its sensors. Modern low-cost IAQ sensors are capable and affordable, but they are not laboratory instruments, and a hospital programme has to be designed around how they actually behave.

8.1 What good sensors can and cannot do

Published reviews of low-cost sensors show a consistent pattern [19], [29]. NDIR CO₂ sensors are now a mature technology and track reference instruments closely, both in the laboratory and in the field. Optical PM sensors correlate well with reference instruments under laboratory conditions, but their field performance varies widely with particle type, humidity and ageing [19]. Low-cost sensors are therefore excellent at detecting trends, relative changes and events, but their readings should not be presented as absolute, metrology-grade concentrations without validation.

8.2 Calibration and drift

Drift is the gradual change in a sensor's reading over time while the air it measures stays the same: a CO₂ sensor that reads 600 ppm correctly when new may, months later, read 550 or 680 ppm in the same air. It is why a sensor cannot be calibrated once and trusted indefinitely.

CO₂ sensors in hospitals need particular care over automatic baseline correction (ABC). Many NDIR sensors periodically reset their baseline on the assumption that the space regularly returns to outdoor CO₂ levels when unoccupied. Wards, ICUs and emergency areas never do, so an ABC sensor in these spaces gradually shifts its baseline and under-reads. The authors therefore recommend CO₂ sensors whose manufacturer specifies long-term stability without ABC and without periodic exposure to outdoor air. Where ABC sensors are already installed, they should be checked against a reference-grade CO₂ instrument at least every six months; a reference instrument kept for periodic checks is good practice in any case.

PM sensors are less mature and have a much shorter working life than CO₂ sensors. The authors recommend replacing or recalibrating them about every three years, and sooner in dusty environments. A hospital should budget for this as an ongoing operating cost, not a one-time commissioning task.

8.3 Data interpretation and integration

Raw sensor data has to be turned into trustworthy signals before it drives control. That means filtering noise; cross-checking related readings, for example confirming a suspicious humidity value against the derived dew point, or disregarding a lone PM spike that no neighbouring sensor sees; handling missing data; and setting alarm thresholds that reflect clinical significance, not sensor jitter. Integration with the BMS adds protocol compatibility (BACnet, Modbus), cybersecurity for networked devices, and clear rules on which readings may move plant automatically and which only alert staff (Section 7.1).

In the authors' experience, the most common failures are not technical. Sensors are placed poorly or left to collect dust, and the data, where it is collected at all, is logged and filed in reports but almost never analysed or used to make decisions. A monitoring programme needs a named owner who reviews the data and acts on it; without that, even good sensors add little.

Table 7: Common IAQ-monitoring challenges and practical mitigations.

Challenge	Mitigation
Sensor drift over time	Recalibrate on a fixed schedule; check periodically against a reference instrument placed alongside.
Cross-sensitivity to T and RH	Apply the manufacturer's compensation; cross-check humidity readings against the calculated dew point.
Absolute accuracy of low-cost units	Use readings for trends and events; validate against a reference before quoting absolute values.
Noisy data triggering false alarms	Smooth the signal and set alarm thresholds on clinical significance.
Integration and cybersecurity	Use BACnet or Modbus; keep sensors on a separate, secured network; decide in advance what may actuate plant.

8.4 Sensor selection in the Indian market, cost and ROI

Choose the sensing technology by measurement principle, not by brand; it matters as much as the choice of supplier. For CO₂, non-dispersive infrared (NDIR) sensors are the practical standard: accurate enough, stable and now inexpensive. For hospitals, pick NDIR models specified for long-term stability without ABC (Section 8.2). Cheaper electrochemical or metal-oxide substitutes should not be used for ventilation control. For particulate matter, laser light-scattering sensors dominate the affordable end of the market. They follow trends well but need humidity compensation and periodic checks against a reference; gravimetric and beta-attenuation instruments remain the metrology-grade option for validation, at far higher cost. For VOCs, low-cost metal-oxide (MOS) sensors give a single indexed TVOC value that is useful for spotting trends and events. Photo-ionisation detectors (PID) quantify better but cost more, and neither identifies individual compounds. Temperature and RH sensing is mature and cheap. Multi-parameter monitors covering T, RH, CO₂, PM and TVOC are widely available in India, and dew point then comes free in software (Section 6).

On cost and return on investment, the practical message for Indian hospitals is to match sensor grade to purpose: dense, low-cost nodes for trend and event detection across many zones, backed by a small number of reference-grade instruments for periodic checks and validation. The return comes from three sources: energy savings from demand-controlled ventilation and dehumidifying to need (Section 7), avoided cost and downtime from predictive maintenance, and, hardest to price but most important, reduced infection and condensation risk. Because tariffs, labour and equipment prices vary widely, this paper does not quote a single payback figure. Each facility should instead build a simple business case from its own energy bill, maintenance history and the marginal cost of adding sensing to zones it already conditions.

9. IAQ Monitoring Guidelines: Sampling, Deployment, and Specifications

Continuous monitoring is only as good as its implementation. The guidelines below cover how often to sample, where and how many sensors to place, how to display the data and what sensor performance to specify. They complement, and do not override, the per-space engineering requirements of ASHRAE 170 and NABH [1], [7], and are consistent with the monitoring provisions of NBCS 2026 [10].

9.1 Sampling frequency

Temperature, relative humidity, CO₂, TVOC and PM should be logged continuously, 24 hours a day. The authors recommend a one-minute logging interval. A five-minute interval has been accepted as a minimum to ease adoption in a market new to monitoring, but it offers no technical saving: any system that can log every five minutes can log every minute, and the shorter interval captures brief events that a five-minute record can miss. Where a reading drives an automatic

control action or a life-safety alarm, such as oxygen in a pipeline room or differential pressure in an isolation room or theatre, it should be monitored continuously, with the alarm raised as soon as the limit is crossed. For compliance purposes, missing data should be treated as an exceedance for that period, so that gaps in the record are never counted in a facility's favour.

9.2 Deployment: where and how many sensors

Two decisions govern deployment: where each monitor goes and how many are needed. Monitors should sample the air people actually breathe, which means the breathing zone, between roughly 1.1 m and 1.7 m (3.6–5.6 ft) above the finished floor. In rooms with low ceilings, around 2.4 m (8 ft), ceiling mounting is acceptable if air distribution is uniform enough for ceiling readings to represent the breathing zone. Monitors should be kept at least 1 m (3 ft) from doorways, openable windows and supply or return air vents, which otherwise distort the reading [10].



Figure 2: IAQ sensor placement guidelines for healthcare environments, showing common mistakes (grey) and recommended positioning (green) relative to the breathing zone, windows, doors and supply-air diffusers. Distances are practical rules of thumb; where they differ from a minimum in the text (e.g. ≥ 1 m from vents), apply the more conservative value.

For hospitals, device density should follow clinical risk, not floor area alone. Each operating theatre, each airborne-infection isolation (AII) room and each protective-environment (PE) room should have its own dedicated monitoring, in addition to the differential-pressure meter NABH already requires in every OT [7]. Intensive-care units should be monitored at least zonally, with oxygen sensing where pipelines run. Every enclosed clinical or office room occupied for an average of at least half the working day should have its own device; general wards and common areas should have at least one device per 450 m² of floor area, and more where the space is large or subdivided [10].

Figure 2 summarises the placement principles visually: keep sensors in the breathing zone (not at ceiling level), and hold a sensible distance from windows, doors and supply-air diffusers so that readings reflect the occupied space, not a local anomaly.

9.3 Display of data

Monitored IAQ parameters should be visible at a glance to staff and, where appropriate, to patients and visitors. A practical arrangement is at least one common display per floor or clinical section showing a live view of that area's monitors, a single lobby display summarising the whole facility, or both [10]. A visible display also creates accountability: a drifting or alarming parameter is seen before it becomes an incident.

9.4 Recommended sensor specifications

Sensor selection largely determines data quality; an unsuitable sensor produces confidently wrong numbers. Table 8 gives the recommended measurement range, accuracy and resolution for continuous-monitoring sensors, as specified in ISHRAE IEQ Standard 10001 [8]. Dew point is not listed because it is calculated from the temperature and RH channels (Section 6); its quality follows from theirs.

Table 8. Recommended range, accuracy and resolution for continuous-monitoring sensors, from ISHRAE IEQ Standard 10001 [8]. For hospital-specific parameters not covered here, oxygen and waste anaesthetic gases, specify instruments against the NFPA 99 and NIOSH criteria [14], [15] in Sections 3.2 and 3.3.

Parameter	Unit	Range	Accuracy	Resolution
PM10	µg/m ³	0 – 1000	±10% of reading	1 µg/m ³
PM2.5	µg/m ³	0 – 1000	±10% of reading	1 µg/m ³
CO ₂	ppm	400 – 5000	±50 ppm + 5% of reading	1 ppm
TVOC	ppb	0 – 5000	±20 ppb ±15% of reading	1 ppb
Temperature	°C	0 – 100	±1°C	0.1°C
Relative humidity	%	5 – 95	±5%	1%

10. Implementation Framework

The steps below let a hospital introduce monitoring and smart control in stages, and show results at each stage before moving to the next.

Assess and prioritise. Map each space to its governing requirements (Section 4), identify the highest-risk zones and those whose conditions vary most, and take short-term measurements to establish a baseline. In most hospitals this will be the first time the air has been measured at all.

