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Inflation static pressure-volume curves of the total respiratory system determined without any instrumentation other than the mechanical ventilator *

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Abstract. *Objective:* To assess the accuracy of static pressure-volume (PV) curves of the total respiratory system performed with the data directly obtained from the Servo 900C vs. the data obtained from an external calibrated device.
Design: Performance of the PV curve by the method of Levy with simultaneous recording of data obtained from both systems.
Setting: The general ICU of Hospital de Sabadell.
Patients: Ten sedated and paralyzed patients ventilated in the control mode for acute respiratory failure were evaluated.
Interventions and measurements: Inflation static PV curves were performed by the method of Levy. We simultaneously measured airway pressure and volume by means of calibrated pressure tranducer and pneumotachograph and by the internal devices built in the ventilator Siemens Servo 900C. Statistics were concordance analysis between the two methods and covariance analysis between derived curves.
Results: concordance analysis between both methods showed a 95% confidence interval of (+4%, −5%) in volume and (+2.2 cmH_2O, −1.7 cmH_2O) in pressure. Derived PV curves analyzed by MANOVA showed no significant differences whichever the method used within subject ($p = 0.579$).
Conclusion: Inflation static pressure volume curves of the total respiratory system can be accurately performed with the data directly obtained from the Servo Ventilator 900C without the need of any other external device.

Key words: Pulmonary function test – Pressure-volume curves – Mechanical ventilation – Acute respiratory failure

Determination of the pressure/volume (PV) curve of the total respiratory system is recommended in the ICU setting to assess pulmonary mechanics during respiratory failure. The value of the PV curve has been emphasized as a diagnostic, prognostic and therapeutic tool [1]. Conventionally, the static volume-pressure relationship of the total respiratory system has been assessed in this setting using the "super-syringe" technique [2, 3]. This method requires a prolonged time, disconnection of the patient from the ventilator and shows a number of errors in critically ill patients [4, 5]. The influence of autoPEEP in PV curves has also been reported [6]. The effect of externally applied PEEP in data obtained from the "super-syringe" method has been studied in some recent investigations [7, 8], which showed a decrease in hysteresis related to increasing PEEP. Recently, Sydow et al. [9] have compared a computerized system that performs automated repetitive occlusion at single volume steps against the syringe method. These authors suggest that hysteresis could be an "artifact" of the syringe method. Therefore, inflation limb of the PV curve seems to be the most reliable and important part of this pulmonary function test.

In 1989, Levy et al. described a method for studying the static PC curves during mechanical ventilation without disconnecting the patient from the ventilator [10]. They obtained the signals of volume and pressure from the ventilator and recorded the data on an external multichannel electrostatic device and/or a computer system for data acquisition. This method has been utilized by Ranieri et al. [11] to study the effect of PEEP in ARDS patients.

In order to extend the ability to perform PV curves to ICU teams without technical facilities, we designed the present study in which we have tested whether PV curves could be performed with the data obtained directly from the ventiltor.

Material and methods

Material

We have studied 10 critically ill patients undergoing mechanical ventilation for clinical reasons as summarized in Table 1. All patients were ven-

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Table 1. Patients' characteristics

Patient no.	Age yr	Sex	Diagnosis	Apache II	AutoPEEP cmH_2O	PaO_2/FiO_2 mmHg	Outcome
1	63	F	Lung fibrosis	10	5	385	Survived
2	68	M	Cardiac arrest	12	6	186	Survived
3	43	M	Postsurgical peritonitis	16	3	234	Survived
4	63	M	Pulmonary tuberculosis	17	0	360	Survived
5	85	F	Staphylococal sepsis	20	6	214	Died
6	63	M	Cardiac arrest	16	8	107	Survived
7	76	M	AMI. Cardiac arrest	12	6	142	Died
8	73	M	Peritonitis. Lung fibrosis	30	1	77	Survived
9	70	F	COPD. Respiratory arrest	36	8	230	Survived
10	76	M	Peritonitis. Pneumonia	27	8	290	Survived
Mean	68			19	5	222	
± SD	10			8	2.7	101	

AMI = Acute myocardial infarction; COPD = Chronic obstructive pulmonary disease

tilated with controlled mechanical ventilation with constant inspiratory flow waveform, and were sedated and paralyzed and in a stable period of illness during the study. The baseline minute ventilation, respiratory frequency, tidal volume, duration of inspiration, and inspiratory, and inspiratory flow rate were set according to the clinical status as prescribed by the primary physicians. Informed consent was obtained from the patients or relatives. The research protocol was approved by the institutional ethics authorities.

