

## *Humidity in Inhalational Therapy*

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THE production and utilization of high humidity as a therapeutic agent in the treatment of infections of the respiratory tract has long been recognized as beneficial, particularly in children. The steam kettle, now rarely used in modern hospitals, is still a modality in homes for the treatment of upper respiratory infections. It provides varying degrees of humidity, but control can neither be achieved nor humidity accurately gauged. In many hospitals an attempt has been made to improve the circumstances of therapy by construction of a "steam room" to provide more consistent and perhaps more comfortable conditions for the treatment of respiratory disorders. The term "steam room" is actually a misnomer in that the high humidity was created by nebulization of water forced through a fine nozzle under high pressure. This method had disadvantages in that the droplets were of varying size and tended to coalesce and fall out as 'rain,' with the collection of moisture on the ceiling and walls and ultimately on the patient's bedclothes and on the floor. Where hot water was employed there was the added disadvantage that the environmental temperature was increased to such a degree that not only was the patient uncomfortable but if fever were already present the hyperpyrexia was aggravated by heat retention.

There is a significant relationship between environmental humidity, room temperature and heat regulation in the human body. It was realized that a knowledge of the mechanisms whereby the body maintains thermal regulation was essential if high humidity were to be used scientifically as a therapeutic agent. Body temperature is regulated by the thermal center located in the midbrain.<sup>1, 2, 3</sup> This sensitive biologic thermostat maintains a level of equilibrium where the rate of heat production is equal to the rate of heat loss.<sup>4</sup> Heat is produced by the metabolic processes in

active muscle and in metabolizing cells like those in the liver. Heat is lost from the body in two areas: from the respiratory tract principally by the evaporation of water and from the skin by conduction, radiation, convection and evaporation of water.<sup>5</sup> The circulating blood collects heat at its source and distributes it to the lungs and skin where it is lost to the atmosphere by the four mechanisms. Heat lost by evaporation of water of perspiration, approximately 0.58 kilocalories per gram of water vaporized,<sup>6</sup> occurs only if the rate of loss by radiation, conduction and convection is inadequate to maintain equilibrium.<sup>3</sup> Since the production of perspiration with loss of heat by evaporation is the final mechanism to be involved in normal heat regulation it must be thoroughly appreciated that interference with this mechanism<sup>7</sup> will put a strain on the cardiovascular system.<sup>8</sup> When sweating becomes necessary to maintain thermal equilibrium not only is the cardiovascular system more actively at work but an additional physiologic stress concerned with water and electrolyte metabolism may be introduced. In order to provide appropriate facilities for inhalation of a highly humid atmosphere it was necessary to take these circumstances into consideration. It was obvious that air conditioning was a prerequisite to humidification.

### **The High Humidity Oxygen Tent**

The high humidity oxygen tent was developed in an attempt to provide a high moisture content at controlled temperatures.<sup>9</sup> This new facility for therapy has made possible the combination of humidification and oxygen in high concentration in the respired atmosphere at a controlled temperature in which the patient is comfortable. Since atmospheric circulation within the tent canopy is rapid cutaneous loss of heat is facilitated by radiation and convection and is controlled by the vapor pressure gradient between the cutaneous surface and the ambient atmosphere that is constantly in motion. In addition, because

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of the rapid circulation of the ambient atmosphere through the cooling coil of the air conditioner, water is constantly removed before the small droplets coalesce and fall out as rain. New droplets of appropriate small size are constantly added to the ambient atmosphere which is temperature controlled in the patient's comfort range. Drastic interference with the patient's thermal regulation is avoided.

The high humidity tent has major disadvantages. For some patients it may create a sense of confinement and continuity of nursing care is difficult. If a tent must be opened frequently for nursing care, the tailor-made atmosphere is lost and the patient fails to receive the benefits of both high humidity and a high concentration of oxygen in the breathing atmosphere.