Instrument for visibility. Install T, RH, PM, CO₂ and VOC sensing in priority zones, following the placement and density guidance of Section 9, and calculate dew point in software at every point. Add oxygen sensing where medical-gas pipelines run. Start with monitoring and alarms, including a dew-point exceedance alarm, before automating any control.

Integrate with the BMS. Bring sensor data into the BMS over standard protocols, assign a named owner for the data, and validate readings against reference instruments and against each other. Smaller hospitals that cannot install a BMS still need a monitoring system. For them, the cloud dashboard offered by the IAQ sensor manufacturer is usually the most practical choice: it needs no installation on site beyond connecting the sensors to Wi-Fi, and it provides trending, alarms and reports ready to use. Even where a BMS exists, the authors' experience is that it seldom does more than store raw readings. BMS vendors typically trend the numbers without IAQ-specific interpretation, which is why so many buildings with sensors collect data and do nothing with it. IAQ sensor manufacturers' dashboards are generally better equipped for this analysis: they are built around IAQ metrics and often include AI-based analytics that flag patterns and suggest likely causes. A practical arrangement is to use the manufacturer's dashboard for IAQ analysis and the BMS for control. When choosing a dashboard, the hospital should confirm that it owns its data and can export it, and that the sensors sit on a network segregated from clinical systems.

Automate control, safely. Introduce demand-controlled ventilation in general areas (Section 7.4) and event-response logic across zones, always within the clinical minimums of critical spaces.

Add predictive maintenance and optimise. Use the accumulated data to drive condition-based maintenance, starting with filter changes based on measured pressure drop, and to tune energy performance against both IAQ and energy targets.

Sustain. Treat calibration, validation and threshold review as continuing operations. Periodic formal validation, such as six-monthly OT validation [7], remains the assurance backbone; continuous monitoring adds to it and does not replace it.

11. Recommendations

Adopt a performance-based IAQ strategy that optimises energy above, and never below, the clinical minimums for air changes, pressure and filtration in each space.

Monitor the core parameters continuously (temperature, RH, PM, CO₂ and VOCs) in priority zones, logged at one-minute intervals and placed as set out in Section 9, and calculate dew point in software from T and RH instead of installing dedicated dew-point sensors.

Treat dew point as a primary control and alarm parameter by holding it at or below 15 °C in all mechanically cooled spaces whenever the outdoor dew point is higher [27], and alarming on every exceedance.

Add targeted monitoring where the risk is specific: oxygen where medical-gas pipelines run (NFPA 99: above 23.5% is oxygen-enriched) [14], and waste anaesthetic gases in operating theatres (NIOSH limits) [15], alongside effective scavenging.

Apply demand-controlled ventilation selectively in general wards and outpatient areas, triggered at 1,000 ppm CO₂ or about 700 ppm above outdoor (800 ppm during outbreaks), while keeping continuous minimum ventilation and pressure in theatres and isolation rooms.

Choose and maintain sensors for hospital conditions by specifying CO₂ sensors that are stable without automatic baseline correction, checking CO₂ sensors periodically against a reference instrument, and replacing or recalibrating PM sensors about every three years (Section 8.2).

Govern the data and its authority to act by deciding in advance which readings may move plant automatically and which only alert staff, securing the device network, and assigning a named owner to review the data and act on it, through a BMS or, in smaller hospitals, the sensor manufacturer's cloud dashboard.

Build a facility-specific business case from the hospital's own energy bills, maintenance history and sensing costs, not from generic payback claims.

Anchor the design in the applicable standards (ASHRAE 170, WHO guidance, NABH 2018, the ISHRAE HVAC Design Guidelines for Healthcare Facilities, NBCS 2026 and ISHRAE IEQ 10001) [1], [3]–[10], and verify all numeric figures against the primary documents.

12. Conclusion

Hospital air is a clinical resource, and in India it is under steady pressure from polluted outdoor air and a heavy humidity load. Yet in most Indian hospitals it is not measured at all: temperature is set on a thermostat, humidity is left to chance, and the only formal check is a periodic validation of the operating theatres. Continuous monitoring closes that gap. Linked to a BMS or, in smaller hospitals, to a sensor manufacturer's dashboard, it lets a facility see its air, act on it and show that it has done so, while saving energy by ventilating and dehumidifying to measured need. Dew point shows the case in miniature: it is the parameter that best predicts condensation and mould, it can be calculated from sensors hospitals already install, and it is almost never tracked.

The authors' conclusion is that continuous IAQ monitoring should become standard practice in Indian hospitals of every size. The technology is mature and affordable, it does not necessarily depend on a BMS, and the first step, measuring the air, is one any facility can take now.

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White Paper
**Climate-Specific Building
Envelope Strategies for
Healthcare Facilities:**
**A Passive-First Active Next approach to IAQ,
Moisture Control and HVAC Energy Optimisation.**

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Indian Society of Heating, Refrigerating and Air Conditioning Engineers

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This white paper reflects not only my efforts but also the collective guidance and expertise generously shared by these respected professionals. I offer my sincere gratitude to each of them for their invaluable contributions, thoughtful feedback, and unwavering support.

Dr. Sachin Gupte

Executive Summary

Healthcare facilities across India operate in diverse climatic zones – Warm-Humid, Hot-Dry, Composite, Temperate and Cold. These climatic conditions influence building-envelope performance through variations in solar exposure, heat transfer, air infiltration and moisture movement. A major challenge across these zones for the HVAC engineers is to maintain Indoor Air Quality (IAQ), ensure effective moisture management, controlled indoor Relative Humidity and ensure Thermal stability in sync with the climatic conditions.

In Warm-Humid regions, elevated latent loads are accompanied with enhanced infiltration sensitivity, condensation risks and increased possibility of microbial proliferation. Composite climates necessitate adaptability to seasonal changes. In case of Hot-Dry regions, the challenge is of high solar heat gain coupled with dust infiltration. Cold climates face challenges more related to heat loss prevention and low outdoor-air moisture content, which can result in low indoor RH when the air is heated. The effectiveness of the Healthcare facilities is closely linked to the performance of the building envelope.

This white paper proposes a Passive-First, Active-Next approach.

In the context for this paper, “Passive-First” is a design approach which prioritises and optimises climate-responsive building-envelope measures at the early design stage to reduce avoidable thermal, solar, air-infiltration and moisture-related loads. By reducing the energy demand at the source, passive measures help the designers improve building performance and reduce loads which are then addressed by the optimised HVAC system. “Active-Next” is the next step and comprises of designing and optimising the HVAC systems after the passive measures have reduced the heating, cooling, and ventilation loads. This approach ensures that the remaining building loads meet the required indoor environmental conditions by ensuring the HVAC systems are optimally sized and operated based on actual loads rather than on unoptimised loads.

Key passive envelope interventions should focus on controlling heat and moisture transfer through measures such as appropriate thermal insulation, airtightness and control of uncontrolled infiltration, vapour control, minimisation of thermal bridges, climate-responsive glazing and shading, reflective roof/wall finishes, and appropriate wall and roof construction systems such as EIFS or insulated panel systems. Exterior Insulation and Finish Systems (EIFS), polyurethane (PU) insulation and reflective roof coatings are considered as representative envelope interventions rather than as universally applicable or code-mandated solutions. Their suitability depends on climate, building function, assembly design, constructability, moisture behaviour, and applicable performance requirements to avoid surface and interstitial condensation.

These interventions act a first line of defence and can result in lower capital expenditure (CAPEX) and operational expenditure (OPEX) both on a life cycle basis, due to optimised HVAC equipment sizing. Moreover, they can provide consistency and compliance with evolving regulatory frameworks such as the Energy Conservation and Sustainability Building Code (ECSBC) and the prevailing green building rating systems.

Keywords

Passive-first design; Healthcare facilities; Building envelope performance; Indoor air quality (IAQ); Moisture control; HVAC optimisation; Climate-responsive design; Energy efficiency; Exterior Insulation and Finish Systems (EIFS); Polyurethane (PU) insulation; Energy Conservation and Sustainability Building Code (ECSBC).

Key Messages

1. Building envelope optimisation should be considered in the early design stage of the healthcare facility design, to reduce external heat gain, infiltration and moisture related loads, before finalising the HVAC systems.
2. Passive envelope interventions – including appropriate thermal insulation, airtightness and infiltration control, vapour control, high-performance glazing, shading, reflective surfaces, and mitigation of thermal bridges – can reduce heating and cooling loads, improve thermal stability, and enable more efficient HVAC operation. The HVAC systems are interdependent; optimising one without the other may limit the overall building performance.
3. EIFS, PU insulation and reflective roof coatings are representative interventions within this broader framework of envelope performance enhancements and not as universally applicable or code-mandated solutions.
4. Leading national and international codes, standards, and sustainability frameworks increasingly advocate high-performance building envelopes as a key strategy for reducing energy consumption and improving operational efficiency.
5. A Passive-First, Active-Next approach provides a practical pathway towards resilient, energy-efficient, and sustainable healthcare facilities with improved lifecycle performance

Abbreviation

Abbreviation	Full Form / Meaning
AEDG	Advanced Energy Design Guide
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
COP	Coefficient of Performance
ECBC	Energy Conservation Building Code
ECSBC	Energy Conservation and Sustainability Building Code
EIFS	Exterior Insulation and Finish System
GRIHA	Green Rating for Integrated Habitat Assessment
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
IGBC	Indian Green Building Council
ISHRAE	Indian Society of Heating, Refrigerating and Air Conditioning Engineers
LCCA	Life Cycle Cost Analysis
MEP	Mechanical, Electrical and Plumbing
NBC	National Building Code of India
OT	Operation Theatre
PU	Polyurethane
RH	Relative Humidity
SHGC	Solar Heat Gain Coefficient
SRI	Solar Reflectance Index
U-Value	Overall Thermal Transmittance
WHO	World Health Organization
WWR	Window-to-Wall Ratio

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Climate-Specific Building Envelope Strategies for Healthcare Facilities: A Passive-First Active Next approach to IAQ, Moisture Control and HVAC Energy Optimisation.

