

Humidity Output of the Circle Absorber System

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The humidities of gases inhaled from the circle absorber system were measured in a model "patient." The periods of stabilization of the system following variations in fresh-gas and CO₂ inflows, exhaled water vapor, and previous use of the apparatus were assessed. The effects of variations in fresh gas and CO₂ inflows, respiratory rate, and tidal volume were measured in stabilized systems. After stabilization, humidities were found to range from 27 per cent at room temperature (with low minute volumes and CO₂ inflow and high fresh-gas inflow) to 90 per cent (with high minute volumes and CO₂ inflow and low fresh-gas inflow). Data collected were used to construct nomograms capable of predicting the humidities of gases inhaled by patients. The safety of the system is discussed in that respect. (Key words: Humidity; CO₂ absorption; Anesthesia machines; Circle absorber system.)

WE DEMONSTRATED previously that dry anesthetic gases breathed by patients for more than an hour damaged the ciliated columnar epithelial cells of the tracheobronchial tree.¹ No significant cellular change occurred, however, when the gas was humidified to 60 per cent at room temperature (22–26 C) or saturated with moisture at body temperature. We question the ability of commonly used anesthetic apparatus to meet this requirement. The circle absorber system particularly attracted our attention because large alterations in the humidity of inspired gases can be expected with variations in fresh-gas inflow, ventilatory minute volume or CO₂ exhalation. In addition, carbon dioxide is neutralized by an exothermic reaction which liberates 14 kilocalories and two moles of water for each mole of CO₂ absorbed.² There will, therefore, be a

period of stabilization during which the temperature and humidity of the system will increase. Finally, 15 per cent of water, weight for weight, is incorporated in the granules of barium hydroxide lime or soda lime, U.S.P. This water in itself will contribute significantly to the humidification of inspired gases.³ Various studies^{3, 4, 5} have described changes in temperature and relative humidity in a variety of anesthetic systems; however, we have not found data which could predict variations in the humidity of the circle absorber system during its clinical use. We therefore studied humidity in a circle system and erected a series of curves and nomograms which allow the anesthesiologist to estimate humidity of inspired gases in relation to fresh-gas inflow, respiratory minute volume, and exhaled CO₂ after stabilization.

A model was constructed by attaching a 5-liter anesthetic bag to the patient end of a Foregger circle absorber system (fig. 1), flowing CO₂ from a calibrated metered source through its tail end, and placing a Cascade humidifier † in the expiratory limb at the Y-piece. Ventilation was provided by an Airshields Ventimeter ventilator. A hygrometer sensor connected to a HygroDynamics electric hygrometer indicator § was inserted in the inspiratory limb at the Y-piece. Thermometers were placed so that their bulbs reached: 1) the centers of both compartments of the canister; 2) the expiratory limb gases at the outlet of the humidifier; 3) near the hygrometer sensor. All temperatures, including ambient temperature, were measured at 10-minute intervals, and humidity was recorded simultaneously. The thermostat of the humidifier was regulated to keep outlet temperature at 37 C. In addition, recordings of humidity were made by connecting the output of the hygrometer to

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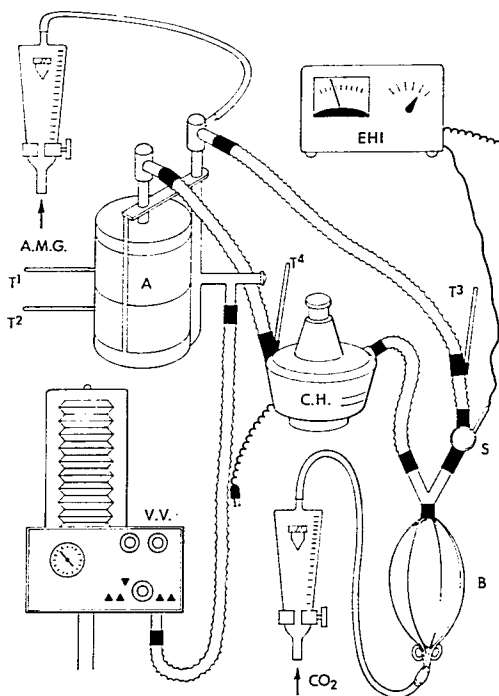
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§ Model 15-3001. Hydrodynamics, Inc., Silver Springs, Maryland.