As a reference method we used a measurement device containing a heated pneumotachograph Fleish no. 2 and a differential pressure transducer (MP45, Valydine Corp., Calif.), That was attached between the Y piece of the ventilator and the endotracheal tube. From this device we measured airflow rate and airway pressure. Volume was obtained by electronic integration of the flow signal (Gould 13-4615-70, Gould Instruments, Cleveland). Data were recorded on a multichannel thermal paper recorder (Gould TA 2000, Gould Instruments, Cleveland).

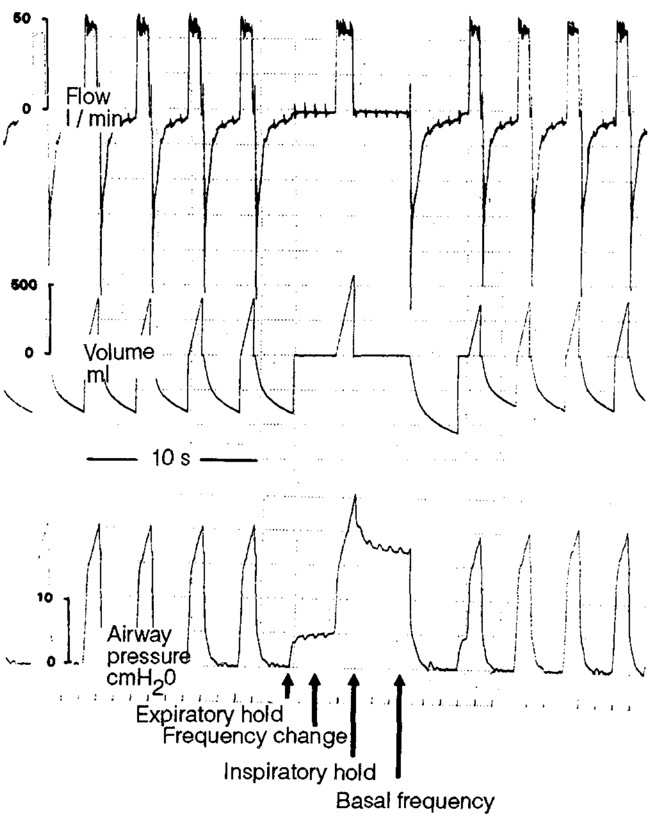

Fig. 1. Tracing of flow, volume and airway pressure obtained from the Gould device when performing a reduction in respiratory frequency. It can be observed on the pressure tracing that autoPEEP was present

The system subjected to test was the Servo ventilator 900C (Siemens, Solna, Sweden) which is provided with built-in sensors for flow and pressure, as well as end-inspiratory and end-expiratory airway occlusion devices. In order to develop the study in conditions very similar to the clinical setting, we used the ventilators without any calibration other than the regular maintenance provided by the manufacturers.

Methods

Tracheobronchial secretions were carefully aspirated before starting the protocol. Inspired oxygen concentration was increased 0.2 points for safety reasons despite the fact that disconnection of the patient from the ventilator is not needed. Positive end-expiratory pressure, when present, was removed. The upper pressure limit was set at 40 cmH_2O to prevent the likelihood of barotrauma.

We firstly determined autoPEEP by pressing the expiratory hold knob. In this way, the ventilator stops at the end of a standard expiration with both inspiratory and expiratory lines closed, the airway pressure increases until a plateau is reached, which corresponds to autoPEEP. This point of pressure at the start of the PV curve [6] represents the end-expiratory lung volume, i.e. functional residual capacity plus trapped gas.