Chapter 1: Introduction and Evaluation Framework

1.1 India's Climate Diversity as a Design Driver

Healthcare infrastructure in India is spread across varied climatic zones such as Warm-Humid, Hot-Dry, Composite, Temperate and Cold. Every zone poses a different challenge on the Healthcare facilities.

The Bureau of Energy Efficiency (BEE) has classified these zones based on the solar heat gain, relative humidity, rainfall patterns etc. which form the basis for designing climate-responsive buildings.

In healthcare facilities, unlike other building typologies, climatic variability becomes particularly important due to the nature of the occupants of the building which need to have a continuous operation while maintaining prescribed indoor temperature and humidity conditions, ventilation rates, filtration levels and pressure relationships appropriate to the healthcare spaces for patient safety, infection control, and uninterrupted medical functioning.

Climate has strong impact on Healthcare facilities beyond occupant comfort. Buildings in Warm Humid climates the latent cooling loads are high, in hot dry climates excessive solar heat gain and dust infiltration is a major concern. Composite climates present seasonal variations that demand adaptable building responses, while cold regions

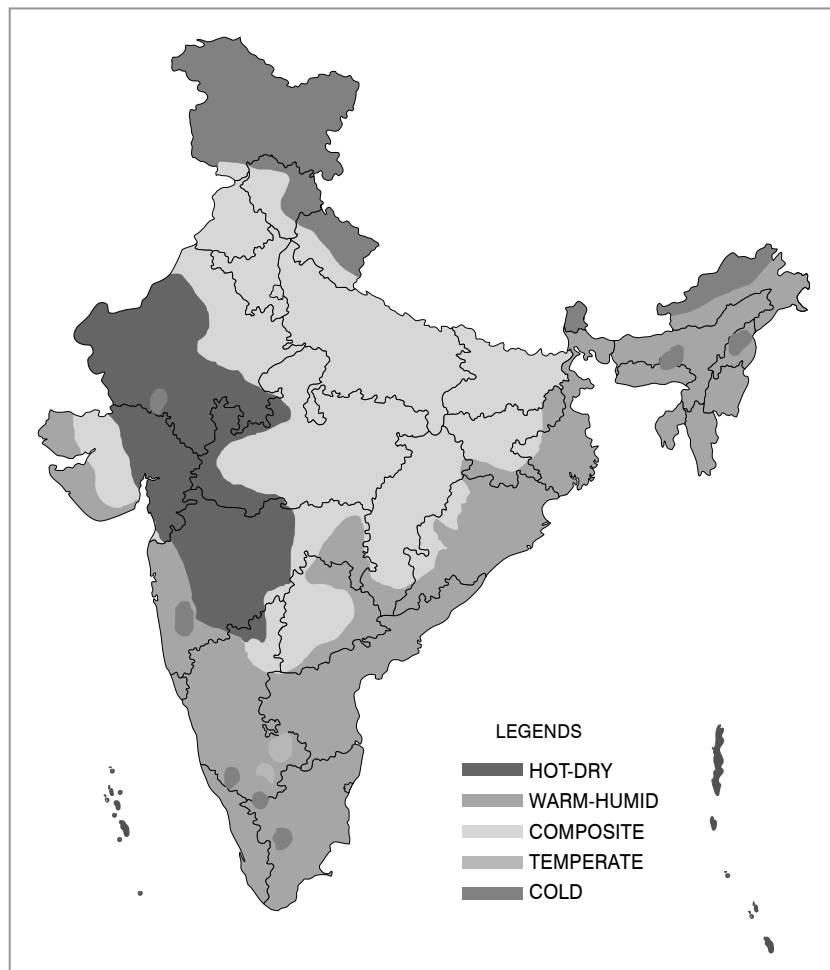


Figure 1: Climatic Zone Map of India (Source: ECBC)

experience heat-loss-related inefficiencies and condensation risks.

These climatic conditions influence conductive and solar heat transfer, air and moisture infiltration, vapour transport and the potential for surface or interstitial condensation through the building envelope.

With the increase in penetration of healthcare facilities across these diverse climatic regions building envelopes need to be more climate responsive alongwith maintaining prescribed indoor environmental conditions, operational efficiency, and long-term resilience.

1.2 Role of HVAC Systems in Healthcare Environments

Heating, Ventilation, and Air-Conditioning (HVAC) systems are critical to the functioning of healthcare facilities from a perspective of maintaining controlled indoor environments for the wellbeing and catalysing the health improvement of the occupants. The important functions comprise of temperature regulation, humidity control, ventilation, pressure management, and filtration of airborne contaminants. These functions support infection prevention and control, appropriate patient recovery conditions, occupant comfort and staff safety.

Guidelines issued by World Health Organisation identifies ventilation and environmental management as important components of infection prevention strategies in healthcare facilities (WHO, 2009). Similarly, ASHRAE standards provide guidance for ventilation, filtration, and humidity management in hospitals and healthcare environments (ASHRAE 170, 2025) .

Healthcare HVAC systems differ significantly from conventional comfort-conditioning systems. Critical spaces such as operation theatres, ICUs, isolation rooms, and certain diagnostic areas may have specific requirements for ventilation rates, filtration, temperature and humidity control, and pressure relationships depending upon their function.

Interestingly the efficiency and effectiveness of HVAC systems are strongly influenced by the performance of the building envelope. Excessive external heat gain, uncontrolled infiltration, and moisture ingress increases the load on HVAC systems, forcing them to continuously compensate for unstable external conditions.

1.3 Limitations of Active First Design approach

Electromechanical systems have traditionally been relied upon to maintain indoor environmental conditions and often compensate for envelope deficiencies through increased cooling, dehumidification and ventilation loads.

With the HVAC system left solely to defend, there are limitations which are bound to seep in which prevents the whole ecosystem from delivering the designed outputs.

Air-Conditioning System Oversizing Due to Envelope Deficiencies – Poorly insulated and inadequately sealed envelopes can result in increased conductive and solar heat gains and uncontrolled air infiltration, thereby increasing sensible and latent cooling loads. Designers, in a bid to offset these deficiencies, tend to oversize system capacities, leading to higher CAPEX and OPEX, especially under part-load operating conditions, often at the cost of stable humidity control in critical healthcare spaces.

Challenges in Maintaining Indoor Humidity and Moisture Control – Particularly in Warm-Humid climates moisture ingress through walls, roofs and poorly sealed joints lead to surface condensation creating a conducive environment for microbial growth affecting the IAQ and increasing concerns related to hygiene, contamination and hospital-acquired infections (HAIs).

These limitations highlight the need to examine the role of the building envelope in governing indoor environmental conditions and reducing external thermal and moisture stress on healthcare facilities.

1.4 Role of the Building Envelope in Healthcare Performance

The building envelope acts as the primary interface between outdoor climatic variability

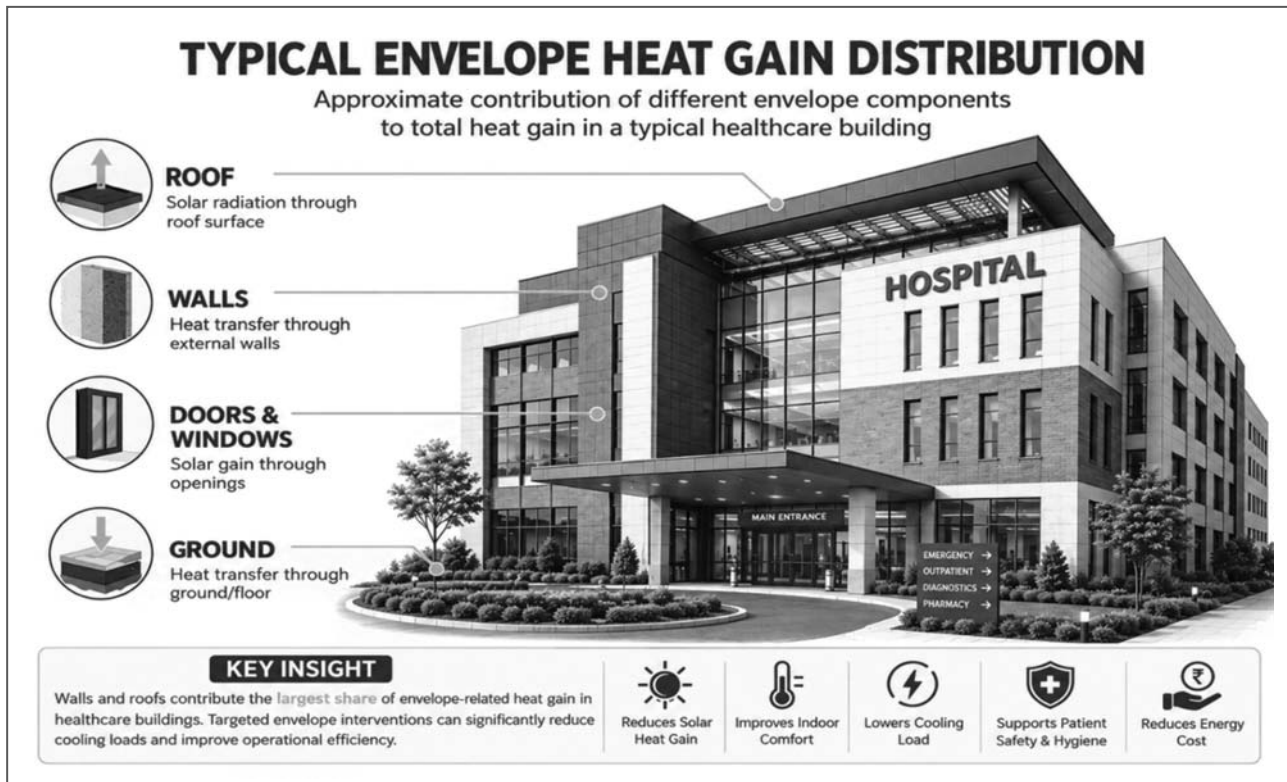


Figure 2: Typical Heat Gain distribution in a Building Envelope.

and controlled indoor healthcare environments. Its performance influences heat transfer, air infiltration, moisture ingress and vapour movement, all of which affect the magnitude and variability of the loads handled by HVAC systems. In healthcare facilities, where prescribed indoor temperature, relative humidity (RH), ventilation and pressure relationships must be maintained continuously, envelope performance becomes an important contributor to environmental stability.