FIG. 1. Model "patient" on circle absorber system. AMG, fresh gas inflow; A, absorber; EHI, electric hygrometer indicator; S, hygrosensor; CH, Cascade humidifier; VV, Airshields Ventilometer ventilator; B, 5-liter anesthesia bag; CO₂, carbon dioxide inflow from calibrated metered source; T₁, T₂, T₃, T₄, thermometers.



a Beckman Type R Dynograph with strain-gauge coupler number 9803.

In a preliminary experiment, curves of temperatures in the canister when the lower compartment was filled with barium hydroxide and when it was filled with gauze were compared. The gas flow through the canister was from above downward.

The first phase of the study included five experiments in which the time necessary to obtain constant humidity was determined. All experiments were started with a fresh dry system (fig. 1) with barium hydroxide lime, U.S.P., as carbon dioxide absorbant. 1) A "standard-adult" experiment was conducted using a fresh-gas inflow (FGI) of 5,000 ml/min, a CO₂ inflow (\dot{V}_{CO_2}) of 200 ml/min, a

respiratory rate (f) of 12/min and a tidal volume (V_T) of 500 ml. 2) A "closed-system" experiment was run with similar settings, but FGI was reduced to 500 ml/min. 3) In a "pediatric" experiment, "standard" FGI was maintained, but \dot{V}_{CO_2} , V_T , and f were adjusted to 100 ml/min, 200 ml, and 20/min. 4) The contribution of exhaled water vapor to humidity at the Y-piece was studied under "standard" conditions but without the Cascade humidifier in the circle. 5) The effect of previous usage of the system was assessed at "standard" settings, but the apparatus was used for four hours and allowed to cool to ambient temperature before the ventilator was restarted and measurements recorded.

The second phase included humidity mea-

surements made in systems that had already reached steady state. A dry reservoir bag was intermittently switched into the circle at the patient end of the Y-piece and the average humidity of several breaths obtained. Variables included \dot{V}_{CO_2} , FGI, V_T and f . High and low adult \dot{V}_{CO_2} settings of 300 and 200 ml/min were used at V_T 's of 500, 700, and 900 ml and f 's of 12, 24, 16, and 18/min. A pediatric \dot{V}_{CO_2} of 100 ml/min was also used at V_T 's of 180, 240, and 300 ml and f 's of 16, 18, 20, and 22/min.

All experiments were repeated five times and the mean and standard deviation from the mean calculated in each instance.

Results

Humidity at the Y-pieces fluctuated with phases of the respiratory cycle (fig. 2). Because the waveform is essentially triangular, the mean value for all experiments in phase I approximated minimal value plus one third of the difference between maximal and minimal value. Therefore, when humidity was plotted against time in the first five experiments, both maximal and minimal readings were indicated. Canister temperatures were shown above humidity values.

Humidity values in the "standard adult" model (FGI 5,000 ml/min, \dot{V}_{CO_2} 200 ml/min, V_T 500 ml, f 12/min) are shown in figure 3. At the onset, fluctuations between 29 (dashed line) and 32 per cent (solid line) were noted, so that mean humidity at that time approximated 30 per cent, rising to 61 per cent in 90 minutes. Temperatures in the upper and lower compartments of the canister were originally 22.5 C, rising to 43 C in 50 minutes. The increase in temperature in the upper compartment preceded that in the lower compartment by 20 minutes. When the lower compartment was loosely packed with gauze instead of barium hydroxide, the temperature curves in that compartment followed very closely those shown in figure 3.

When FGI was reduced to 500 ml/min (fig. 4), original mean humidity was 47.5 per cent, increasing to 93 per cent and stabilizing in 100 minutes, but the width of the variable component between the dashed and solid humidity lines was approximately 33 per cent of that found with "standard adult" settings. How-

ever, the temperature increase in the canister exceeded values obtained with "standard adult" settings by approximately 20 per cent.

When \dot{V}_{CO_2} was reduced to 100 ml/min (FGI 5,000 ml/min, V_T 200 ml, f 20/min) initial mean humidity (fig. 5) was 29 per cent reaching 57 per cent in 100 minutes. The temperature increases in the canister were less steep than in the "standard adult" model and reached only 88 per cent of values obtained in that experiment.

