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Review Article

Oxygen generation and delivery: Start to end

Ravneet Kaur Gill[1], Puja Saxena[1*], Ashwani Mudgil[2], Agrawal Kavita Khemchand[3], Roli Saxena[4]

[1] *Dept. of Anaesthesia, Dr B R Ambedkar State Institute of Medical Sciences, Mohali, Punjab, India*
[2] *Dept. of Orthopaedics, Civil Hospital, Ambala Cantt, Haryana, India*
[3] *Dept. of General Surgery, Dr B R Ambedkar State Institute of Medical Sciences, Mohali, Punjab, India*
[4] *Dept. of Biochemistry, Kalpana Chawla Medical College, Karnal, Haryana, India*

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ABSTRACT

Oxygen is vital for our life. In hospitals, the medical team should also have knowledge of its generation and how it ends till it is ready for consumption at the patient end. Various oxygen generation plants like pressure swing adsorption (PSA) plants, Liquid medical oxygen plant are available at every medical institute but basic technical knowledge holds importance. Medical gas pipeline system is a well designed network spread through out the hospitals which boost life in the patients but utmost handling and care of these necessitates regular check and audits to that every point of the system provides maximum usage with minimum leakage. **Key Messages:** (Provide appropriate messages of about 35-50 words to be printed in centre box): Oxygen is the very basis for survival of the patients. Careful planning and knowledge is the essential requirement. Why is it important is well known, but how and whats of the oxygen generation plants is the need of the hour.

1. Introduction

Oxygen, just one word but it lays down the very existence of human life. Deficiency or even excess of it can have fatal consequences. Medical oxygen is essential in sustaining life which had been very aptly emphasized during the Covid 19 pandemic. The burden faced by the medical infrastructure during the second wave that hit India in April 2021, exposed our preparation and the deficiencies. Oxygen which was considered a basic medicine became the most sought after. This issue was more highlighted in resource deficient countries where demand surpassed the supply. It was even present before the pandemic era, which was emphasised by Meara et al in 2015.[1] The medical gas supply system mainly involves delivery of oxygen, nitrous oxide and air to bedside of the patient. Out of which, oxygen is the most utilized. Medical grade oxygen which is supplied, is 99.5% pure without any contaminants.[2] It is essentially life saving in critical areas like ICU, emergency wards, operation theaters but it is also substantially used in indoor wards. But the proper utilization requires in depth knowledge starting from the source, its delivery and its consumption at the patient end. What, how, when and why shall be all be answered before starting the oxygen therapy. As pointed out by Heuer et al., 3 P's must be considered; purpose, Patient and Performance.[3]

2. Learning Objective

The objective of this review is to provide information related to production, storage, transport and delivery of oxygen to bed side of the patients. The safety measures will also be

* *Corresponding author*.
E-mail address: puja.saxena36@gmail.com (P. Saxena).

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addressed.

In this review, we aim to understand the process right from the beginning to the end.

3. Oxygen Generation

Oxygen is present in concentration of 21% in our atmosphere but medical oxygen needs to be 99% pure, odourless, free from any contaminants. Oxygen is separated from the atmospheric air either using fractional distillation or by adsorption. The main sources of medical oxygen in a medical facility are pressure swing adsorption (PSA) plant, liquid medical oxygen tanks,oxygen concentrators, prefilled cylinders.

3.1. Pressure swing adsorption (PSA) plants

Pressure swing adsorption technology had gained momentum in the pandemic. PSA technology has been operational since many decades but the pandemic highlighted it when there was scarcity of medical oxygen cylinders.

Both oxygen concentrators and PSA plants work on the same technology.

The first patent application where PSA technology was described, was presented by Charles Skarstrom in 1960 which was for oxygen enrichment.[4] Since then it has gone under various modifications but the basic principle remains the same.