We performed inflation PV curves using the method of Levy et al. [10]. Briefly, it consists of intermittently changing the inspired volume at which occlusions are performed while keeping the inspiratory flow rate constant, thus allowing measurement of static pressure at different inflation volumes [12]. After each test breath, baseline ventilation is resumed, thus keeping the volume history constant. The procedure is illustrated in Fig. 1. From the initial ventilator setting, the first step is to perform an end-expiratory pause. As soon as a plateau in P_{aw} is obtained, frequency knob is rapidly set at a desired value, and the expiratory pause hold knob is released. As the inspiratory flow rate is kept constant, changing the frequency, and thus the inspiratory time, will change the tidal volume. The next inspiratory tidal volume will be equal to minute ventilation divided by the new frequency. Following this, the inspiratory pause hold knob is immediately pressed and the ventilator stops at the end of the test inspiration with both inspiratory and expiratory limbs closed. Both the inspiratory volume delivered and plateau pressure showed in the display of the ventilator were manually recorded. During the end-inspiratory pause, which lasts until a plateau in P_{aw} is obtained, the frequency is reset to its basic value. When the hold knob is released, a normal expiration can take place. The whole sequence can be performed in approximately 8 s. After at least 5 standard breaths in order to reach the same end-expiratory lung volume, the procedure is repeated with another frequency, yielding a higher or lower tidal volume. The inspiratory volume-pressure curve can then be con-

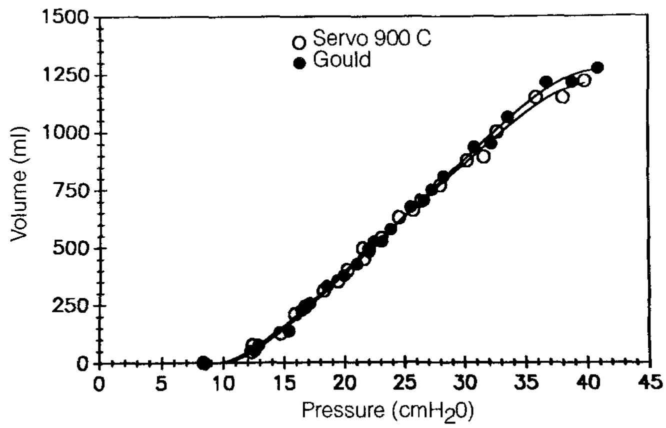

Fig. 2. Representative PV curves obtained with both methods in patient no. 9. An autoPEEP level of 8 cmH_2O, an inflection point at 12 cmH_2O can be observed and failling into the flat overdistended portion at 35 cmH_2O. The figure also shows that PV curves obtained with both methods in this patient were identical

structed by plotting volume against the corresponding static P_{aw} (Fig. 2).

Statistical analysis

We compared volume and airway pressure obtained from the Servo 900 C to those obtained from the external calibrated device by concordance analysis [13].

We performed a multiple linear regression with pressure as dependent variable and with volume and patient as independent variables. We tested differences between PV curves obtained by the two methods with MANOVA.

Results

Inflation static pressure volume curves were performed on the 10 patients by obtaining a mean of 18 pairs of pressure and volume determinations with both methods, with a range of 13–28. Figures 2–4 show representative PV curves in very different patients. No significant changes in hemodynamics and clinical status were observed during the whole procedure. All the patients except one showed autoPEEP, which ranged from 1 to 8 cmH_2O (mean 5.1 cmH_2O).

Pressure measurements obtained from the display of the Servo ventilator 900 C (Pressure Servo) and from the external device (Pressure Gold) showed a very good correlation ($r = 0.99$ $p < 0.001$), with a regression equation ($y = 0.008 + 0.98x$) that did not differ from the identity line (Fig. 5). Furthermore, concordance analysis demonstrates that for a given Pressure Servo value, we can expect with a 95% confidence interval that the true value of pressure differs from +2.2 cmH_2O to −1.7 cmH_2O (Fig. 6).

Volume determinations by the Servo ventilator 900 C (Volume Servo) and by the external device (Volume Gould) also showed a very good correlation ($r = 0.99$, $p < 0.001$), with a regression equation that did not differ from the identity line ($y = 0.002 + 0.99x$) (Fig. 7). Furthermore, concordance analysis demonstrated that values slightly varied in a systematic way over the range of measurement (Fig. 8). Therefore, a logarithmic transformation [13] was performed and it showed that Volume Servo can differ from Volume Gould by 4% above to 5% below.