Removing the humidifier from the adult model did not change the period of stabilization, which remained 90 minutes, but the increase in humidity was delayed 20 minutes. Temperature elevations were similar in pattern but the final mean temperature was only 75 per cent of the value in the adult model containing a humidifier.

Previous use of the "standard adult" model resulted in an original humidity of 45 per cent stabilizing at 65.5 per cent in 90 minutes. This represents a higher initial humidity than that in a fresh dry system, but at stabilization the values were similar, and the period of stabilization remained the same. There was also no appreciable difference between the patterns of temperature increases in the canister.

Mean gas temperature at the humidity outlet in the first five experiments, totaling 270 measurements, was 37 ± 0.36 C. Similarly, gas temperature near the hygrometer remained between 22 and 26 C throughout all experiments.

The data derived from phase II experiments were used to erect the nomograms in figures 6 and 7.

Discussion

The variations in humidity which accompany the respiratory cycle (fig. 2) are the result of variations in the proportion of moist gases coming from the system and ventilator and dry gases coming from the anesthesia machine. During the expiratory pause, the gas that enters the inspiratory limb is mainly dry fresh gas. As inspiration starts, this gas flows past the hygrometer sensor which, therefore, records minimal humidity. The inspiratory limb is now filled with humidified gases from the ventilator. During expiration, the fresh-gas inflow continues the movement of gases in the circle. Since the inspiratory limb now

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holds humid gases, the hygrometer records maximal humidity.

The initial humidity in every fresh dry system is derived from the water content of the barium hydroxide granules. In a previously used system, which contains water of condensation, the original humidity is naturally higher.

Temperature rise in the upper compartment is due to the heat of the reaction of neutralization. The temperature rise in the lower compartment, until the barium hydroxide in the upper compartment is exhausted, is passive, and is caused by warm gases from the upper compartment flowing downwards. The proof of this phenomenon lies in that the same temperature curve was obtained when the lower compartment was packed with gauze. We confirmed that two hours of usage, with CO_2 flows of 200 ml/min, failed to neutralize the lime in the upper compartment, so that the results of our first five experiments reflect the chemical activity of the upper compartment. The lime in the lower compartment, of course, would be active in temperature elevation after exhaustion of the content of the upper compartment.

The increase in humidity that followed the rise in temperature in the canister may have been caused by an excess of water produced by the reaction of neutralization of CO_2 or the rise in temperature in the lime granules, or both. The gas that reaches the hygrosensor is a mixture of fresh dry gases and gases fully humidified from the ventilator, the final humidity being determined by the relative contribution of each of these. The time necessary to reach steady-state humidity depends on the time needed to saturate the gases in the ventilator with water vapor. Humidification of this gas is from two sources: 1) the patient humidifies and warms expired gases (humidifier in our system) and 2) the heating of the granules in the canister vaporizes water (pre-existing or newly formed). This explains the prolongation of the period of stabilization without change in final humidity when the humidifier is removed. However, for the same reason, reducing the fresh-gas inflow will of course prolong the period of stabilization (figs. 3 and 4), leading to a much higher final humidity, the time to reach 60 per cent humidity remain-

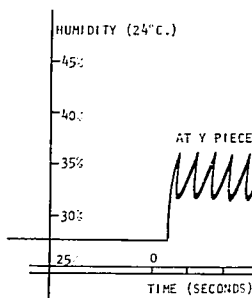


FIG. 2. Recording of the output of the hygrometer on Beckman Type R Dynograph.

ing unaltered. In the same way, the distance between the minimal and maximal humidity curves is reduced when ventilation is reduced (figs. 3 and 5) and when fresh-gas inflow is reduced (figs. 3 and 4).

It is probable that reduction in \dot{V}_{CO_2} (fig. 5) will compound the effect of reduced minute volume on the distance between maximal- and minimal-humidity curves and that both these factors will contribute to the slight decrease in final humidity values.

