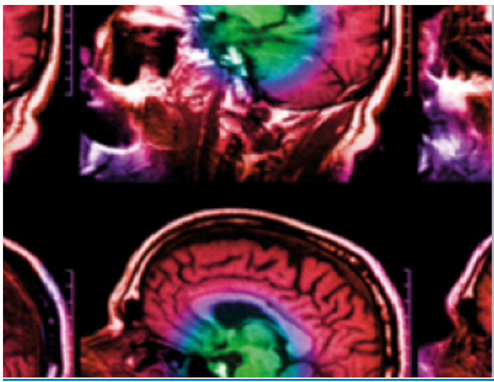
Hydration status measurement by radio frequency absorptiometry in young athletes—a new method and preliminary results*



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Hydration status measurement by radio frequency absorptiometry in young athletes—a new method and preliminary results*

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Abstract

A new method for non-invasive measurement of the human state of hydration is presented. This method is based on frequency-dependent absorptiometry of radio-waves passing through tissues. A device utilizing this method was constructed and applied to 12 young (24 ± 1) male volunteers, who were dehydrated for 1–2.5% of their weight by performance of a physical effort (two 30 min bouts of treadmill walking/running at 2, 3, 4, 5, 6 and 7 mph, 5 min at each speed, separated by 10 min rest), under moderate heat stress (40 °C, 40% RH). Hypohydration level was determined by body weight measurements taken before each session, after 30 min and at the end of each session. Concomitantly, measurements of radio frequency (RF) absorption were taken. Each volunteer underwent the heat stress exercise twice: one in which no drinking was permitted, and another with free drinking. A correlation ($R^2 = 0.734$) between weight loss and a change in the radio-waves absorption pattern was observed in most of the volunteers, in both hypo and euhydration sessions. Further work to establish the reproducibility and validity of the RF methodology in larger and different populations, i.e., females, other age groups and different health conditions, is already being researched.

Keywords: sweat rate, dehydration, RF absorption, non-invasive

* US and International Patents pending.

1. Introduction

The degree of hydration is an important factor in the well being of humans, and severe deviation from the normal hydration state may have fatal results.

Current technology provides hydration (osmolality) status measurements only by blood samples, analysed in laboratories. Although accurate, this process is impractical in many circumstances, especially in fieldwork with wounded or collapsed persons in urgent need of fluid resuscitation for maintaining correct body fluid levels.

Measurements of the electrical impedance of the body have been used to measure the hydration status (Lozano-Nieto 1998) by measuring the electric current passing between two electrodes attached to two body parts (i.e. wrist and opposite ankle). This current is, however, contingent mainly on the size of the organs involved and not only on the fluid osmolality, thus making this method extremely dependent on the anatomy of the examined person and on factors such as temporary constriction or dilation of the blood vessels in the body. This method is therefore limited to the detection of shifts in body fluid balance, and is not applicable to direct measurements of this parameter. In 1999, O'Brien *et al* concluded that bioimpedance is sufficiently sensitive to detect moderate hypohydration; however, the resolution of this technique diminished with isotonic fluid loss (O'Brien *et al* 1999). In 2002, O'Brien *et al* concluded in another study that the bioimpedance methodology is not valid for different levels of hypohydration (O'Brien *et al* 2002).

Development of a new device based on a non-invasive method for measuring hydration status is thus of practical value. The work presented here reports the results of a preliminary feasibility check of a method, based on radio frequency (RF) absorption pattern by tissue, for measuring the dehydration state of human beings *in vivo*, in a non-invasive manner.

1.1. Physiological background

Active populations, including athletes, blue-collar workers and military personnel, under heat stress, frequently become hypohydrated by 2–4% of their total body weight (TBW). These values are equivalent to a loss of 1–3.5 l for a 75 kg individual. This amount is enough to increase heat strain (Montain *et al* 1998), cardiovascular strain (Montain and Coyle 1992, Saltin 1964b) and to reduce or degrade aerobic and anaerobic (Webster *et al* 1990) exercise performance (Webster *et al* 1990, Armstrong *et al* 1985, Burge *et al* 1993, Saltin 1964a).

Hypohydration might accelerate depletion of energy stores, accumulation of metabolites (e.g., lactate, phosphor inorganic, H_+) and induce changes in intracellular electrolyte concentration (Montain *et al* 1998, Costill and Saltin 1975, Fogelholm *et al* 1993, Horswill 1992, Nielsen *et al* 1981), which is expressed in reduction of muscle endurance. The reduction in body weight increases heat strain during exercise, and the higher the reduction, the higher the elevation in core temperature (Montain and Coyle 1992, Adolph 1947, Montain *et al* 1995, Sawka *et al* 1985, Strydom and Holdsworth 1968). The latter is mainly due to the fact that hypohydration impairs the ability to dissipate body heat.