Multiple linear regression analysis and covariance analysis demonstrated that tests involving the within-sub-

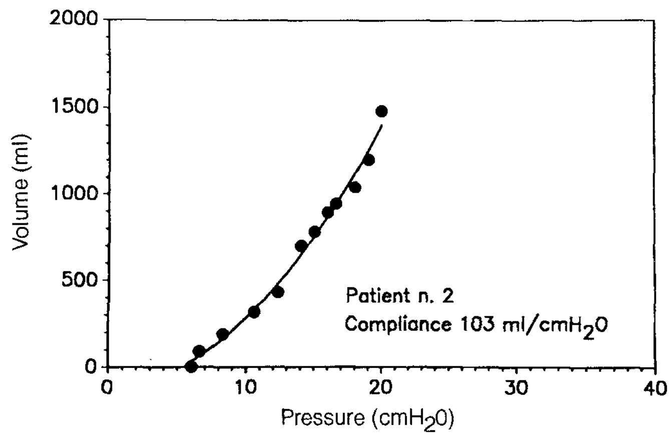

Fig. 3. Inflation PV curve obtained in patient no. 2, showing autoPEEP, high compliance and an upward concavity

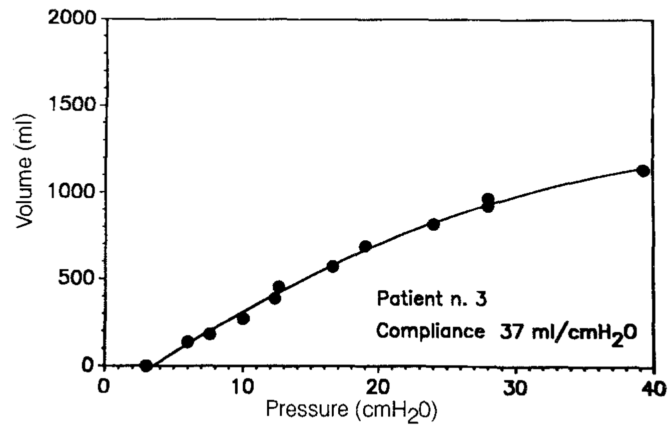

Fig. 4. Inflation PV curve obtained in patient no. 3, showing autoPEEP, low complicance and a downward concavity

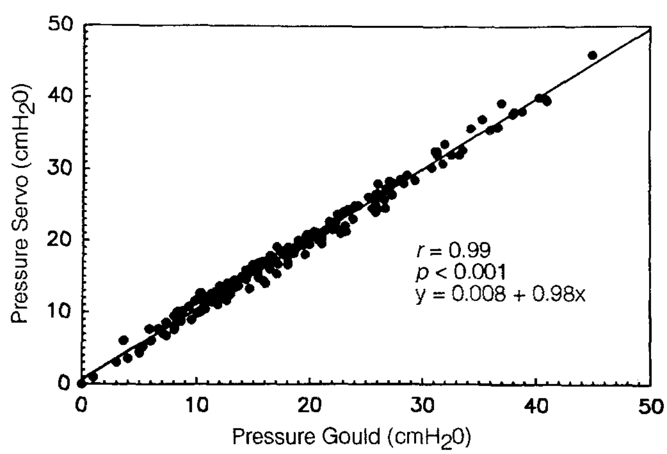

Fig. 5. Correlation in pressure measurements between both systems. The regression line did not differ from the identity line ($y = 0.008 + 0.98x$)

Table 2. Individual values of compliance (Cst) obtained as the slope of the PV curve by both methods in each patient

Patient no.	Cst GOULD $ml \cdot cmH_2O^{-1}$	Cst SERVO $ml \cdot cmH_2O^{-1}$
1	39.1	40.9
2	103.2	103.9
3	37.7	37.4
4	33.0	33.1
5	52.7	51.8
6	67.7	69.0
7	71.7	75.0
8	38.3	35.4
9	52.1	48.6
10	61.8	65.0
Mean	55.7	56.0
±SD	21.4	22.4

ject effect showed that PV curves determined by both methods were not significantly different for a given patient ($p = 0.579$), showing that the two methods are interchangeable.