The earliest models of high humidity tents incorporated a mechanism for nebulization of heated water. In order to guard against the hazards of an electrically operated heater it was necessary to design an apparatus whereby the mechanism for heating was not in contact with the oxygen-enriched atmosphere. Utilization of a nebulizer, although relatively inexpensive, was found to have disadvantages. Droplets of nonuniform sized were produced and only a small proportion of them were of appropriate size to provide effective therapy. The use of a spinning disc type of humidifier provided an advantage in that a greater amount of moisture could be added to the atmosphere per hour. The return air from the tent canopy was split into two streams after it was drawn into the upper section of the cooling duct. One pressurized stream followed the normal course of the oxygenated air to the cooling coil where it was cooled to approximately 60° to 65° F. and then returned in the saturated state to the upper part of the oxygen tent canopy.<sup>9</sup> The other stream of air under pressure passed with maximum velocity over the heated water and through the spinning disc until it reached a temperature of 85° to 90° F. This supersaturated atmosphere at high temperature then passed through a corrugated duct where many heavy particles were trapped out on the convolutions. Continued passage through a settling chamber permitted additional heavy particles to fall out due to reduction in velocity

of the air stream. This warm supersaturated stream then passed to the top of the canopy where it blended with the cool air at 60° to 65° F. that had been in contact with the Freon cooling coil. The mixture of these two streams, one saturated and cool, the other supersaturated and warm, created a fog when the two strata of air at different temperatures and moisture content blended. This fog circulated through the canopy and was removed and replaced every thirty seconds. On return to the air conditioner the moisture-laden atmosphere was passed through the cooling coil where condensation of moisture occurred. At this point the new cycle was initiated. The precipitation of moisture from the air twice a minute by the cooling coil effectively removed large dust particles thereby reducing the concentration of microorganisms which tend to become attached to particulate matter in the atmosphere. The condensate containing the washed out waste matter from a patient's exhalation, entrained dust and associated microorganisms was then drained into a waste receptacle outside of the oxygenated atmosphere.

This system was remarkably efficient in that only fine particles of water were delivered to the patient's airway and at the same time agglomeration and coalescence of droplets of water into free moisture was prevented. The system has been abandoned because of the inherent difficulties of maintaining the electrical apparatus in proximity to an oxygen-enriched atmosphere in safe operating condition without the use of oil for lubrication. For these reasons manufacturers have adopted mechanisms for nebulization utilizing the Venturi principle and using oxygen under pressure to entrain water from a reservoir to create fine droplets by passage through an improved nebulizer. The oxygen supply is introduced through the Venturi under pressure of 50 p.s.i. The air conditioner creates a continuous circuit of the atmosphere within the tent canopy. A second circuit is maintained by the Venturi. The atmosphere within the canopy is aspirated through a duct opening into it. After the water in the reservoir is aspirated and nebulized the supersaturated atmosphere is propelled through the second leg of a U-shaped duct into the canopy. Coales-

cence of droplets is prevented by circulation over the cooling coils of the air conditioner. Condensation on the walls of the canopy occurs only when the room temperature is cooler than the atmosphere within the canopy.

Credit for the development of the original high humidity tent is due the late Professor Francis S. Schwentker of The Johns Hopkins University. With the development of the prototype tent for the production of high humidity in 1952 it was soon realized that many aspects of such therapy needed elucidation. The production of a cloud or fog brought into question the term *relative humidity* which had been defined to express the amount of moisture actually existing in air as compared to the amount of moisture necessary to fully saturate the same air at the same temperature. The term lacks scientific exactitude inasmuch as the relative humidity of air varies with changes of both temperature and pressure. The term "relative humidity" was considered inadequate in reference to a completely saturated atmosphere that, in addition, possessed water in the form of droplets of extremely small size. It was recognized that "absolute humidity" was therefore a preferable term<sup>9</sup> for moisture content since it describes the given weight of water contained in a unit volume of air.

*Absolute humidity* is expressed as a number of grains by weight of water per pound of dry air and is thus a figure which can remain constant despite variations in temperature or pressure of the atmosphere. A *grain of moisture* may be defined as the weight equal to 1/7000 of a pound of water. A pound of dry air has a specific volume of 13.33 cubic feet. The hope has been expressed that members of the medical profession would adapt their discussions to use of the term "absolute humidity" rather than "relative humidity." A point is made of the difference in terminology because the term "relative humidity" can only logically be applied to moisture that is invisible in the air, whereas therapists are interested in those conditions of the atmosphere in which 100 per cent relative humidity obtains and, in addition, visible droplets exist in the form of fog.