Dehydration of healthy persons under excessive heat stress is due mainly to loss of fluids through sweating. Although sweat contains some solutes, typical sweat osmolarity is $\sim$60 mmol l^{-1}, which can elevate during intense sweating due to sweat reabsorption, as compared to typical plasma osmolarity of $\sim$285 mmol l^{-1} when euhydrated (Sawka 1992). These values are also valid for other common causes of dehydration (vomiting, diarrhea). Loss of more than 8% of body weight in fluids is considered fatal. It is thus evident that rapid sweating produces an increase in the osmolarity of body fluids. The method and device presented in the following aim at measuring non-invasively this change in osmolality, and at deducing the hydration state from this.

1.2. Physical background

Electromagnetic (EM) waves interact with tissue water and solutes, but the mode of interaction varies according to the wave frequency: at a few MHz (center frequency ~3 MHz) ion currents are induced in the tissue fluid. It should be noted that although a free ionic conduction path does not exist for most of the fluids, a large capacitive conduction prevails. This is due to the very large (total) cell membrane area versus its very small thickness, resulting in a large capacitance. The electrical conduction in this frequency range depends strongly on the quantity of water solute available for conduction. This ionic conduction process results in energy absorption by the tissue, and consequently, in the attenuation of the wave amplitude, which is dependent on the solute quantity. This absorption process is commonly referred to as the *Beta* dispersion of EM waves in tissue (Polk and Postow 1996).

At higher frequencies the masses of the various ions dissolved in tissue fluid are too large to permit considerable motion of the ions in response to the fluctuating EM field, and the *Beta* dispersion diminishes. Instead, an interaction mode known as the *Gamma* dispersion (Pethig 1979), takes over; the water molecules themselves rotate to align their electric dipole with the fluctuating EM field. This rotational motion absorbs part of the EM wave energy, but here the absorption is dependent on the quantity of water molecules. It should be noted that the transition from *Beta* to *Gamma* dispersion is rather gradual. Below ~1 GHz, the beta dispersion is dominant, while above ~3 GHz the *Gamma* dispersion takes over.

The aim of this study was to examine a new (Bickels and Margaliot 2000) non-invasive method of measuring hydration state *in vivo*, based on the comparison of attenuation of radio waves by tissue at two frequencies, the lower one in the *beta* dispersion region, representing the solute quantity in the tissue under examination, and the higher in the *gamma* dispersion region, representing the water quantity in the same tissue. Comparing the attenuations at these two frequencies is thus indicative (Bickels and Margaliot 2000) of the ratio of the quantities of ionic solutes and the water in the tissue examined, namely, of the osmolality in this tissue.

2. Materials and methods

2.1. Physiological parameter measurements

Subjects. Twelve young, healthy males volunteered to participate in this study. The physical characteristics of the subjects were as follows (mean ± SE): age 24 ± 1 yr; height 175 ± 2 cm; weight 71.54 ± 3.13 kg; and body surface area 1.71 ± 0.15 m^2. Prior to the experiment, each subject underwent a medical examination that included a complete medical history, electrocardiogram at rest, urine analysis and blood screening biochemistry. Subjects were informed as to the nature of the study and potential risks of exposure to exercise in a hot climate. This study was approved by the human use committee of the Sheba Medical Center, and all subjects signed an informed consent form.

Protocol. The study was conducted in the climatic chamber at the Heller Institute of Medical Research, Sheba Medical Center, Tel Hashomer, Israel. Twenty-four hours prior to each measurement session, the subjects were examined and found to be in good medical condition and stated that they had not taken any prescribed or unprescribed medication or alcohol. The subjects wore only shorts and sport shoes, and performed the exercises in hot-dry climatic conditions of 40 °C, 40% relative humidity (RH) for 70 min, consisting of two 30 min bouts of treadmill walking separated by a 10 min rest period. Each subject performed two exercise sessions, which differed in their hydration state. In one exposure session, subjects were allowed to drink *ad libitum*, while in the other they had to refrain from drinking. In both heat stress exposures (hypohydration and euhydration), the subjects walked or ran for two 30 min bouts on a treadmill at 2, 3, 4, 5, 6 and 7 mph (5 min at each speed) separated by 10 min rest. Hypohydration level was determined by measurements of fluid balance based on body weight measurements corrected for water intake, at three points: before the exposure, and at the end of each bout (after 30 and 60 min, respectively).