The nomograms (figs. 6 and 7) can be used to predict inhaled humidity in the absence of a hygrometer, but there are limitations to their use. They should not be consulted until the system has reached steady-state humidity. For example, figure 3 shows a delay of 60 minutes until steady state was achieved. Estimation of per cent humidity 30 minutes after the start of anesthesia with a fresh dry system would result in overestimation by nearly 50 per cent. From a practical standpoint, monitoring temperatures in the upper and lower compartments of the canister will permit close approximation, since a glance at figures 3 to 5 suggests that when both temperatures exceed 35 C humidity will be at least 50 per cent (or reach this value in 10 minutes).

The use of the nomograms is as follows: The CO_2 output of an anesthetized patient (estimated from his weight, height, and medical history) is judged to be in the region of 200 ml/min. He is placed on a circle absorber system with a fresh-gas inflow of 5 l/min. The

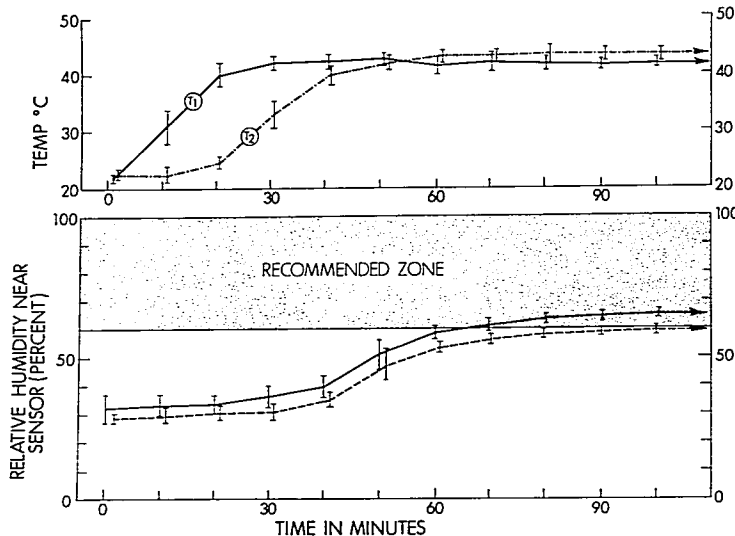


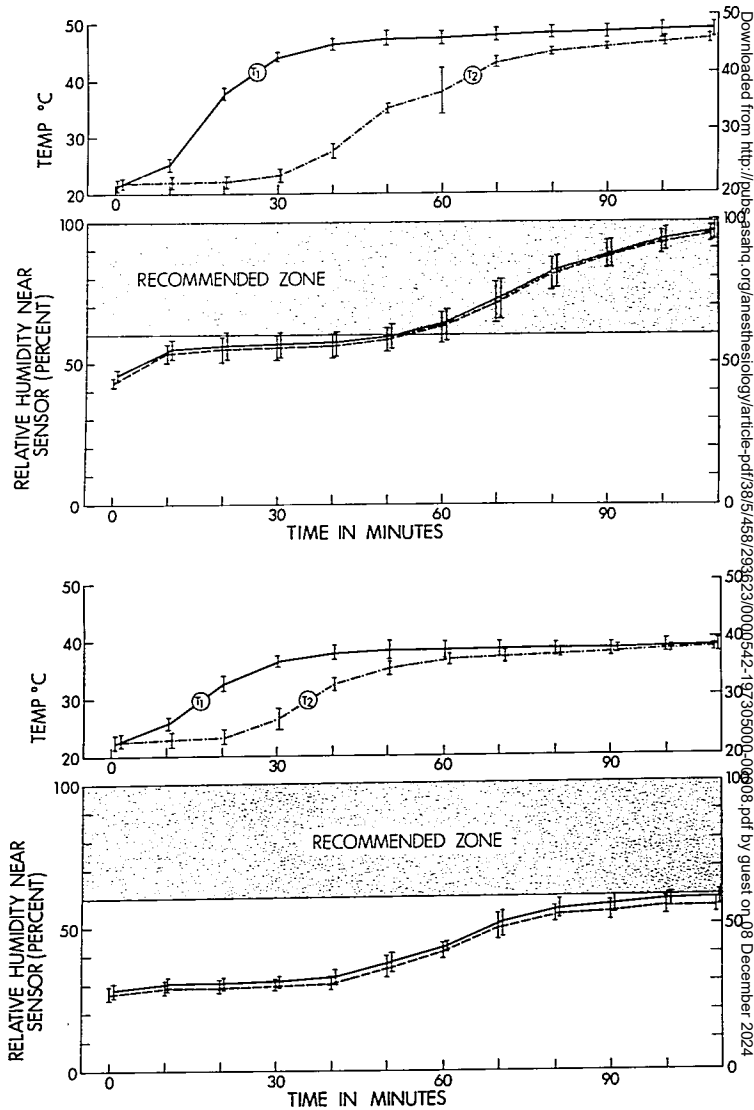
FIG. 3. Mean recordings from "standard adult" experiment. FGI, 5,000 ml/min; V_{CO_2} 200 ml/min; V_T 500 ml; f 12/min. T_1 and T_2 , temperatures in the upper and lower compartments of the canister. Lower curves: dashed line minimal and solid line maximal humidity. Brackets indicate ± 1 SD, $N = 5$.