In Healthcare facilities, roofs, external walls, windows and other openings can constitute significant pathways for external heat gain or heat loss. Their relative contribution depends on climatic conditions, building geometry and orientation, window-to-wall ratio, glazing and shading characteristics, and the thermal performance of the respective envelope components.

This makes envelope performance a critical factor not only in determining HVAC loads but also in sustaining environmental stability within critical healthcare spaces such as operating theatres, intensive care units, protective environments and isolation rooms. Stable temperature, relative humidity and pressure conditions are fundamental to infection-control strategies and occupant wellbeing.

Thus, a high-performance envelope can therefore reduce conductive, solar and infiltration-related loads while limiting unwanted moisture transfer through the building enclosure. By reducing these external stresses, HVAC systems can operate under more predictable conditions and more effectively maintain the temperature, relative humidity (RH), ventilation and air-quality requirements associated with healthcare environments.

These outcomes establish the building envelope as a critical component of healthcare environmental performance rather than merely an architectural enclosure.

1.5 Passive-First Healthcare Design Approach

This white paper proposes a passive-first healthcare design approach wherein the building envelope acts as the first line of defence against external thermal and moisture loads, enabling

the HVAC systems to maintain the required indoor environmental conditions more efficiently and reliably.

Passive envelope systems can reduce external thermal, and moisture loads before they enter conditioned spaces, with the remaining loads being addressed by the HVAC systems. Reductions in heat gain, uncontrolled infiltration and moisture ingress can reduce both sensible and latent load variability, enabling HVAC systems to focus on maintaining prescribed indoor environmental conditions rather than continuously compensating for avoidable envelope-related loads.

Properly designed envelope assemblies incorporating continuous insulation and moisture-management provisions can help reduce condensation potential and support environmental stability within healthcare facilities.

The passive-first approach is based on three key approaches:

- Minimise the external thermal and moisture stress before it reaches occupied spaces.
- Optimise the HVAC systems based on the reduced thermal and moisture stress.
- Utilise the HVAC systems to maintain controlled conditions rather than continuously offsetting uncontrolled external loads.

This approach shifts from the conventional design philosophy to a new approach wherein the passive system establishes the baseline, and the active system optimise the indoor conditions.

By focussing on passive envelope interventions, healthcare facilities can improve environmental stability, reduce the potential for uncontrolled moisture accumulation and support more consistent HVAC operation. These outcomes can assist in maintaining prescribed indoor temperature, relative humidity and air-quality conditions while also reducing avoidable energy demand and lifecycle operating costs.

Such an approach becomes increasingly relevant in climate-diverse regions where Healthcare facilities are expected to maintain operational stability under continuously varying environmental conditions.

Chapter 2: Climate Responsive Passive Envelope Strategies for Healthcare facilities

2.1 Climate as a Determinant of Healthcare Building Performance

Healthcare facilities are particularly sensitive to climatic conditions because they must continuously maintain prescribed indoor environmental parameters regardless of outdoor weather conditions. Unlike many commercial buildings, hospitals contain spaces with specific temperature, relative humidity, ventilation, filtration and pressure-control requirements that support patient care, infection prevention and uninterrupted clinical operations.

Liu et al. (2017) demonstrated that moisture migration, condensation behaviour and thermal transport within building-envelope assemblies are closely interrelated and can significantly influence the thermal performance of the envelope and the heat-transfer loads imposed on conditioned spaces. These interactions become particularly relevant in healthcare facilities where HVAC systems are required to maintain prescribed indoor environmental conditions continuously.

Since different climatic conditions create their own version of challenges, we cannot generalise the passive measures and performance benchmarks, across all these regions. Failure to identify and address these envelope-climate interactions can force HVAC systems to operate in a compensatory mode. Uncontrolled heat and moisture transfer can increase both sensible and latent load variability, making it more challenging to maintain stable indoor relative humidity (RH), airflow conditions and pressure relationships while simultaneously increasing energy consumption.

The following tabular composition vividly puts forth climatic zone based challenges that are posed and what needs to be addressed at the design stage.

Climate Type	Primary Challenge	Failure Symptoms	Design Priority
 Warm-Humid	High latent loads, humid air infiltration and moisture ingress	Condensation, Sweating ducts, Fungal growth	Moisture control, Vapor barriers, Continuous insulation
 Hot-Dry	High solar gain, Dust infiltration	Overheating, Filter clogging, Indoor dust	Insulation, Airtightness, Reflective coatings
 Composite	Seasonal variability	Overheating, Heat loss	All-season insulation, Airtightness
 Temperate	Moderate loads	System inefficiency, Overdesign	Optimized insulation, Solar control
 Cold	Heat loss, Condensation	Thermal discomfort, Surface condensation	High Insulation, Airtightness, thermal bridge and vapour control

Figure 3: Climate Specific Design Priorities

While the nature of challenge may vary across the climatic zones, a consistent pattern can be seen : Inadequate envelope performance leads to higher loading and lower efficiencies on the HVAC system.

2.2 Passive Design Strategies in Healthcare facilities

Passive design strategies comprise architectural, planning and envelope measures that enhance indoor air quality and thermal comfort through non-mechanical means. These strategies include building orientation, climate-responsive envelope design, shading, insulation, daylight optimisation, and other measures that reduce external environmental loads and energy demand.

In healthcare facilities, these strategies may be broadly considered across site planning, solar control, ventilation, daylighting, and building-envelope design. While these are not strategies unique to Healthcare facilities, their application in healthcare requires greater attention to the function of individual spaces, infection-control requirements, operational continuity, patient safety, and the constraints associated with new construction or retrofit. The suitability of a given passive strategy must therefore be assessed in relation to the specific space and function it serves, rather than assumed to be uniformly applicable across the facility.

Passive strategies are not intended to replace HVAC systems. Rather, they complement them by reducing external thermal and moisture stresses acting on the building envelope. In healthcare facilities, this can help reduce fluctuations in building loads, allowing HVAC systems to maintain environmental-control objectives more consistently and efficiently.

Jamaludin, Ahmad, & Aziz (2019) describe passive measures as load moderators — they reduce the stress placed on HVAC systems and support building resilience during periods of climatic stress.

Heat and moisture transfer through the building envelope can significantly affect HVAC loads, indoor environmental quality, and microbial growth risk. This highlights the importance of viewing the building envelope not only as a thermal barrier but also as a key determinant of hygrothermal conditions in healthcare environments.

Each intervention addresses a distinct aspect of building performance. Orientation and external shading minimise direct solar exposure. Glazing balances daylight admission, views, privacy, and thermal performance. The wall-to-window ratio influences the amount and distribution of daylight while limiting unwanted heat transfer and glare. Insulation reduces

conductive heat transfer through walls and roofs. Reflective roof treatments limit solar heat absorption at the roof surface.

Envelope systems therefore need to be climate responsive not only for long-term durability but also for environmental stability (Silva, Henríquez, & Castro, 2023).

2.3 Comparing Passive Interventions: The Case for Envelope Focus

Healthcare facilities require a more cautious approach, as infection-control and operational requirements often determine the suitability of individual interventions. Passive interventions should therefore be evaluated not only for their energy-saving potential, but also for their influence on environmental stability, moisture management, maintainability, retrofit feasibility and their ability to support the HVAC systems responsible for maintaining healthcare-specific indoor environmental requirements.

The Intervention Priority Matrix compares commonly adopted passive strategies against healthcare-specific criteria including environmental stability, moisture-control potential, maintainability, retrofit feasibility, compatibility with infection-prevention objectives and support for HVAC environmental-control requirements.

Daylighting is a key passive-design strategy in healthcare, supporting visual comfort, circadian regulation, wellbeing, and a more therapeutic patient experience. These benefits should be balanced against glare, solar heat gain, privacy, and energy-performance considerations through measures such as appropriate wall-to-window ratios, orientation, shading, window placement, and glazing performance. Well-designed openings can provide quality daylight and restorative views while maintaining thermal, visual, and operational comfort.

Natural ventilation should be limited to areas where infection-control, ventilation, air-quality, and environmental-control requirements permit, and is generally unsuitable for highly controlled spaces such as ICUs and recovery rooms.