Measurements. During the exposures, rectal temperature (T_{re}) and heart rate (f_c) were continuously monitored and recorded at 1 min intervals. T_{re} was measured by a thermistor probe inserted 10 cm beyond the anal sphincter (Yellow Spring Instruments series 401). Heart rates were monitored and recorded on-line through bipolar chest leads using Polar™ belt electrodes (Polar CIC). Sweat rate and hypohydration were calculated from changes in body weight (Shinko Denski $\pm$5g) before, after 30 min and after 60 min of the heat stress/effort, corrected for water intake and urine. The physiological strain index (PSI), constructed from simultaneous measurements of heart rate and core temperature and which assesses the strain on a universal scale of 0–10, was calculated according to Moran *et al* (1998).

2.2. RF device and measurements

RF absorption measurements were conducted on the wrists of the subjects. The wrist was chosen for two main reasons. First, the planned final device is a wristwatch-like instrument, since the location is convenient and the watch can then also be used for other functions. Second, the wrist is a relatively non-hydrated organ that includes bones and ligaments, with a few muscles, and contains a relatively large amount of blood vessels. This composition minimizes the possible measurement of artifacts due to the transfer of water between body compartments.

The measurement device consisted of a power source (Wavetek 2002A signal generator operating at 13 dBm output), two antennas (transmission and reception, $1/8\lambda$ at 916 MHz), a power sensor (Bontoon 51013), and an exposure chamber, holding the transmission and reception antennas, and incorporating a space for the insertion of the wrist. The antennas were basically patch antennas, 4.1 cm long and 1.5 cm wide, placed with a separation of 9 cm in a wave-guide (7.5×5 cm internal cross-section) in which a gap was opened for the insertion of the wrist. Insulation of 3 mm thickness was placed over the gap to ensure that there was no contact between the wrist and the antennas. The output of the power meter was taken as the voltage difference at its output port in mV. The frequencies used in this experiment were 450, 916, 1340 and 2120 MHz (two frequencies were used to represent each dispersion region).

A schematic description of the device is presented in figure 1(a), and an actual picture of the device is shown in figure 1(b).

2.2.1. Design considerations

Choice of frequencies. The basic idea described above does not necessitate the use of specific frequencies, and thus the frequencies used were adopted because of the presence of local resonances in the combination of signal-generator, transmission/reception antennas and the chamber itself.

Reflection damping. The device construction incorporates RF absorbent sheets at the edges of the chamber (figure 1(a)) in order to reduce internal reflections, but these are also strongly attenuated by the presence of the wrist itself.

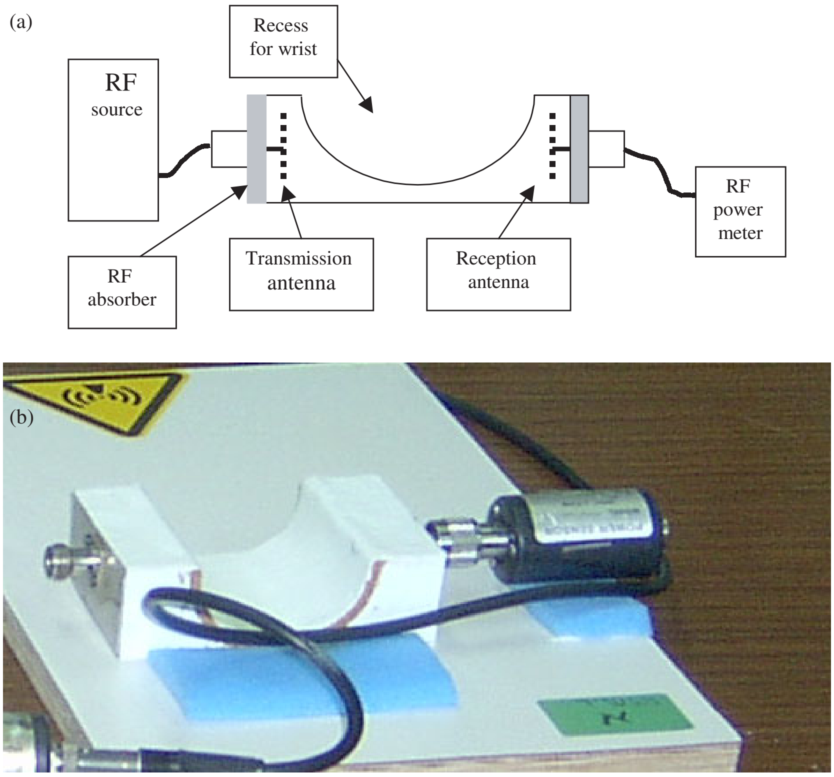

Figure 1. A schematic description (a) and picture (b) of the RF absorption device for hydration status measurement.