In spite of the hope that the more definitive term would come into general usage, we are

still forced to think in terms of relative humidity because there is no readily available, practical apparatus that will measure humidity beyond 100 per cent. Although such an apparatus has been developed and its design reported,<sup>10</sup> there is no commercially available unit. Nevertheless we are forced to consider that by adding heat to a given air condition the dry bulb temperature is raised without any concomitant change in the moisture content although the relative humidity is altered.<sup>11</sup> Similarly, moisture can be removed or added without effecting any change in the dry bulb temperature, and finally, air may be made more saturated by removing heat from it without actually changing the moisture content. If the temperature is decreased, the same relative humidity may be maintained, but less water in vapor form is required.

In order to elucidate the condition that may exist in a room at any one time, we refer to a psychrometric chart which graphically depicts the moisture content of air at varying wet and dry bulb temperatures with relative and absolute humidity indicated at the standard atmospheric pressure of 760 mm. of mercury. An increase in atmospheric pressure will reduce the ability of air to hold water, much like the squeezing of a sponge; but for most considerations in the field of air conditioning, changes of atmospheric pressure of less than 1 inch of mercury may be disregarded.<sup>9</sup> A great many different conditions of air may exist at a given relative humidity. At 70° F. a saturated atmosphere will hold 111 grains of moisture per pound of dry air. At body temperature (98.6° F.) this moisture content would represent only 40 per cent relative humidity, since it would require 290 grains of moisture per pound of dry air to produce saturation at that temperature.<sup>12</sup> This situation is duplicated in a tent canopy maintained at 70° F. and with the atmosphere maintained at 100 per cent relative humidity. When that atmosphere enters the body through the trachea and is warmed to 98.6° F., it has a relative humidity of only 40 per cent.

There are still other factors that must be taken into consideration by both the engineer and the physician in regard to efficacy of therapy. One of these factors is *droplet size*.<sup>9</sup>

There can be almost perfect visibility at 100 per cent saturation when all water has flashed into saturated vapor. This is usually a fluctuating condition that can be observed in any high humidity tent. If the temperature is lowered even one degree the saturated vapor will become supersaturated and will create water droplets which will be visible, if not in strong daylight, at least in darkness when the beam of a flashlight is reflected on them. When air is supersaturated there can be varying degrees of visibility in direct proportion to the weight of water per pound of dry air. Therefore, if the ultimate in available moisture content is desired, visibility will be necessarily poor. The size of the droplets which disturb visibility is of some significance in terms of therapy. The unit of measure of fog particles is the micron, which is a droplet size equal to 1/1,000 of a millimeter in diameter. Visible fog may contain droplets from a fraction of a micron to 40 microns in size and mist with particles of up to 100 microns in diameter may be entrained in the atmosphere. Nebulized sprays contain a mixture of heavy and light particles from 100 microns down to less than one micron in diameter. The heavier particles above 10 microns are continuously breaking up into fine particles because of air friction or they drop out of the atmosphere due to their own weight. The droplets of 10 microns or less tend to remain suspended for a short time. Unless recirculated they will fall out in the form of condensation within a few minutes. Since there is no static condition, it is difficult to obtain a record of droplet size in any atmosphere.

The research of Abramson,<sup>13</sup> Segal,<sup>14</sup> Bryson<sup>15</sup> and others has contributed to our general understanding of particle size in aerosol therapy. It appears that particles 30 microns in diameter or larger are baffled out in the trachea. Those from 10 to 30 microns reach the terminal bronchioles, those of 10 microns stop in the alveolar ducts and those of 0.5 to 3 microns in diameter penetrate into the air sacs themselves. Particles smaller than 0.5 microns in diameter enter the air sacs; but because of their extreme lightness, approximately half of these are expired at once and serve no useful purpose. The indications are that droplet

sizes smaller than 10 microns and larger than 0.5 micron are therapeutically desirable.