PSA technology uses adsorbent materials which are porous solids, preferably having a large surface area per unit mass which are usually shaped as spherical pellets. The use of high pressure (usually 4-8 bar) with swing technology (twin vessel in which one pressurizes, other one depressurizes) and adsorption (with molecular zeolite which is a porous mineral with aluminium and silicon as its constituents) is the basic principle which produces oxygen as the end product. Based on this repetitive cycle, the so called Skarstorm cycle has four phases: feed, evacuation, purge and pressurization.[5]

This oxygen which is about 90-94% in purity is then connected to the medical gas pipeline system through the manifold control and provides oxygen to the bedside of the patient. Although they are utilised in various industries like metallurgy, glass and chemical industries, fish farming, ozone generation, they have gained popularity for medical grade oxygen generation also.

Vacuum type PSA plants was another modification over the conventional PSA which was introduced by Guerin de Montgareuil and Domine.[6] Zeolite is the adsorbent here also for separating oxygen and nitrogen. Instead of a air compressor as in a conventional PSA plant, VSA plant uses a vacuum blower. It is more energy efficient and produces oxygen at ambient pressure; which is why they need a high pressure oxygen compressor to boost and maintain the pressure required in MGPS of the hospital. It can be utilised at high altitudes also but is more expensive than PSA plant for initial setup.

A conventional PSA plant typically consists of an air compressor, dryer, filters, dual separation chambers, a reservoir, and control panel.[7] (Figure 1)

Figure 1: Conventional PSA plant

The control panel is the most important interface which is handled by the technical team on site. (Figure 2) The display may show:

1. Oxygen concentration(%)
2. Oxygen production per hour
3. Output pressure
4. Hours of operation
5. Any maintenance need

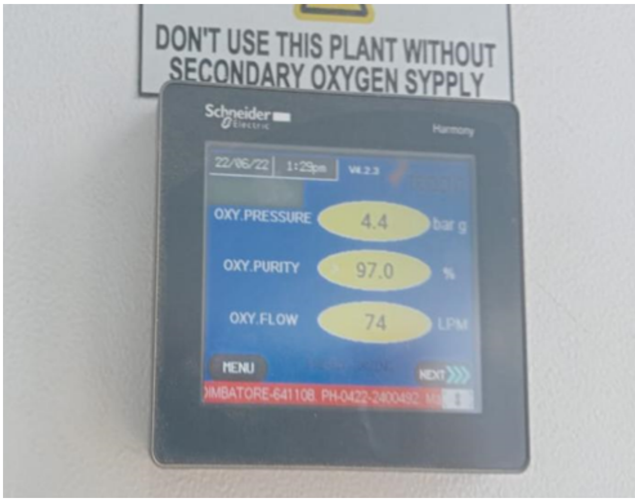

Figure 2: Control panel

Another important aspect is of audio- visual alarms. Various alarms which are present are for:

1. High temperature;
2. Low/high pressure;
3. Low oxygen concentration (<90%);
4. Power failure;
5. System failure;
6. Second/reserve source active;
7. Air dryer pressure dew point (>3°C)

PSA plants can vary in production capacity. Most of the plants generate in capacity of 500-1000 litre per minute (LPM). But they can be smaller also producing 45 (LPM). Todur et al.[8] had calculated that for 100 patients, a PSA plant of 1 ton capacity (7,00,000 gaseous O2) is sufficient, if the requirement of each patient is on an average of 5 L/min. But as the requirement increases especially in critical areas where non invasive ventilation (NIV), invasive ventilators, high flow nasal cannula (HFNC), non rebreathing mask (NRM) are used, increased production is required to meet the demands. Johnson etal has calculated that approximately, the NIV mode of ventilation consumes 40-50 LPM, which amounts to 67-84 L of liquid oxygen (57,600-72,000 gaseous O2) per day per patient.[9]

During the pandemic, when the supply was not able to meet the demands, oxygen was judiciously utilised. For optimum usage, India's Ministry of Health and Family Welfare had fixed the maximum limit for oxygen supply to 40 L/min for an intensive care bed and 15 L/min for a regular bed.[10] With the help of the above calculations, requirement of any particular medical facility can be done.[10,11] For example, in our hospital with 250 oxygen beds and 30 intensive care beds, if all are occupied, the maximum requirement of oxygen is:

Total oxygen required =(No. of beds x Flow rate for ICU beds)+(No. of beds x Flow rate for regular beds)=(30×40 L/min × 60)+(250 × 15 L/min × 60)=2,97,000 L/h.