Static compliance, calculated as the slope of the PV curves, ranged from 33.0 to 103.2 $ml \cdot cmH_2O^{-1}$ (mean 55.7 $ml \cdot cmH_2O^{-1}$) when obtained with the external device, and from 33.1 to 103.9 $ml \cdot cmH_2O^{-1}$ (mean 56.0 $ml \cdot cmH_2O^{-1}$) when obtained with the ventilator (Table 2). The mean difference between both calculations was 0.28 ± 2.29 $ml \cdot cmH_2O^{-1}$, resulting in a 95% confidence interval for concordance between them of +4.86 and −4.30 $ml \cdot cmH_2O^{-1}$.

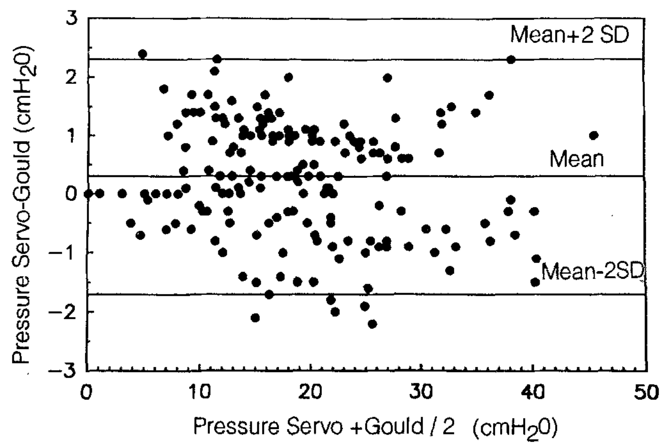

Fig. 6. Concordance analysis for pressure measurements between both systems. The 95% confidence interval ranged +2.2 and -1.7 cmH_2O

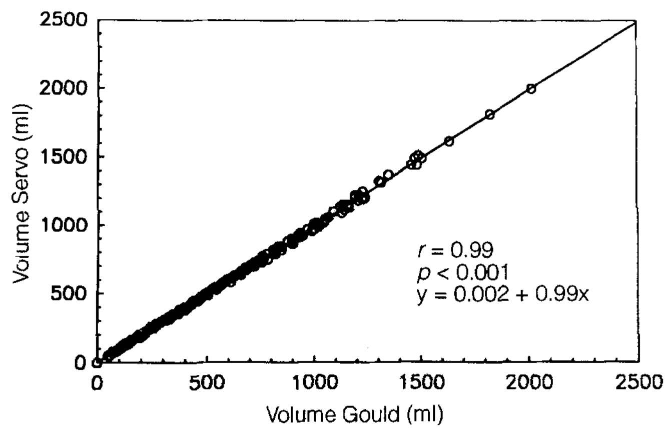

Fig. 7. Correlation in volume measurements between both systems. The regression line did not differ from the identity line ($y = 0.002 + 0.99x$)

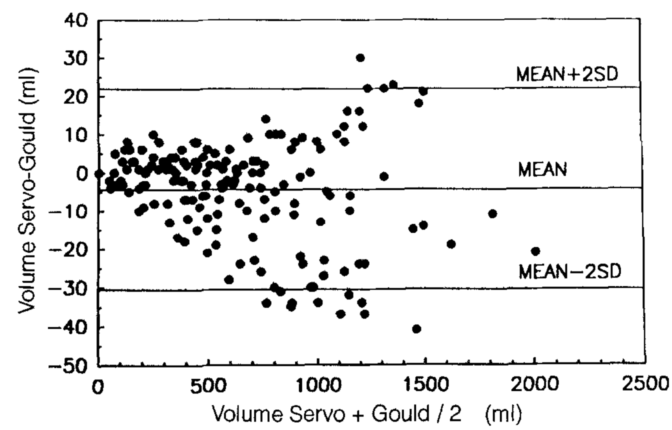

Fig. 8. Concordance analysis for volume measurements between both systems. It can be observed that values slightly vary in a systematic way suggesting the need of a logarithmic transformation

Discussion

The results of the present study demonstrated that inflation PV curves performed direrctly from the ventilator are a very accurate method to determine the elastic properties of the respiratory system in the clinical setting. Because of the arrival of this technique, the use of other sophisticated devices would no longer be required in order to obtain static pressure-volume curves.