### The Fog Room

The shortcomings of a high humidity tent were recognized when patients complained of a sense of claustrophobia and physicians recognized that maintenance of a prescribed tailor-made atmosphere was difficult if not impossible where frequent entry into the tent canopy was necessary to permit adequate nursing care. A natural fog generator<sup>9</sup> was developed to create, in a full-size patient room, conditions of humidity previously only approached within the high humidity tent canopy. This development was justified because experience in the treatment of patients demonstrated that in the vast majority of instances where high humidity therapy was provided for the treatment of tracheobronchitis, emphysema or pulmonary fibrosis with superimposed acute infection that the real need was more for the beneficial effects of high humidity rather than for the presumed beneficial effect of high concentrations of oxygen. In this air conditioning unit, steam has been harnessed in a different way by cooling, blending and injecting it into the room atmosphere in such a manner that the objectionable heat is either removed or used to control room temperature as desired. When live steam under controlled conditions is introduced into the cold air stream of an over-sized air conditioner, the resultant superfine particles of moisture are recirculated at the rate of one air change per minute before being swept from the room and precipitated out as water by the cooling coil of the apparatus. Under these circumstances there is not time for agglomeration and subsequent precipitation to take place within the room and the droplets remain in the range of therapeutically useful particle size. The fog generator eliminates the need for enclosing the patient in a canopy, thus lessening the tendency toward claustrophobia and permitting nursing care without interruption of therapy in an atmosphere that is acceptable once the nurses realize the benefits that accrue to their patients.

Oxygen therapy in a fog room is limited to the use of an intranasal catheter. An open-top canopy for administration of oxygen is

useless because the oxygen is washed out of it by the constant and rapid movement of air in the room. It is seldom necessary, however, to discontinue high humidity therapy and to transfer cyanotic patients to a high humidity tent for the benefit of its higher oxygen content.

### Clinical Application of High Humidity

With the development of both a high humidity tent and a fog room, clinical experience gained since 1955 has demonstrated the efficacy of these modalities for therapy. Tovell and Little<sup>12</sup> reported that the diseases treated varied greatly with the time of year, reflecting the incidence of diseases at certain seasons. During the summer and fall months the great majority of patients treated were suffering from poliomyelitis and were placed in a Drinker respirator after a tracheostomy had been established. The benefits of humidification were demonstrated by the prevention of the drying of secretions to the point of becoming tenacious and mechanically obstructing respiration. The development of atelectasis manifested by hyperpyrexia was avoided. The secretions remained liquid and could either be coughed up by the patient, and when this was impossible, aspirated through the tracheostomy tube. During the fall and winter months, laryngotracheobronchitis, which tends to occur in epidemic sequence, was successfully treated by placing patients in the supersaturated atmosphere. Children suffering from croup were particularly benefitted by this form of therapy, and furthermore, it seemed probable that in a number of instances the performance of a tracheostomy was obviated. The contribution of humidification to such satisfactory results was difficult to determine, but the remarkable clinical improvements in the presence of laryngotracheitis, with or without croup, were more than merely coincidental. The importance of humidification for the patient with the tracheostomy was impressively emphasized by the group of patients with poliomyelitis requiring care in a respirator located in a fog room. Under normal circumstances inspired air breathed through the nose is warmed and humidified.<sup>10</sup> When it reaches the bifurcation of the trachea at a temperature of approximately 98.8° F., it is approximately 98 per

cent saturated with moisture. When air, breathed through a tracheostomy, reaches the bifurcation of the trachea, it has much the same temperature and humidity as room air. In consequence, the air takes up moisture in the bronchi, the mucous membrane becomes dry and secretions become tenacious. This disastrous handicap to patients with an impaired power to cough and in whom the crusting of secretions in the air passages may threaten life can be avoided by treatment in a supersaturated atmosphere.

The control of temperature provided in a fog room within the patient's comfort range of 70° to 74° F. has proven to be a significant asset, particularly when the hyperthermia inherent to the pathological process is accentuated by high environmental temperature occurring during the summer months. The lower ambient temperature realized in this form of cold humidification facilitates the loss of heat from the body and tends to control the hyperpyrexia from which patients may be suffering. In addition, there is further loss of heat because of the flashing of extremely small particles of fog into vapor in the trachea, bronchi and lungs, a process that requires the heat of vaporization which is taken from the body. Even supersaturated air, containing 166 grains of moisture at 75° F., if allowed to reach equilibrium in the lung, has only a 58 per cent relative humidity at body temperature. In this sense, therefore, it is not that moisture is being added so much as it is that moisture is being conserved. However, such equilibrium is not entirely reached and many small droplets are actually deposited by contact on the mucous membrane and thus saturate and soften mucous secretions. Herein lies the clinical utility of fog as a therapeutic tool. Another advantage is the production of high degrees of humidity at a temperature that is comfortable to the patient. Usually the range is between 68° F. and 75° F. In 1957, Tovell and Little<sup>12</sup> reported a comfort range extending to 80° F. Accumulated experience since that time has definitely established<sup>10</sup> the limit of comfort at 72° F.  $\pm$  2° for adults.