(This figure is in colour only in the electronic version)

Calibration. The very complex electrical properties of an organ such as the wrist, combined with the extremely complex behavior of the electromagnetic waves in the reactive near field present in the chamber, render a simple simulation impractical. Therefore, we had to use the human experiment itself for the basic calibration procedure.

2.2.2. Statistical analysis. All the data obtained in the present experiment (the RF device readings and the loss of body weight) were analysed by two-way analysis of variance. The statistical parameters presented below have a significance of $P < 0.05$. The data are presented in the following as mean ± SE.

The readings obtained from the RF device at the above four frequencies were used as parameters in a formula (equation (1)) to yield a predictor, or RF index of the hydration state. This predictor represents the least-squares best fit between the RF index derived from the RF readings and the loss of body weight.

3. Results

The responses (mean ± SE) of f_c (top panel), T_{re} (middle panel) and the obtained PSI (bottom panel) in the euhydration and hypohydration states are described in figure 2. Higher

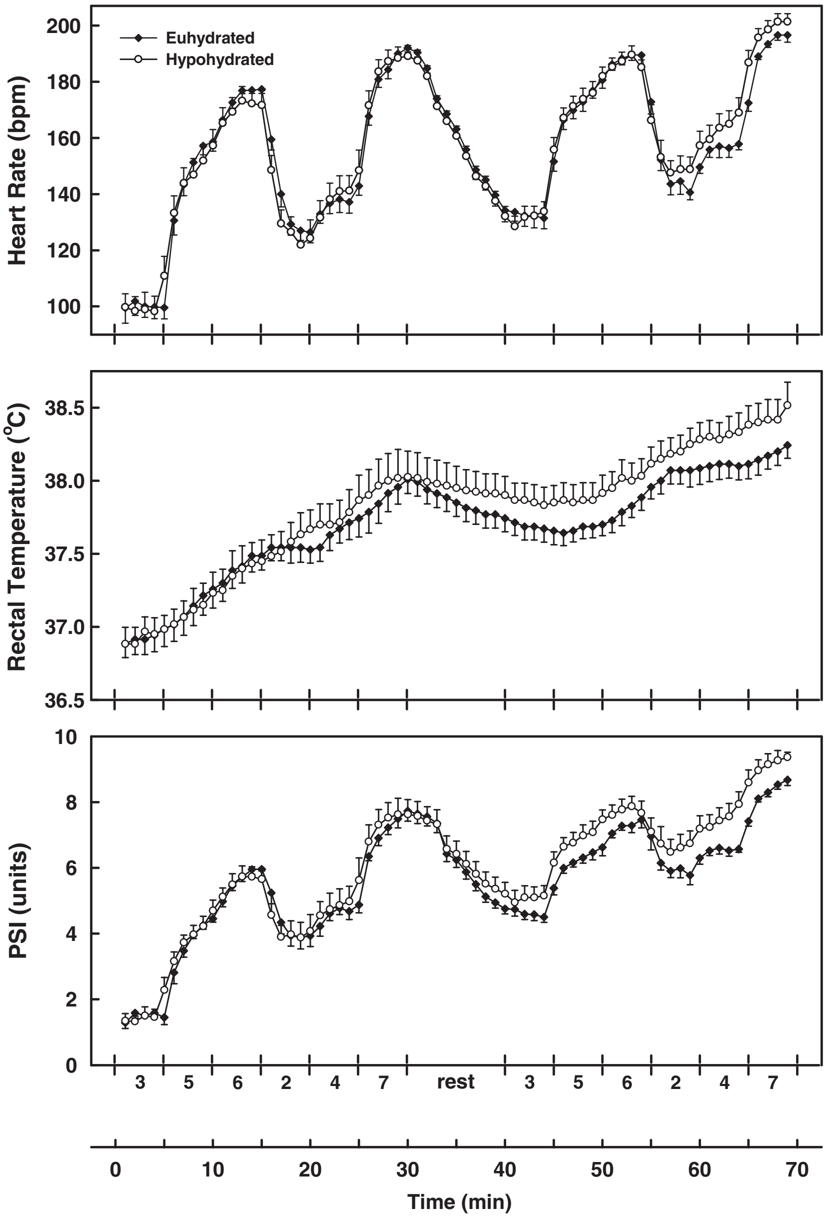

Figure 2. Mean(±SE) of the physiological strain index (PSI) (bottom panel) calculated from rectal temperature (middle panel) and heart rate (top panel) obtained from 12 subjects during 70 min of heat stress (euhydration (♦) and hypohydration (O)).