Normally, this isn't the scenario and the calculations help to carefully audit the oxygen consumption. But during Covid 19 peak, various hospitals faced scarcity to provide oxygen to every patient as the distribution was there but not met with adequate production and storage.

This emphasized our short comings and urged the National medical commission to direct every medical college to equip their oxygen supply with PSA plants in addition to the liquid medical oxygen tank within the next 6 months. These PSA plants shall act as an additional production and storage facility to meet the exponential high demand (if such situation arises again).

3.1.1. Advantages of PSA plants

1. Raw material is atmospheric air which is abundantly available.
2. Clean technology.
3. Provides continuous supply of medical grade oxygen with concentration of 90-95%.
4. Requires an open space, only with a platform.
5. Can be used for 10 years easily. Once installed can be used for oxygen utilization.
6. Refilling of oxygen cylinders can be done using booster compressor, hence any extra oxygen can be diverted to smaller medical facilities.

3.1.2. Disadvantages

1. Requires continuous supply of electrical connection. Any failure can lead to catastrophic events. A UPS or DG set back up is essentially required.
2. Initial cost for installation is quite high but can be cost effective in long run.
3. The purity of oxygen ranges from 90-95%. Most of the ventilators are calibrated at 100% oxygen. Therefore if PSA plant is the primary source of oxygen, recalibration at the said concentration is required otherwise it may lead to ventilator malfunction.
4. Noise pollution: long duration of exposure to PSA plants can have deleterious effect on the technical team on site. They need to take precautions against the same if longer duration of exposure is anticipated.
5. PSA plants can't be the sole oxygen source as any technical malfunction can lead to interruption of supply. Therefore, oxygen cylinders in the manifold area should always be kept as back up storage.
6. Technical team should be present 24 x 7 for any malfunction, as any event can lead to critical patients being endangered.
7. Fire safety is always an issue where oxygen is generated. Fire safety guidelines should be strictly implemented.
8. Repeated training sessions are required for technical personnel for any trouble shootings. The technical team handling the plants should be skilled enough. Various sessions which are conducted on national and local levels to enhance the skills but implementation should be confirmed by the administration of the medical facility.

3.2. Oxygen concentrators

Oxygen concentrators were developed in the 1970s for home usages. It is based on same principle of pressure swing adsorption by zeolite or membrane separation technology. Modern day use concentrators are capable of producing oxygen at 5-10 LPM. The purity range is 93±3%. Portable oxygen concentrators provide numerous advanatges including ease of transport, to allow oxygen delivery in almost any location including remote areas, high altitude, the ability to run on battery power for several hours, and increased economic efficiency as oxygen cylinders do not need to be purchased or transported.[12–14] It provides cost effective and reliable method to provide oxygen where there is scarcity of oxygen cylinders and supply.[15] As they are easily movable, they can be shifted to any area wherever the need arises.

This portable machine draws in the atmospheric air through a filter and moves it through an air compressor. Initially the first cylinder receives the air from the compressor. The pressure in the cylinder at that time is 2.5 times of the normal atmospheric pressure.The pressurised air is then passed through a heat exchanger to reduce the temperature and move over to the sieve beds containing zeolite pellets. It is here that the nitrogen is adsorbed and released as each bed get depressurised. It can be a double bed or multiple bed of sieves. The remaining gas contains oxygen in purity of 93±3% which is then flowed into the pressure equalizing reservoir and finally provided to the patient through the attached flowmeter.[16]

3.2.1. Advantages

1. Portable
2. Cost effective
3. Provides upto 10 Lpm of continuous oxygen.
4. Can work uninterrupted 24 hours 7 days for upto 5 years
5. Easy to use especially where cylinder or MGPS not available

3.2.2. Disadvantages

1. Fire hazards.
2. Continuous supply of electricity is required.
3. Higher flow rates above 10 LPM can't be obtained.

3.3. Liquid medical Oxygen

Liquid oxygen, which has been rightly called as amrut (immortal nectar) by Mediratta,[17] is a life saving drug which needs to be given as soon as possible. As reported by Usher etal in pre Covid 19 era, there already was scarcity of oxygen. Only one fifth of the patients had access to oxygen.[18] Liquid medical oxygen, which is now the lifeline of most hospitals is the best means to store large quantities of oxygen with relatively small footprints.[19,20]

Although Joseph Priestley discovered oxygen, liquid oxygen was first produced by a German scientist Carl Von Linde in 1895. It is a cryogenic liquid which are liquefied gases that have a normal boiling point below – 130°F (−90°C).