Experience has been gained by the treatment of patients suffering from marked emphysema and pulmonary fibrosis. High humidity therapy has been of definite value in pro-

ducing liquefaction of tenacious mucus to the point that it could be coughed up by such patients or aspirated through a catheter introduced into the trachea or through a tracheostomy. Treatment of patients suffering from carbon dioxide narcosis, as a superimposed symptom of emphysema and pulmonary fibrosis occurring when an acute upper respiratory infection complicates and aggravates the condition of these chronic respiratory cripples, has been particularly gratifying. Patients in coma thought to be hopelessly ill have gradually emerged from coma with change of the inspissated, infected bronchial secretions to a watery consistency. Baker<sup>17</sup> has reported five years' experience with a high humidity room. He emphasizes that maintenance of hydration is facilitated in the presence of high humidity. In his experience the incidence of cross infection with more than one patient being treated in a single high humidity room was remarkably low.

Blackfan and Yaglou<sup>18</sup> postulated in 1933 that premature infants did better in highly humid atmospheres than in the presence of low humidity at the same temperature. Silverman<sup>19</sup> failed to substantiate the theory that high humidity was advantageous to infants for the relief of respiratory distress. In a subsequent paper Silverman,<sup>19</sup> testing the hypothesis that high humidity increased the survival rate of premature infants, found that the survival rate was the same for the first three days of life, both in the presence of the detergent-treated mist and in an atmosphere at 90 per cent relative humidity. Nebulization of water had no advantage over the production of a 90 per cent relative humidity insofar as survival rate was concerned. In his opinion, the beneficial effects of high humidity were mediated through a reduction of heat loss. Similar results were reported by Miller and his associates.<sup>20</sup> If the body temperature was kept constant, the survival rate was the same for infants kept in environments of low relative humidity as in those instances where the relative humidity was high.

Burch,<sup>21</sup> reporting on the influence of a hot and humid environment on patients with coronary heart disease, expressed the opinion that little attention is given to atmospheric conditions during management of patients with

cardiac disease because this aspect of therapy is ignored. The cardiovascular system does participate significantly in adjustments to variations in environment. He emphasized that a hot and humid environment may be particularly treacherous as evidenced from experiences in communities suddenly struck by a heat wave when people of the elder age groups and those with degenerative diseases are especially prone to succumb. Elderly patients and particularly those suffering from diseases of the cardiovascular system should be warned against the use of Turkish baths and working in a hot and humid atmosphere. Burch makes a point that thermal sweating is not so pronounced in patients suffering from chronic congestive failure as in normal individuals and that the degree of thermal sweating is inversely related to severity of the failure. Inability to sweat adequately in a hot and humid environment by an individual suffering from chronic congestive failure demands that more cardiac work be expended to meet the requirements for thermal regulation. Approximately 10 per cent of body heat is lost through the respiratory tract of man when breathing in a comfortable, ambient atmosphere.<sup>22</sup> This capability is lost in hot and humid environments and heat may be actually gained.<sup>23</sup> Under these circumstances the cardiovascular system is put under additional stress in an attempt to eliminate heat. A hot and humid environment, therefore, is tolerated poorly by patients with chronic cardiac disease with associated impairment of their cardiac reserve. Venous pressure is increased by a hot and humid environment,<sup>24</sup> and the patient with chronic congestive failure tends to be made worse by any factor that increases his systemic venous pressure which in turn would be expected to increase his pulmonary venous pressure. Therefore, the effect of a hot, humid environment on venous pressure should not be disregarded. During hot weather the cool air of an oxygen tent often seems to offer more benefit to the patient than the oxygen itself, and a room temperature of 78° F. with a relative humidity less than 60 per cent seems to be satisfactory for cardinals at rest in bed.<sup>25</sup> The environment should be made comfortable not only for the patient with heart disease but also for aged

people and for patients with debilitating states in which thermal regulation should be facilitated. In a subsequent paper Burch and Hyman<sup>25</sup> reported experiments on normal subjects and patients with chronic congestive heart failure which revealed that with subjects at rest a hot (111° F.) and humid (86 per cent, relative) environment produced a considerable increase in cardiac output and stroke volume in normal individuals and a definite but less increase in patients with congestive heart failure. The increase in cardiac work and output occurred more as a result of a larger stroke volume than greater cardiac rate. They commented that this finding was at variance with the work of others in reference to the effect of exercise.