Evaluation Matrix for Envelope Interventions in Healthcare Buildings							
Intervention	Primary Envelope Area	Healthcare Applicability	Moisture Management	Retrofit Applicability	Maintenance Requirements	Climate Responsiveness	Overall Assessment
 Shading devices	Windows / facades	Moderate	Low	High	Moderate	Strong in hot climates	Useful in reducing solar gain
 Glazing optimization	Windows	High	Low	Moderate	Moderate	Moderate	Suitable in selected areas
 Thermal mass	Walls / floors	Moderate	Neutral	Low	High durability	Strong in temperate climates	Climate dependent
 Cavity walls	Walls	Moderate	Moderate	Low	Moderate	Strong in cold climates	Limited retrofit suitability
 Green roofs	Roofs	Moderate	Moderate	Low	High maintenance	Strong in hot-humid climates	Limited applicability in healthcare
 Ventilated facades	Facades	High	Moderate	Moderate	Moderate	Strong adaptability	Higher system complexity
 Natural ventilation	Windows / openings	Low in critical care	Low	High	High	Strong in temperate climates	Limited in infection-sensitive areas
 Reflective roofs	Roofs	High	Moderate	High	Moderate	Strong in hot-dry climates	Useful low-cost intervention
 EIFS	Walls	High	High	High	Moderate	Strong across climates	Effective wall insulation strategy
 PU Foam Spray Insulation	Roofs	High	High	Moderate	High	Strong in composite and cold climates	Effective roof insulation strategy
 Airtightness strategies	Joints / seals	High	High	Low	Moderate	Strong across climates	Important for infiltration control
Assessment Rating Guide:  Favourable (Generally suitable with normal good practice)  Moderate (Suitable with limitations or specific conditions)  Limited (Significant constraints or requires major modifications)  Not Recommended (Not suitable for healthcare buildings)							

Figure 4: Intervention Priority Matrix

Envelope-based interventions are increasingly important in healthcare infrastructure because they directly influence conductive heat transfer, solar heat gain, uncontrolled air infiltration and moisture movement. These factors affect the magnitude and stability of the loads imposed on HVAC systems, which in turn influence the ability to maintain prescribed indoor environmental conditions within healthcare facilities.

Architectural strategies such as building orientation, window placement, wall-to-window ratio, and shading complement these measures by reducing solar heat gain, supporting useful daylight, and improving overall envelope performance.

This is one of the reasons why envelope-focused passive systems receive increasing attention in healthcare infrastructure (Balali & Valipour, 2021).

Envelope-focused measures, including insulation, reflective roofs, glazing optimisation, feasible wall-to-window ratio adjustments, and airtightness improvements, can enhance thermal performance and are often practical to implement through maintenance and retrofit programmes.

While other passive strategies such as green roofs may provide additional benefits, envelope interventions offer a robust and widely applicable starting point for healthcare facilities, particularly across India's diverse climatic conditions.

For these reasons, we adopt an envelope focussed approach as the primary passive strategy for Healthcare facilities .

2.4 Core Envelope Performance Principles

The three important principles that are related to the healthcare envelope design are thermal continuity, airtightness, and vapor control.

A) Thermal Continuity

Thermal continuity refers to the state, wherein there is an alignment between all insulation layers across all envelope assemblies including walls, roofs, fenestration and importantly structural

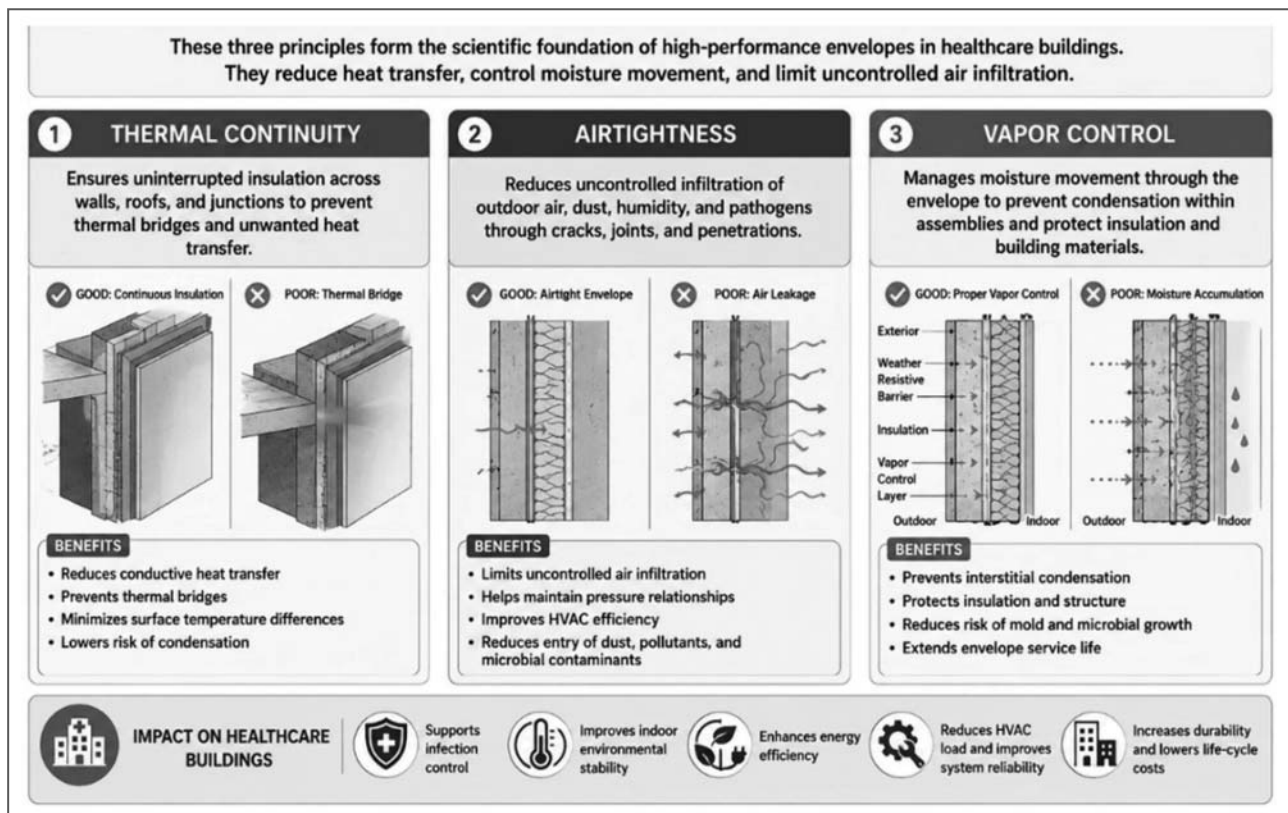


Figure 5: Core Envelope Performance Principles

junctions. Any disruption in insulation continuity creates Thermal bridges, which acts a localised pathways for heat transfer and reduces the thermal resistance of the envelope assembly. The discontinuity causes surface temperature differentials, elevates conductive heat gain /loss resulting in increased HVAC loads and can increase the risk of localised surface condensation where the surface temperature falls below the dew point temperature of the adjacent air.

In healthcare facilities, thermal stability contributes to maintaining consistent environmental conditions within patient-care spaces. Thermal bridges can create localised cold spots that increase condensation potential and place additional load on HVAC systems responsible for maintaining prescribed indoor environmental conditions.

Jiménez Mejía, Barbero-Barrera, & Rodríguez Pérez (2020) in their study on hospital building envelope have demonstrated that inadequately insulated envelope junctions influence the thermal energy demand and affect the overall building performance, especially in high cooling intensity climates.

B) Airtightness

Airtightness is the ability of the building envelope to contain uncontrolled air leakage through varied sources such as cracks, joints, penetrations and assembly interfaces. Airtightness testing determines air leakage through the building envelope by pressurising or depressurising the building to specified pressure differences and measuring the airflow required to maintain those pressure differences.

In healthcare facilities, airtightness is particularly important because uncontrolled infiltration can introduce unconditioned air, airborne particulate matter and moisture while also increasing latent cooling loads. Excessive leakage can undermine the stability of airflow patterns and pressure relationships maintained by HVAC systems in operating theatres, isolation rooms and other controlled healthcare environments.

From a building physics perspective, better airtightness results into better control over sensible and latent loads and operate under predictable airflow design conditions. Airtight envelope designs in high performance buildings contributes in a significant way towards thermal stability, ventilation effectiveness and moisture control further improving the overall HVAC operational efficiency (Lstiburek, 2013; Passivhaus Institute, 2016).

C) Vapor Control

Vapour control can be stated as a phenomenon wherein the movement of water vapour is managed through the building assembly in a way that prevents moisture accumulation and interstitial condensation within various construction layers.

A significant proportion of healthcare infrastructure in India is located within Composite and Warm-Humid climatic zones. In warm-humid climates, moisture can migrate into wall and roof assemblies through vapour diffusion and, more significantly in many cases, through air leakage. If this moisture encounters a surface or layer whose temperature is below the local dew-point temperature, interstitial or surface condensation can occur.

Continued exposure to such conditions can reduce insulation effectiveness, accelerate material deterioration and create conditions favourable for microbial growth. In healthcare facilities, where vulnerable patient populations often occupy conditioned spaces for extended durations, avoiding persistent dampness and condensation becomes important from both building-performance and indoor environmental quality perspectives.