Liquid O2 has a boiling point of−297°F (−183°C). This is produced away from the medical facility and transported through special oxygen trucks to the hospital where it is stored in oxygen tanks. The open area of LMO tank should be connected well so that the transportation trucks can easily navigate during the refilling. It is also advisable to have 1-2 days reserve supply of oxygen as back up oxygen cylinders as refilling is dependent on third party and may take time due to unforeseen circumstances.

The liquid medical oxygen tank is usually situated away from the hospital and connected to the central MGPS system through underground piping. And once the valve is open, it flows into the MGPS requiring no electrical connection or manpower. The liquid oxygen is converted into its gaseous state by self vaporization and it is not electrical dependent. The manufacturing, storage, installation, transportation of liquid oxygen is controlled by Petroleum and Explosives Safety Organization (PESO) which is under the Department of Promotion of industry and internal trade of Ministry of Commerce and Industries of Government of India.[21,22] Licensing through this body is essential if liquid oxygen is to be handled at the medical facility. Local governing body helps in coordinating the same. PESO also had designated state wise nodal officers which would coordinate with the local oxygen manufacturers, local gas fillers, All India Industrial Gas Manufacturers' Association (AIIGMA) and the user hospital or medical facility. As per the guidelines, the nodal officer is entrusted to ensure uninterrupted oxygen supply. This was highlighted during the second wave of Covid 19 caused by Delta variant in April 2021.[23]

Most of the LMO tanks are a double walled vacuum insulated vessel with Maximum Allowable Working Pressure of 16 to 18 Kg/square cm with certified standards. The capacity of the tanks can range from 2 Kilo Liters to 20 Kilo Liters. They are made of stainless steel designed for a positive pressure at cryogenic temperature, with a vacuum between them (Filled with perlite under vacuum), to insulate the contents from the ambient heat.

The LMO tank should be equipped with pressure valve, safety devices, two separate liquid withdrawal valves with dual parallel regulator system for uninterrupted supply, 3-way gauge valve for isolation of line pressure with manual control.

Typical system requirement for hospital installation is as follows:[23]

1. LMO Storage Tank
2. Ambient Air Vaporizer
3. Should provide ambient air heat exchange which is able to vaporize 300-600 N cu M per hour LMO into vapours.
4. Pressure regulation skid
5. Interconnecting pipe between tank and vaporizer.
6. Foundation bolts for tank and vaporizer

As pointed out earlier, the space for installation of the LMO tank should be away from the hospital premises. It should be open spaces and should adhere to PESO guidelines:[24]

1. Allocated space should be minimum 9M (W) X 16 M (L) at ground level and should be accessible for smooth movement of LMO tanker from/to the site.
2. Avoid installation of LMO tank in the indoor environment or near drain or pits.
3. The site should not have overhead power or other utility cable.

4. The site should be fenced having a gate for entry/exit.
5. Fire extinguishers & water connection, lighting, safety warnings, earthing pit etc.
6. Vacant space should be provided within a radius of 5 meters around the tank.

Liquid O2 for medical use is expressed in m^3 of liquid. Once the total flows are known in L/min of gas, total volume of liquid can be calculated over a specified period of time, using the following formula: 1 L of liquid O2=861 L O_2 gas (21°C at sea level) and 1 m^3 O2 gas = 1000 L of O_2 gas.[8]

LMO is a very cost effective and reliable source of oxygen which is maintenance free but always a backup system of cylinders should be present in event of delayed refilling. Connection with the manifold room should be with copper alloy pipes which have bacteriostatic properties and no interaction with medical gases.[25] This connection layout should be leak free and checked regularly to avoid any mishaps.