At first glance, the work of Silverman and of Burch and his associates might seem to provide data indicating that the utilization of high humidity was not warranted in the treatment of cardiorespiratory ailments. Admittedly, cardiac patients with an excessively high venous pressure might better not be subjected to an environment that tends to increase hydration, and certainly they should not be subjected to an environment that puts a demand on the cardiovascular system for greater work output in order to dissipate heat. The circumstances are vastly altered in a high humidity room in which the environmental temperature is kept within the comfort range, therefore not exceeding 75° F. Even though the relative and absolute humidity may be maintained at the highest level commensurate with adequate visibility, deleterious cardiorespiratory reactions are not engendered if the ambient temperature does not exceed 74° or 75° F. In many instances patients will express favorable opinion regarding their comfort when the ambient temperature of the high humidity room is more nearly in the range of 70° to 72° F.

Büttner<sup>26</sup> found that when an adult is subjected to an environment of air at a temperature exceeding 86° F. where a relative humidity of 100 per cent exists, he will suffer from disturbance of his thermal regulating mechanisms. Hyperpyrexia and cerebral edema may supervene with resulting unconsciousness and ultimate brain damage leading to death, if untreated. Because of

this potential, it was realized that natural fog generators need close supervision and, in addition, warrant the installation of safeguards against faulty mechanical action that could result in producing room temperatures exceeding 80° F. As a consequence Lovell<sup>10</sup> designed and installed visual and audible alarms set to trigger at 80° F. for the fog generators installed at Hartford Hospital. His final design depended upon certain decisions of policy stipulated by medical personnel. It was decided that the alarm system should be entirely separate in circuitry except for inclusion of the master switch of each fog generator. When the fog generator was turned on the circuit of the alarm system was closed for action should a temperature of 80° F. be exceeded in the fog room. It was decided that there should be no manual means to turn off an alarm except by shutting off the fog generator. The temperature setting of the alarm was fixed and could not be altered except by a qualified electrician armed with the necessary key. Activation of the alarm would not automatically turn off the air conditioning apparatus but would shut off the steam supply. Both the visual and audible alarms were installed at the nurses' desk and the nurses were instructed to turn off the master switch when the alarm sounded and to open the door of the patient's room. To design the system that would have done these things automatically would have increased the complexity of the circuitry and increased the cost. Because temperatures in rooms with a westerly exposure sometimes exceed 80° F. in summer, it was necessary to warn the nurses that should they turn on the generator under those conditions the audible alarm would sound for a few minutes until the air conditioner reduced the room temperature to less than 80° F. Only in those circumstances were they to disregard the instructions to shut off the generator and open the door. This seemed the preferable alternative to having an installed facility to shut off the alarm and/or to have an adjustable setting at which the alarm would trigger. The object was to so design the alarm system that to abate the attention-calling disagreeable sound it would be necessary for the nurse to visit and observe the patient when she opened the room door.

By these installed means the hazards of high humidity therapy in the presence of an excessively high ambient temperature can be avoided. Because of our concern regarding the inability of cardiovascular patients to accommodate satisfactorily to both high humidity and a high environmental temperature, it is our belief that every natural fog generator should be equipped with visual and audible alarms connected with a mechanism that will "fail safe" and will by positive action interrupt the flow of steam should room temperature exceed 80° F.

### Summary

The usefulness of controlled humidity as a therapeutic agent is gaining widespread recognition. If it is to be used intelligently and safely, this therapeutic modality must be controlled scientifically as accurately as the dose of any potent drug. The collection of scientific data to elucidate the relationships of high humidity therapy to water balance and thermal regulation in the presence of hypovolemia, congestive heart failure and carbon dioxide narcosis is warranted and constitutes the direction in which progress may be made in the future.

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