To ensure effective vapor control, strategies can include climate responsive selection of vapor retarders, air barriers and moisture tolerant materials to regulate the hygrothermal behaviour in an integrated envelope assembly. ASHRAE guidance on damp buildings and moisture management identifies inadequate vapor and moisture control as a major contributor to Mold proliferation and occupant health risks, particularly in healthcare environments housing vulnerable patient populations (ASHRAE 2020,Damp Buildings, Human Health, and HVAC Design.fm)

2.5 Key Passive Envelope Interventions

Healthcare facilities require envelope solutions that improve thermal comfort, thermal performance and moisture control while accommodating continuous operation, stringent indoor environmental requirements, maintenance constraints, and, in many cases, retrofit conditions. Several passive strategies exist, but their applicability may be limited by maintenance requirements, operational constraints, or retrofit complexity.

The interventions discussed in this section are presented as representative examples of envelope-based strategies rather than as an exhaustive or preferential selection of technologies. Their suitability depends on climatic zone, existing construction, building orientation, occupancy and operational requirements, constructability, maintenance provisions, and lifecycle performance.

EIFS, spray-applied PU foam insulation, and high-SRI reflective roof coatings are examined here as illustrative examples of how continuous insulation, seamless application, and solar-reflective finishes can address different heat-gain pathways within the building envelope. Respectively, these interventions target heat transfer through external walls, roofs, and solar-radiation absorption at roof surfaces. They are not the only available solutions, and each involves specific benefits, limitations, and implementation considerations.

A. Exterior Insulation and Finish Systems (EIFS)

Exterior Insulation and Finish Systems (EIFS) is multi-layer external wall assemblies consisting of adhesive and/or mechanical fixings, insulation boards, reinforcing mesh, base coat, and protective finish. By providing a continuous insulation layer across columns, beams, slab edges, and infill walls, EIFS reduces thermal bridging at envelope junctions, thereby limiting conductive heat transfer and internal surface-temperature variations.

Mejia et al. (2020) reported that discontinuities in insulation increase thermal energy demand and reduce operational efficiency in Healthcare facilities, highlighting the importance of continuous thermal-control layers.

The application of EIFS is particularly relevant in reinforced-concrete Healthcare facilities, where structural elements often create thermal bridges. By improving insulation continuity and reducing localised surface-temperature variations, EIFS can help lower the potential for condensation formation at envelope junctions while contributing to more stable indoor environmental conditions.

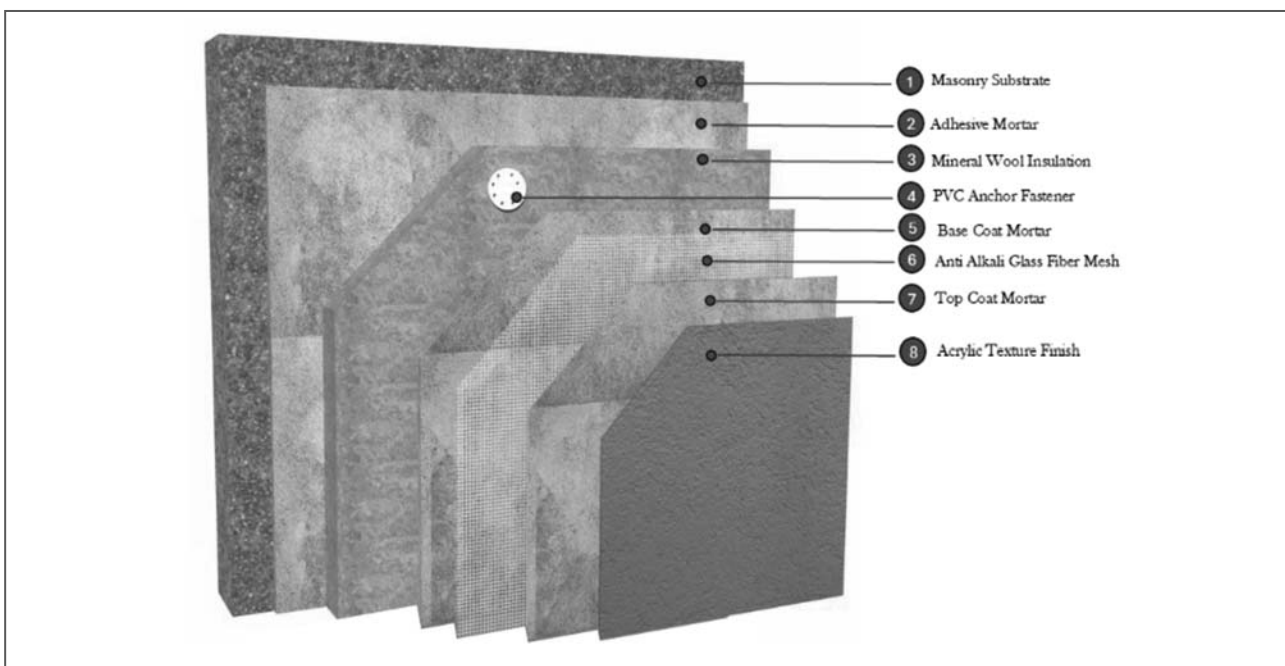


Figure 6: Typical cross sectional layout of EIFS.

In hot-dry, warm-humid, and composite climates, continuous external insulation helps reduce solar heat gains, while in colder climates it minimises heat loss. As EIFS is installed primarily from the exterior, it can be suitable for retrofit projects with limited disruption to occupied clinical spaces.

The effectiveness of EIFS depends on proper detailing at openings, penetrations, and junctions, together with adequate moisture management, drainage, and finish durability. Additionally, the system offers relatively low dead loads, faster installation than masonry-based façade alternatives, and flexibility in architectural appearance through a range of finishes and textures. Consequently, EIFS can support both thermal performance improvements and façade rehabilitation in Healthcare facilities when appropriately designed and detailed.

Limitations: EIFS increases the overall thickness of the external wall assembly and requires skilled applicators for proper installation. Installation may be constrained during periods of heavy rain or snow, while improper detailing at joints, openings, and penetrations can adversely affect system durability and long-term performance.

B. Spray-Applied Polyurethane (PU) Foam Insulation

Spray-applied polyurethane (PU) foam insulation is applied directly on the roof surface after the waterproofing coat is done, forming a continuous insulation layer with minimal joints and good adherence to the substrate thus eliminating the lateral movement of water below the insulation. This seamless application can help reduce thermal bridging, air leakage, and potential pathways for moisture movement when compared with segmented insulation systems. PU foam typically exhibits low thermal conductivity, allowing high thermal resistance to be achieved at relatively modest thicknesses.

The thermal performance of PU foam depends on factors such as formulation, density, thickness, installation quality, and the characteristics of the overall roof assembly. Closed-cell PU foam can also provide resistance to moisture ingress and vapour diffusion; however, it should not replace appropriate waterproofing, roof drainage, or vapour-control measures where these are required.

Its ability to conform to irregular roof geometries makes spray-applied PU foam particularly suitable for retrofit applications in healthcare facilities where operational disruption must be minimised. By reducing heat transfer through the roof assembly, it can contribute to more stable indoor conditions and reduce thermal loads on HVAC systems serving occupied healthcare spaces.

In warm-humid and hot-dry climates, PU foam insulation may be combined with reflective roof coatings to reduce solar heat absorption and cooling loads. In colder climates, it can help limit heat loss and maintain more stable internal surface temperatures. The required insulation thickness

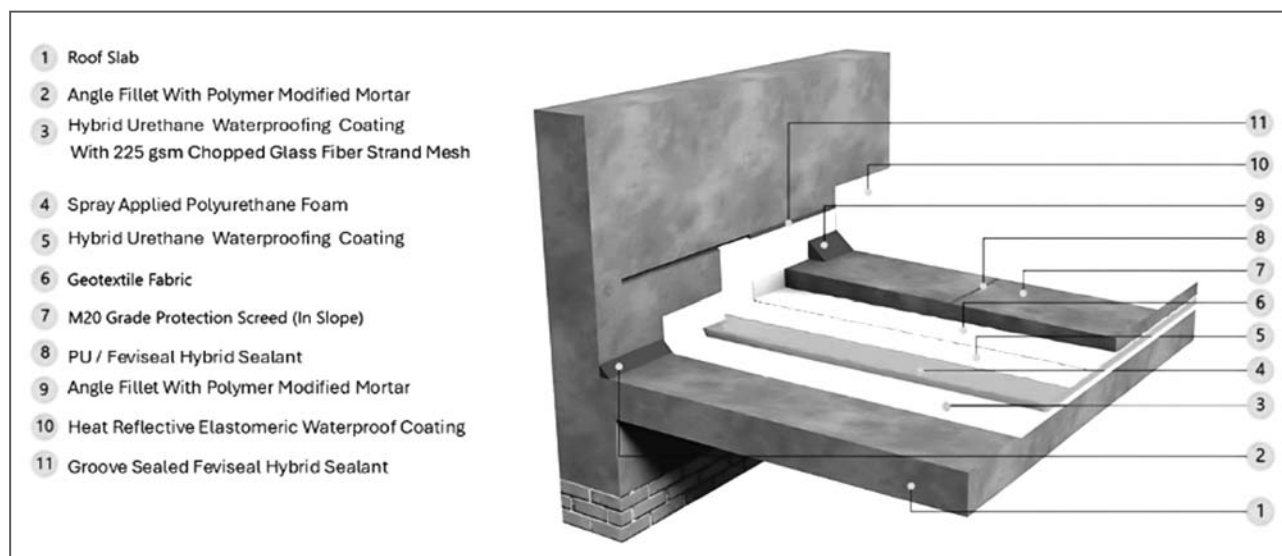


Figure 7: Typical cross sectional layout of PU Spray Foam Insulation system

should be determined through climate-specific thermal calculations and relevant energy-code requirements rather than adopting a standard value.