3.4. Medical gas cylinders

Medical gas cylinders are universal and present in every medical facility irrespective of the patient load. Larger cylinders are utilized in the central manifold room whereas transport cylinders are often seen in the general ward and transportation bay. They are filled with medical gases by the supplier and handed back to the medical facility. But if the demand is too much, the cycle of refilling takes enormous amount of time and manpower. But when everything fails, all the plants shut down, they can be life saving.

Medical gas cylinders are made of light weight chrome molybdenum steel or a composite with aluminium. For special usage in MRI, they are made of aluminium. Usually they have 3 mm thick wall and hold the gases under high pressures.[26] The lightweight composite cylinders are more thick walled (6mm) and hold upto 30% more gas under higher pressure.[27]

All the medical gas cylinders are colour coded and comes in various sizes as per their utilization. They may contain either gas or liquid depending upon the critical temperature of the substance. Each batch of cylinder undergoes various tests eg bend test, hydraulic test, flattening test, tensile test and impact test.[24] They are checked for cracks and defects and also checked ultrasonically for any major deviation.[28,29] A record is maintained and they are repeated after 5 years to ensure the integrity of the cylinder. A label on the neck of the cylinder provides the consumer with the following information:[27]

1. Name and chemical symbol of gas.
2. Product specification.
3. Hazard warning diamond shaped figure denoting hazard class contained gas.
4. Name and address of cylinder manufacturer.
5. Cylinder contents in liters.
6. Tare weight (weight when empty).
7. Maximum cylinder pressure.
8. Cylinder size code.
9. Directions for use.

The cylinders have a tag attached which has three sections labeled, full, in use, empty. All the members of technical team handling should practice using the tag uniformly.

3.4.1. Cylinder filling

The cylinders are filled by a third party supplier off site as respective compressed gas. They do not liquify as their critical temperature is low. As PSA plants have incorporated the use of booster filling at the plant they can be filled at the medical facility itself but it may require technical expertise to do so. These cylinders are filled up to service pressure (defined as the maximum pressure to which the cylinder may be filled at 70° F) but the cylinders should be able to withstand 1.66 times the service pressure. The service pressure is usually kept 2000-2015 psi.[22] These oxygen cylinders are filled according to the filling ratio which is the ratio of the weight of gas in a cylinder to the weight of the water that the cylinder can hold at 60 F.[30] It is 0.75 of oxygen but decreases to 0.67 in tropical areas.[26]

The pressure gauze attached to the cylinders give an estimate amount of gas left in the cylinder using the Boyle's law.[31] Arlas et al gave a formula to calculate the approximate amount of oxygen left in an E type oxygen cylinder attached to an anaesthesia workstation.[32] Approximate remaining in hours = O_2 cylinder pressure in psi/200 × O_2 flow rate per minute. But this is just an estimate, always a back up has to be maintained.

Sometimes, in few areas, the size incongruent cylinders can be utilised using a pressure regulator with flexible pipe attached to a Schrader probe. This may be a stop gap arrangement but requires continuous manual survellaince.

3.4.2. Cylinder transport and storage

During transport, it is advisable to have a labelled, well ventilated vehicle specifically for this purpose only. The cylinders should be pre checked for any leakage with their valves in closed position and be transported in upright position with security cap, secured tightly to the vehicle.

For storage of oxygen cylinders in the medical facility, the following pre requisites must be met:[33]

1. A well ventilated, cool and dry area with temperatures less than 50°C, preferably away from critical areas.
2. Should be easily connectable for delivery of cylinders by transport vehicle.
3. Should have different areas designated for full and empty cylinders. There should be no overlap of the cylinders.

4. Different colour coded cylinders should be separately stored.
5. Area must be marked with no smoking, no open flames, fire hazard signs.
6. The cylinders must be restrained with chains to prevent accidental overturning.
7. They should be away from corrosive or flammable materials.