For many years, it has been widely recognized that routine measurements of pressure-volume curves of the lungs and thorax by the super-syringe method provided supportive evidence for the presence or absence of cardiogenic pulmonary edema, noncardiogenic pulmonary edema, pneumonia, bronchospasm, mucous plugging, intubation of mainstem bronchus, atelectasis and results of subsequent therapy [14]. In many cases, an inflection point can be observed in the inflation limb of the PV curve, representing an abrupt change in thoracopulmonary compliance and suggesting that recruitment phenomena occur. Titrating external PEEP equal to the inflection presssure point had been followed by an amelioration in gas exchange in patients with bilateral pulmonary infiltrates [15, 16]. Thoracopulmonary compliance derived from the static PV curve had been proved as a predictor of mortality in patients with acute respiratory failure [17].

We have previously demonstrated that the presence of autoPEEP is the major determinant of the isovolumetric pressure increment detected at the beginning of some PV curves performed with the syringe method [6]. This artifact may probably mask the low volume inflection pressure when present [7]. The rationale to start PV curves at the pressure measured as autoPEEP, in the present study, was that for clinical purposes it may be more informative to performe this test including the trapped gas induced by mechanical ventilation, thus supporting the suggestion made by Levy and colleagues [10].

In spite of the fact the PV curve provide useful clinical information, its performance is not an ordinary practice in the ICU setting because specialized devices and trained personnel are not currently available, making it difficult to assess respiratory mechanics in ICU without technical facilities. For these reasons, in order to measure thoraco-pulmonary compliance an end-inspiratory hold (either by manual application or as a selected ventilator setting) is more commonly used. It serves to determine the static pressure, and the volume measurement is obtained from a volume-capturing spirometer or from the flow-sensing device built into the ventilator [18].

Recently, Levy et al. described a method for studying PV curves during mechanical ventilation without disconnecting the patient from the ventilator [10]. These authors obtained the signals of pressure and volume from the sensors built into the ventilator and recorded them on an external device to clearly determine the values of pressure and volume. The authors suggested that a computerized flow-integrator can help to measure volume. These requirements stop the method from being used widely. In our study we test whether these devices could be removed without lack of accuracy, making this test available to the vast majority of ICUs.

We only performed the inflation part of the PV curve due to technical restrictions. Static pressures needed to obtain the inflation limb are those achieved during inspiratory pauses at different tidal volumes. These pressures are shown on the digital display of the ventilator as "plateau pressure" and are easy to collect. In contrast, to obtain the deflation limb of the PV curve with the method of Levy et al. the manoeuver is quite different: changing the frequency during an end-inspiratory occlusion modifies the expiratory time. If the end-expiratory pause button is pressed immediately after release of the inspiratory pause button, the expiration will stop after this new expiratory time at a different lung volume. The pressure achieved is now and "end-expiratory pressure" which is visible on the analogic manometer, but not as a digital number on the ventilator display, leading to an obvious interobserver variability that should increase errors, not directly attributable to the measurement devices.

Nevertheless, the usefulness of the deflation limb of the PV curves is currently controversial [4, 5, 9]. With the syringe method there are some artifacts and errors that should be carefully controlled. A major contention about this technique is the variation induced by continuing gas exchange during the manoeuver. In paralyzed patients, the rate of decrease in the thoracic lung volume due to continuing gas exchange should amount to 110 ± 64 ml/min, involving a 50% over-estimation of the area of the hysteresis loop of the respiratory system using the syringe method [4]. This fact leads to the conclusion that inflation compliance is neither influenced by the fall in thoracic volume nor time dependent and is therefore more reliable in clinical practice. It contradicts previous studies that have shown correlations between the amount of volume lost during the manoeuver and the degree of pulmonary edema [19]. Other investigators found static compliance during deflation to be highly dependent on the total volume insuflated [20].

For these reasons, some authors have suggested that hysteresis could mainly be an artifact of the syringe method [4, 9]. An hysteresis area smaller than expected in the ARDS patient was also observed in the descriptive paper of Levy et al. [10]. The inflation limb of the PV curve shows the major components of lung mechanics during mechanical ventilation i.e. autoPEEP, inflection point and static compliance. Moreover, if hysteresis was actually only an artifact, which is not yet completely proven, inflation curve would completely describe the PV curve.

In conclusion, inflation PV curves can be accurately performed using the method of Levy with the data directly obtained from the ventilator.

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