FIG. 4 (facing page, top). Mean recordings when FGI is reduced to 500 ml/min in the "standard adult" model. T_1 and T_2 , temperatures in the upper and lower compartments of the canister. Lower curves: dashed line minimal and solid line maximal humidity. Brackets indicate ± 1 SD, $N = 5$.

FIG. 5 (facing page, bottom). Mean recordings when V_{CO_2} is reduced to 100 ml/min; FGI, 5,000 ml/min; V_T 200 ml; $f = 20$ /min. T_1 and T_2 , temperatures in the upper and lower compartments of the canister. Lower curves: dashed line minimal and solid line maximal humidity. Brackets indicate ± 1 SD, $N = 5$.

ventilator is adjusted at a rate of 14/min and a tidal volume of 700 ml. To calculate humidity of inspired gases at stabilization, take the 5-liter inflow point on the curve at the extreme right of figure 6 and join it to the intersection of the 700-ml tidal volume line with the 14/min rate line on the grid in the center of that nomogram. Prolong this line to the point where it intersects the humidity line on the extreme left and read the humidity at that point. In this instance, it is approximately 73 per cent

at room temperature. An error in the estimation of CO_2 as large as 30 per cent, one of the imponderables in these calculations, would have a small effect on the estimation of humidity. For example, if the CO_2 output had been erroneously estimated at 300 ml/min in the previous example, using the 300 ml/min CO_2 inflow curve would result in a reading of 80 per cent relative humidity, or an overestimation of 7 per cent in relative humidity (approximately a 10 per cent error). However,



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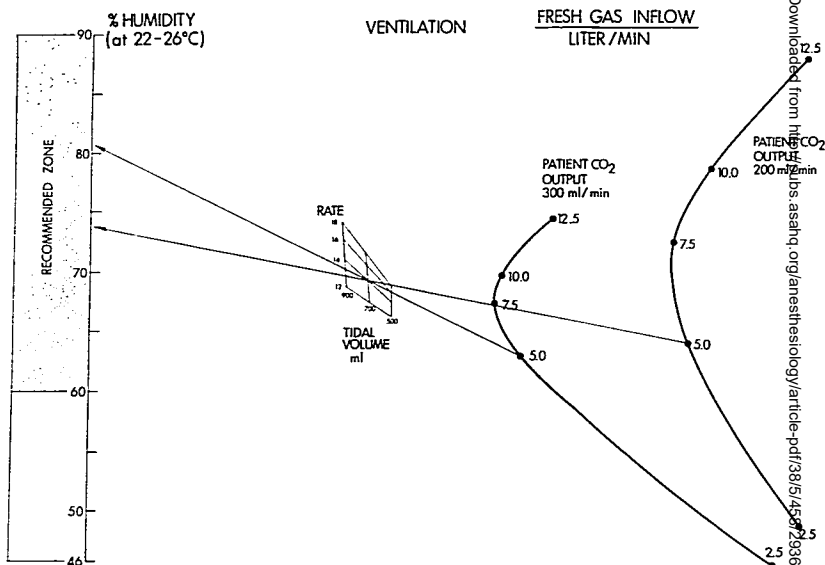


FIG. 6. Nomogram predicting inspired humidity at the Y-piece in relation to \dot{V}_{CO_2} 's of 200 and 300 ml/min, FGI, V_T , and f .