3.4.3. Precautions

Only technical staff trained to handle cylinders must be authorized, shall be involved with the handling of the cylinders. Any untrained staff can lead to various injuries or mishaps. The following precautions must be taken:[26]

1. As cylinders are colour coded, still they should be reconfirmed through the label on the neck of the cylinder.[34]
2. When attaching a freshly filled cylinder to the bank of manifold or patient, it should be opened slightly to remove any dust particles accumulated on the valve. Whilst opening the valve should face away from the technical staff, as high pressures can sometime cause injury to the handler.[35]
3. Presence of Bodok seal should always be confirmed otherwise it can lead of leakage of oxygen and avoidable accident.
4. Confirmation of correct gas filling and correct colour coding is a must. The pin index may be damaged and can lead to wrongful attachment of cylinders which can lead to fatal consequences.[36]

Cylinders are a vital and essential equipment of any medical facility. A lot of mishaps are avoidable with due diligence but still incidents do occur. A strict vigilance at every step is required, which can exponentially reduce the incidence of mishaps.

3.5. Manifold area

The manifold area caters to the supply of medical gases through the MGPS system. The filled cylinders are connected to the bank ports and through a control panel, the flow and pressure is controlled. As stated earlier, a well ventilated, dry room, away from the critical areas is recommended for it. It should have two doors, one large enough for loading and unloading of cylinders (loading bay). The internal walls and doors should be made of non combustible, fire resistant material as per standards.

There should be a primary supply bank (on -duty bank) and a secondary supply bank (standby bank), which kicks in automatically when the flow or pressure drops. (Figure 3) Each port is connected to a cylinder by flexible pigtail connections; a header bar; and an outlet port.[37] A non return valve is fitted along with every cylinder if there is a requirement to change a cylinder without interrupting the supply. The vertically stacked cylinders should be secured with chains when connected to the back bar. All the cylinders are connected through non-return valves to a common pipe. This in turn is connected to the pipeline through pressure regulators.[38] The amount of cylinders to be stored should be calculated individually for each medical facility. It should be based on consumption for 1 week and should always have a reserve for 3 days in advance. The supply through manifold is not electrically driven and hence provide continuous supply in the event of power failure.

Figure 3: Oxygen cylinder bank with digital gas alarm system

3.5.1. Control panel

Now a days, automatic microprocessor based digital control panels are used.(Figure 4) They switch over from primary bank to secondary bank without any change in pressure automatically. Panel shall be integrated with pressure gauges inside, downstream of the pressure regulator. Panel shall be fitted with standby line regulator. There should be provision to manually select which bank to be used. A pneumatic relief valve is provided to avoid excess pressure. The control panel displays for both oxygen and nitrous oxide. They have in built pressure regulators to decrease the high pressure to low pressure system. This will provide outlet pressure of 60 psig.

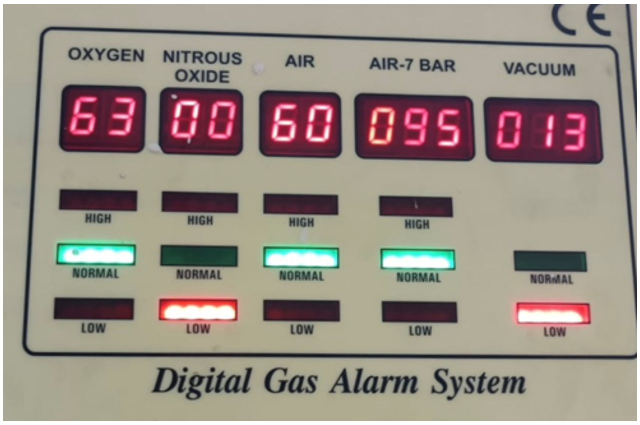

Figure 4: Digital gas alarm system

The control panel should have a display and audio visual alarms to show any switch over. The control panel provides for two individual contact pressure gauges to indicate the cylinder pressure in the two wings of the manifold and common pressure gauges to indicate the delivery / line pressure. It should be kept closed with a suitable cover to avoid any entry of the dust particles.