Limitations: PU foam is susceptible to UV degradation and therefore requires a protective topcoat. Its performance is highly dependent on correct installation by trained applicators, as poor application can compromise thermal performance. Fire-performance considerations should be evaluated at the roof-assembly level in accordance with applicable codes and project requirements. In many healthcare roof applications, the insulation is installed above the structural roof slab and protected by screeds, coatings or other roofing components, and therefore its performance should be assessed as part of the complete roof assembly rather than in isolation.

C. Reflective Roof Coatings

Reflective roof coatings are designed to reduce solar heat gain by providing high solar reflectance and thermal emittance, thereby limiting roof surface temperature rise and reducing heat absorption by the building envelope. Unlike thermal insulation, which primarily reduces conductive heat transfer, reflective coatings act by decreasing the amount of solar radiation absorbed at the roof surface. Their effectiveness depends on factors such as solar exposure, roof construction, coating properties, existing insulation levels, surface condition, and local climate.

Many reflective coating systems can also provide weatherproofing and surface protection when incorporated into a compatible roof assembly. Their relatively simple application and low additional structural load make them particularly suitable for retrofit projects where operational disruption must be minimised. Reflective coatings can be applied to a variety of roof substrates, including concrete and metal roofs and may therefore be suitable for ancillary healthcare facilities such as administrative buildings, residential quarters, storage facilities, and service buildings.

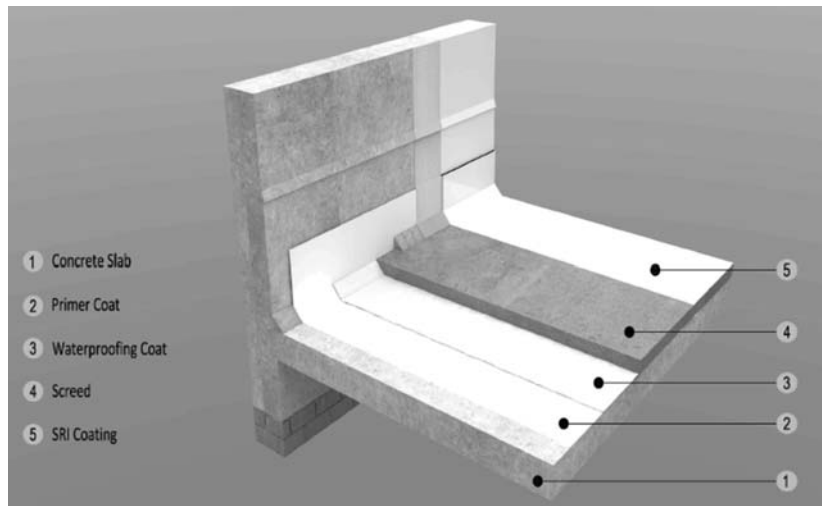


Figure 8: Typical cross sectional layout of Reflective Roof Coating

In hot climates, reflective roof coatings can contribute to lower roof surface temperatures and reduced cooling demand, particularly when combined with adequate roof insulation. However, long-term performance may be influenced by weathering, soiling, ultraviolet exposure, and maintenance practices. Regular inspection and maintenance are therefore important to preserve the coating's reflective and protective properties over its service life.

Limitations: Reflectivity declines with dust accumulation and weathering and requires periodic cleaning to sustain performance — a maintenance dependency that field studies note is often overlooked after installation.

Together, these three interventions illustrate complementary approaches to reducing conductive and solar heat gain through walls and roofs; all three are broadly compatible with ECSBC, IGBC, and GRIHA envelope performance criteria, though compliance depends on project-specific U-value and SRI targets rather than the material choice alone.

2.6 Alignment with Codes, Standards and Sustainability Frameworks

Passive first aligns well with the fundamental principles embodied in national and international building codes, healthcare guidelines and green rating frameworks. All these codes reiterate the

need for high-performance building envelopes as an underlying strategy to support environmental stability, moisture control, occupant wellbeing, energy efficiency and long-term operational performance in healthcare facilities.

The following set of codes, standards and sustainability frameworks work synergistically to make building envelopes more energy-efficient and support occupant safety.

Table 1: Standards and Framework Alignment Table

Sr. No.	Code / Standard / Framework	Relevant Clause / Reference	Compliance / Alignment
1	ASHRAE Advanced Energy Design Guide (AEDG)	Building Envelope Chapter	Recommends improved opaque-envelope performance through measures such as appropriate insulation, reduction of thermal bridging and solar heat-gain control. EIFS, PU insulation and reflective roof systems may be among the methods used to achieve these objectives where appropriate.
2	ASHRAE Damp Buildings Report (2020)	Summary and Recommendations; Health-Relevant Indoor Dampness; Quantitative Metrics; Structural Risk	ASHRAE describes it as summarizing dampness-related health risks, identifying symptoms, and suggesting monitoring instruments and threshold values that can provide early warning.
3	ASHRAE Handbook—Fundamentals, 2021, Chapter 36: Moisture Management in Buildings.	Chapter 25: Heat, Air, and Moisture Control in Building Assemblies; Chapter 36: Moisture Management in Buildings	Provides technical foundation linking insulation strategies in building envelopes with moisture management and condensation prevention. Supports thermal continuity, airtightness, and vapor control to reduce microbial growth risks.
4	ASHRAE Positions on LIMITING INDOOR MOLD AND DAMPNESS IN BUILDINGS (originally approved in 2021 and reaffirmed in October 2024)	The report states the importance of limiting moisture accumulation and avoiding condensation not only inside the building but also inside the assemblies of its exterior walls, foundation, and roof.	Requires integrated envelope insulation and moisture management to support integrated control of heat, air and moisture through appropriate envelope design to limit moisture accumulation, condensation, dampness and associated microbial growth.
5	ASHRAE Standard 90.1	Building Envelope Requirements	Promotes high-performance building envelopes through continuous insulation and reduced heat transfer, thereby lowering HVAC energy consumption.
6	Energy Conservation and Sustainability Building Code (ECSBC)	Chapter 5.3.1 & 5.3.2	Prescribes maximum assembly U-factors for roofs and opaque external walls. Insulation systems such as EIFS or appropriate roof insulation can contribute to meeting U-factor requirements. Cool-roof/high-SRI treatments may separately contribute towards applicable cool-roof requirements through solar reflectance and thermal emittance.
7	GRIHA Version 6	Table 7.1(c)	Specifies threshold limits for Peak Heat Gain with reference to ECBC/ECSBC.
8	IGBC Green Healthcare Rating System	Whole Building Simulation; Prescriptive Approach	Whole Building Simulation prescribed the U-values of insulated roofs and walls, while the Prescriptive Approach requires compliance with ECBC/ECSBC and ASHRAE 90.1 envelope provisions.
9	National Building Construction Standards 2026	Building Typology Related Considerations; Section 12.1.2; Clause 17.3.14.7	NBCS 2026 includes over-deck sprayed polyurethane foam (PUF) as one of the permitted roof insulation systems, subject to specified material and installation requirements.
10	World Health Organisation (WHO) Healthcare Ventilation Guidance (2009)	Part 2 – Section 5.3.8: Humidity and mould growth	Provides climate-responsive building guidance for naturally ventilated healthcare spaces, including the use of lightweight and insulated walls in hot-humid climates.

All these guidelines converge on a common premise that high-performance building envelopes support environmental stability, moisture control and energy efficiency, thereby contributing to more resilient and sustainable healthcare facilities.

2.7 Recommendations for Healthcare Designers and Owners

The core theme of the paper is that external thermal and moisture loads should be addressed at source through passive envelope measures so that healthcare facilities can maintain prescribed indoor environmental conditions more effectively and efficiently.

Healthcare designers and owners, must ensure that envelope optimisation is embedded in every stage of project, this will translate the passive design intents into actionable outcomes.

The adoption of appropriate envelope technologies, including measures such as EIFS, roof insulation systems and reflective roof treatments where technically suitable, can contribute to lower lifecycle costs and improved environmental performance.

The following recommendations provide a pathway for healthcare facilities to deliver sustainable performance across diverse climatic conditions.