a change in ventilation, particularly when FGI is high, will result in a significant increase in per cent humidity. For instance, figure 6 shows that at $\dot{V}_{CO_2} = 300$ ml/min, FGI = 10 l/min, $V_T = 500$ ml, and $f = 12$ /min, humidity is 58 per cent. At the same \dot{V}_{CO_2} and FGI, but $V_T = 900$ ml and $f = 18$ /min, humidity is 82 per cent (an increase in relative humidity of 24 per cent). This is due to the fact that a high FGI causes a large inflow of dry gases to enter the circle. Increasing the ventilation, by mobilizing an excess of humidified gases from the ventilator and absorber, will have a considerable effect on humidity. Reducing FGI to 2.5 l/min will give rise to an initially high humidity. For instance, with $V_T = 500$ ml and $f = 12$ /min, the humidity is 83 per cent. The largest increase in ventilatory minute volume could not increase relative humidity to more than 100, or an increase of 17 per cent relative humidity. In fact, in this case, in-

creasing the tidal volume to 900 ml and the ventilatory rate to 18/min would only produce 90 per cent relative humidity, or an increase of 7 per cent (fig. 6).

For \dot{V}_{CO_2} values between 200 and 300 ml/min, join equal FGI points between the two \dot{V}_{CO_2} curves and divide the lines obtained in proportion to the required correction (e.g., equidistant points between the two curves for a \dot{V}_{CO_2} of 250 ml/min).

For pediatric patients, the second nomogram (fig. 7) is used. This nomogram can be used only for children whose \dot{V}_{CO_2} 's are in the vicinity of 100 ml/min. A 25-kg child, whose \dot{V}_{CO_2} at 4 ml/kg body weight will approximate this requirement, can be used as an example. He is placed on an adult circle system with an FGI of 5 l/min and ventilated with a minute volume of 4 l/min. Join the 5-liter FGI point on the curve on the right of this nomogram to the 4 l/min point on the ventilation curve and

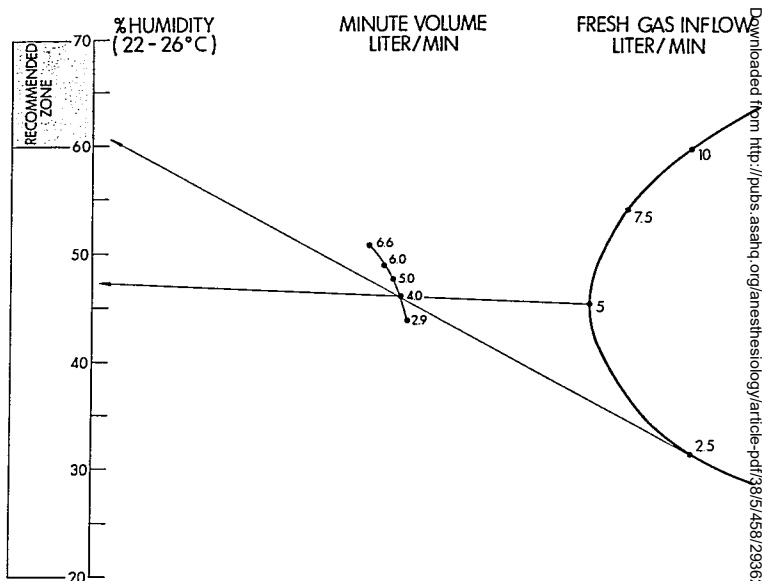


FIG. 7. Nomogram predicting inspired humidity at the Y-piece for a patient with a V_{CO_2} of 100 ml/min in relation to FGI and respiratory minute volume.

prolong to intersection with the humidity line on the left. A 47 per cent relative humidity (22-26 C) is read. This is below the 60 per cent recommended humidity. To find the FGI that will correct this lack of moisture, join the 60 per cent relative humidity point to the 4 l/min ventilation point and prolong to intersection with the FGI curve. It is found that a 2.5-l/min FGI will provide adequate moisture.

Although the usage of this nomogram is limited to children weighing approximately 20 to 30 kg, it amply demonstrates the necessity to reduce FGI when such children are placed on adult circle systems.

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