3.6. Medical gas pipeline system (MGPS)

Medical gas pipeline system provides medical gases from the source (LMO tank, PSA plants, Manifold room) to the patient's bed or critical areas. They maintain a constant pressure of 400 kPa. These specially designed pipelines are made of high quality phosphorous containing, de-oxidized, non arsenical, bacteriostatic copper alloy.[38] They should adhere to the standards to provide direct consumption by the patient. They prevent degradation of gases and are free of any contaminants. The fittings used must be copper- to-copper only, made with a special silver solder brazing alloy. The size of the pipes differs according to demand that they carry. Usually 42 mm diameter pipes are used for leaving the manifold.

The pipelines are colour coded through their entire length for easy identification.

Every area has their own area valve service unit (AVSU) which helps in emergency gas alarm management system in times of crisis. (Figure 5) They can cut off the supply to a particular area in the time of need. They are located outside the area, usually at a height so it is out of reach of common people and covered with a glass.

Figure 5: Area valve service unit (AVSU)

The oxygen supply is provided through the terminal points on the patient bed end. The terminal points have a Schraeder probe at one end and a gas-specific threaded connector at the other end. The gas specific Schraeder valve, uses a unique collar indexing system with a unique diameter that fits the matching recess on the terminal outlet for a specific gas only. This prevents accidental attachment of different gas connection. The terminal point should be leak proof and allow attachment from the front. It should use push to insert and press to release mechanism for probes. They should self seal when the probe is removed to avoid any leakage. They also should be colour coded with label of the gas on the front. (Figure 6)

Figure 6: Colour coded terminal points

The nomenclature for the pipelines is:[39]

1. Main hospital supply pipeline or gas service specific trunk pipeline: from Manifold to building.
2. Feeder pipeline which includes risers: Horizontal & vertical upto distribution pipeline.
3. Distribution pipeline or branch pipeline: serves one floor or a part of it, no vertical movement.
4. Drop pipe: distribution to terminal units.

The pipelines should be subjected to periodic testing to avoid any mishaps:[40]

1. Blow down test using oil free dry nitrogen
2. Initial press test to check for any leaks
3. Standing press test
4. Piping purge till no contaminants are see
5. Cross connection test using O2 analyzer
6. Final tie in test using ultrasonic leak detector

Such maintenance testing shall be carried out before starting the supply of medical gases. Technical team should be well versed with layout of the pipelines and AVSU to respond and react in time of crisis. Proper regular checkups and mock drills should be carried to prevent any critical disaster.

3.7. Oxygen audit

Every medical facility shall take proper steps to conduct oxygen audits at regular intervals to have information regarding the use. It may provide the information regarding the number of beds (general and ICU beds), consumption of oxygen daily in critical and non critical areas, technical staff specifically for designated areas, per day generation of oxygen from all sources and leakage from any source, no of cylinders (empty, filled, in use). A oxygen committee at institutional level and local administration is an important part to oversee the oxygen audit. Regular oxygen audit helps to maintain and calculate the amount of oxygen required in the medical facility. Adequate oxygen distribution plan form the distributor to the consumption by the institution should be implemented. Daily log of production and consumption should be maintained by the technical team, which may also help in predicting the oxygen consumption for the next 24 hours and one week. This exercise will extrapolate the excess or deficiency of oxygen and provide instrumental in oxygen audit.

4. Conclusion

Oxygen is the basic pre-requisite for any medical facility. In depth of knowledge from production to bed side distribution is essential; which may help in combating any crisis. All personnel involved in handling of oxygen must be adequately trained at regular intervals to minimise any critical event. Oxygen audit should be carried out to calculate the demand and supply for the medical facility which may help in judicious use of oxygen.

5. Source of Funding

None.

6. Conflict of Interest

None.

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Author biography

Ravneet Kaur Gill, Assistant Professor https://orcid.org/0000-0003-4568-9609

Puja Saxena, Associate Professor https://orcid.org/0000-0002-4804-0947

Ashwani Mudgil, Medical officer-Consultant https://orcid.org/0000-0002-2454-7401

Agrawal Kavita Khemchand, Assistant Professor https://orcid.org/0000-0002-3191-3094

Roli Saxena, Assistant Professor

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