1. Adopt a Passive-First approach by integrating envelope optimisation during the conceptual design stage of healthcare projects.
2. Optimise the building envelope before finalising HVAC system sizing to reduce avoidable heating and cooling loads and improve overall system efficiency, while meeting the ventilation, pressurisation and other environmental requirements of healthcare spaces.
3. Select climate-responsive wall and roof assemblies that comply with ECSBC, NBC, and other applicable standards.
4. Incorporate continuous insulation systems for walls and roofs, along with appropriate cool roof technologies, wherever technically feasible.
5. Undertake whole-building energy simulation to evaluate the combined performance of the building envelope and HVAC systems during design.
6. Evaluate design alternatives using lifecycle cost analysis (LCCA) rather than first-cost considerations alone.
7. Strengthen awareness and technical capacity among architects, MEP consultants, developers, contractors, and facility managers regarding passive envelope technologies.
8. Support pilot projects, performance monitoring, and post-occupancy evaluations to strengthen the evidence base for passive envelope strategies in healthcare facilities.
9. Foster interdisciplinary collaboration among architects, building envelope specialists, HVAC consultants, and healthcare planners to deliver integrated, high-performance Healthcare facilities .
10. Incorporate envelope commissioning and performance verification, including inspection/testing of insulation continuity, air-barrier integrity, moisture-control detailing and critical envelope interfaces, confirming the building envelope actually achieves its design intent, since a leaking joint or a penetration may be far costlier and disruptive to fix post-handover, particularly considering the critical healthcare facilities where system shutdowns could interrupt essential operations

Conclusion

Healthcare facilities require strict IAQ control, energy efficient electromechanical systems and importantly and thermally resilient design considerations. This white paper demonstrates that maintaining healthcare environments requires more than efficient HVAC systems alone. By reducing external thermal, air-infiltration and moisture-related stresses at the building envelope, healthcare facilities can create conditions that allow HVAC systems to maintain prescribed indoor temperature, relative humidity, ventilation and air-quality requirements more effectively. The resulting benefits extend beyond energy performance to include enhanced environmental stability, reduced

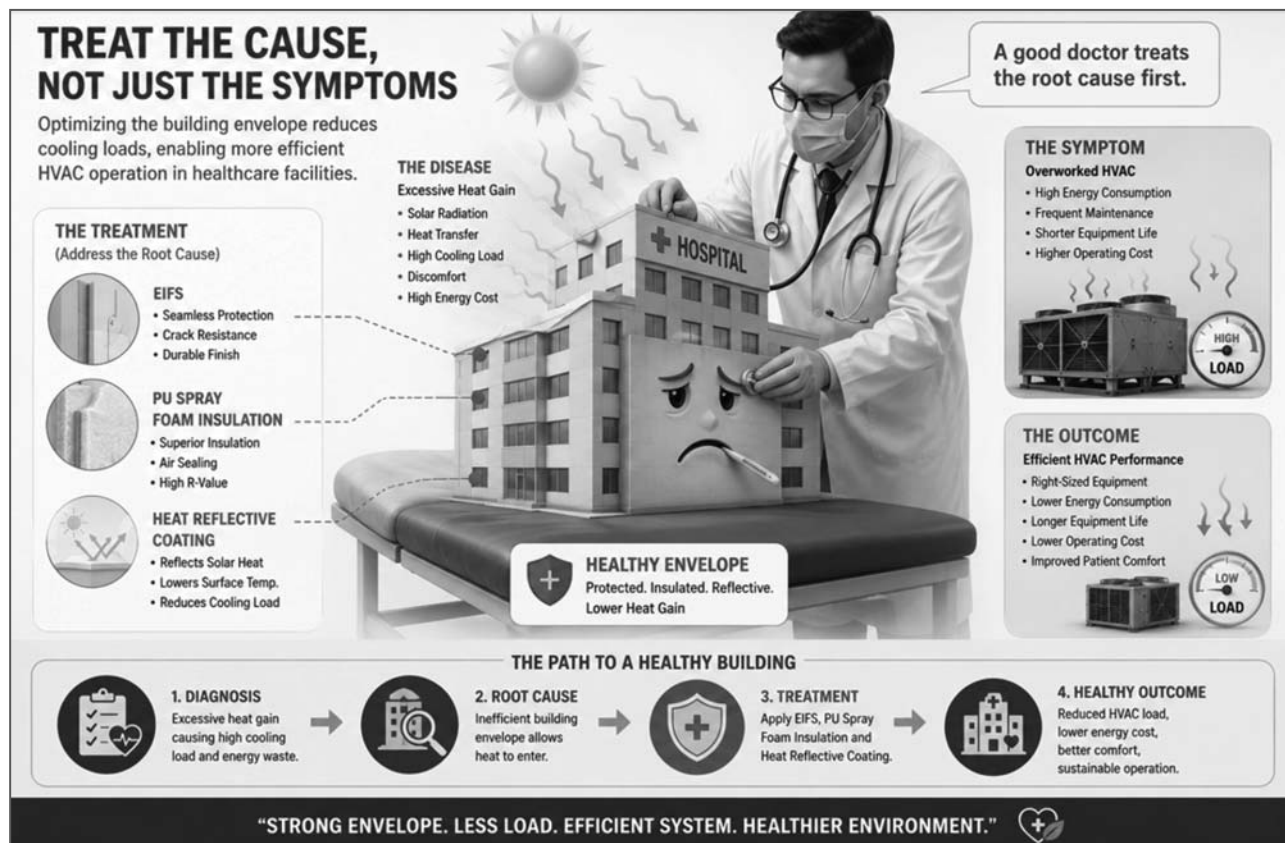


Figure 9: Pathway to Healthy Building

moisture-related risks and improved operational resilience for healthcare facilities operating across diverse climatic conditions.

Passive envelope measures such as Exterior Insulation and Finish Systems (EIFS), spray polyurethane foam insulation and reflective roof treatments can help reduce external thermal and moisture stresses acting on healthcare facilities. By limiting unwanted heat transfer, infiltration and condensation potential, these measures can support more stable indoor environmental conditions and enable HVAC systems to maintain prescribed temperature, relative humidity (RH), ventilation and air-quality requirements more effectively.

With healthcare infrastructure expanding across diverse climatic regions of India, climate-responsive envelope strategies should be integrated into healthcare planning, design and facility-management practices. To improve the long-term sustainability and resilience of healthcare facilities, it is important to address avoidable thermal, and moisture loads at the building-envelope level before relying on mechanical systems. Reducing these external stresses can support more effective environmental control, lower moisture-related risks and improved operational stability throughout the facility lifecycle.

The Passive-First, Active-Next approach highlights the importance of addressing thermal, air-infiltration and moisture-related loads at the building-envelope level before they reach occupied healthcare spaces. By reducing these external stresses, the building envelope enables HVAC systems to operate under more stable and predictable conditions while maintaining prescribed indoor environmental requirements. The resulting benefits extend beyond energy efficiency to include improved indoor air quality, controlled relative humidity, reduced condensation risk, enhanced environmental stability and greater operational resilience. The greatest benefits are achieved when passive envelope measures and HVAC design are considered as an integrated strategy from the earliest stages of healthcare facility planning and design.

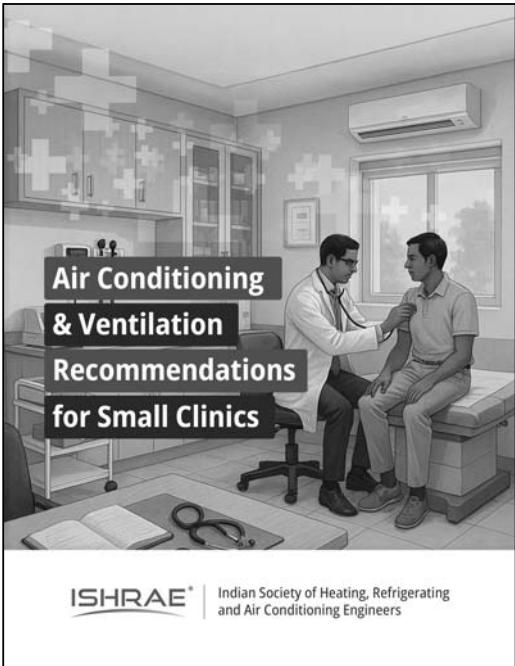
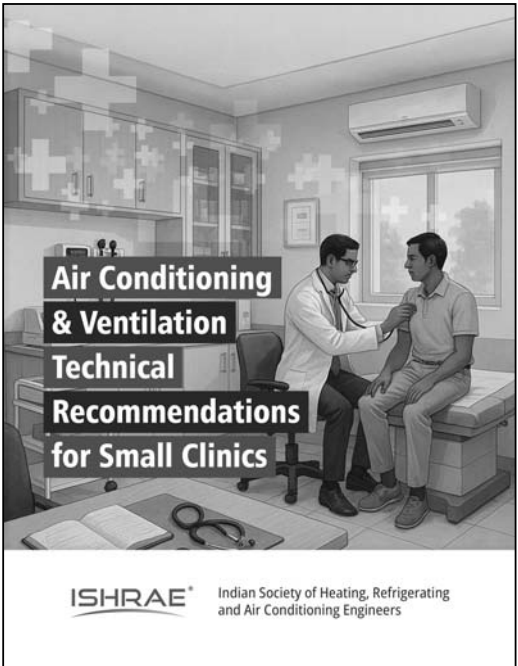
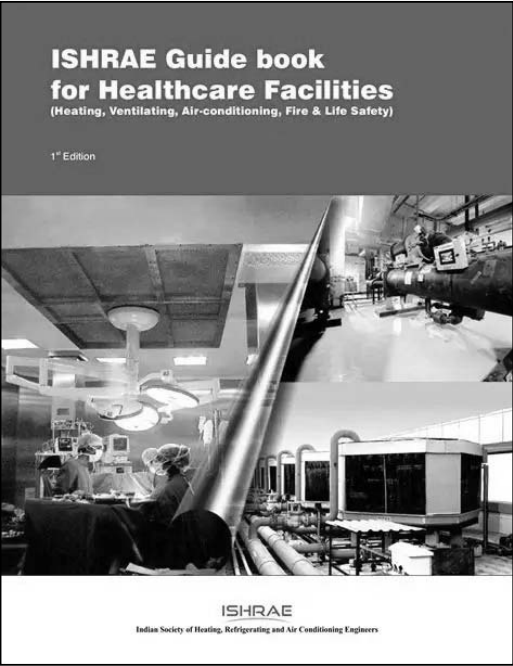
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