physiological strain found for the hypohydrated subjects is depicted in higher values of f_c, T_{re} and PSI. However, significant differences ($P < 0.05$) between these two sessions were found only for PSI during the second bout of heat stress (40–70 min), and reflected higher physiological strain for the hypohydrated subjects, at this stage.

The loss of body water in sweating is expressed in an easily observable loss of weight. In the present study, the weight loss for the hypohydration sessions during the 30 min of heat stress was about 0.78 $\pm$ 0.06 kg, and after 60 min was 1.59 $\pm$ 0.08 kg. This parameter is widely recognized (Pethig 1979) as a reliable dehydration indicator, representing dehydration for these subjects at a range of 1.0–2.5% of total body weight (TBW).

Equation (1) was obtained by fitting a combination of the RF readings to the body weight loss (BWL), using the backward elimination method, where at each stage the variable with the smallest F-value was dropped from the model. The backward elimination resulted in equation (1) including nine independent factors as follows:

$$\begin{aligned}\mathrm{BWL} = \mathrm{IF} &+ 5.77 \times 10^{-4} S_4 + 3.82 \times 10^{-6} S_1 S_3 - 1.344 \times 10^{-6} S_3 S_4 \\ &+ 2.236 \times 10^{-1} S_1/S_3 - 5.98 \times 10^{-2} S_2/S_3 + 1.094 \times 10^{-1} S_2/S_4 \\ &- 3.743 \times 10^{-1} S_3/S_4 - 2.84 \times 10^{-6} S_1^2 \end{aligned} \tag{1}$$

where BWL is the loss of body weight (% of initial weight), IF is a constant (the value of which is different for each person) obtained from each initial RF measurement, and S_1, S_2, S_3 and S_4 are the power meter readings in mV at 450, 916, 2120 and 1360 MHz respectively. IF is obtained by setting BWL = 0 in equation (1) for the S_1, S_2, S_3 and S_4 obtained while the subject is euhydrated (namely, before starting the effort). Applying equation (1) to the data obtained in the experiment yields a good correlation coefficient ($R^2 = 0.734$) between the predicted BWL, and the actual BWL measured.

Figure 3 (bottom panel) presents this correlation between the measured and the predicted body weight losses reflected in hypohydration in all the subjects participating in this study, with the residual distribution (top panel) around the zero line.

4. Discussion

In this study we developed and built a device utilizing RF transmission measurements at four frequencies, conducted on the wrists of human beings (young, healthy males) under various degrees of dehydration. The RF readings thus obtained were combined by an empirical equation, to predict the loss of weight due to sweating. The predicted values thus obtained were compared with the observed loss of weight at different levels of hypohydration (0.5–2.5% from TBW). A good correlation ($R^2 = 0.734$) was obtained between the measured and predicted weight losses.

Each of the subjects was tested twice, during both euhydration and hypohydration heat stress sessions. In all, each person was tested six times by the RF absorptiometer. The above correlation was obtained, although an exact placement of the wrist in the device was only partially attainable because, even though the volunteers were asked to maintain the same position in the device in each measurement, we used no mechanical positioners to ensure this. This fact indicates that it is the amount of tissue inserted into the device cavity that determines the result, indicating some immunity to exact placement. The RF predicted weight loss correlated well with the observed loss under both the hypo and euhydration conditions. Both observations thus back up the conclusion that the changes observed in the RF transmission measurements were due to the changes in the hydration status and not to other confounding physiological factors. In a preliminary test of this RF device, we measured the same values before and after 10 min of heat stress, which explained that RF absorption does not represent body water shifting, but body water loss.

The RF absorption measurements presented above involve a short (a few seconds) exposure to radio waves of a small part of the body at a very low intensity. In the experiment conducted, the power density at the wrist was $\sim$1 μm W cm^{-2}, (determined by a Wandel & Golterman EMR 300 RF power density meter, under valid calibration), which is approximately

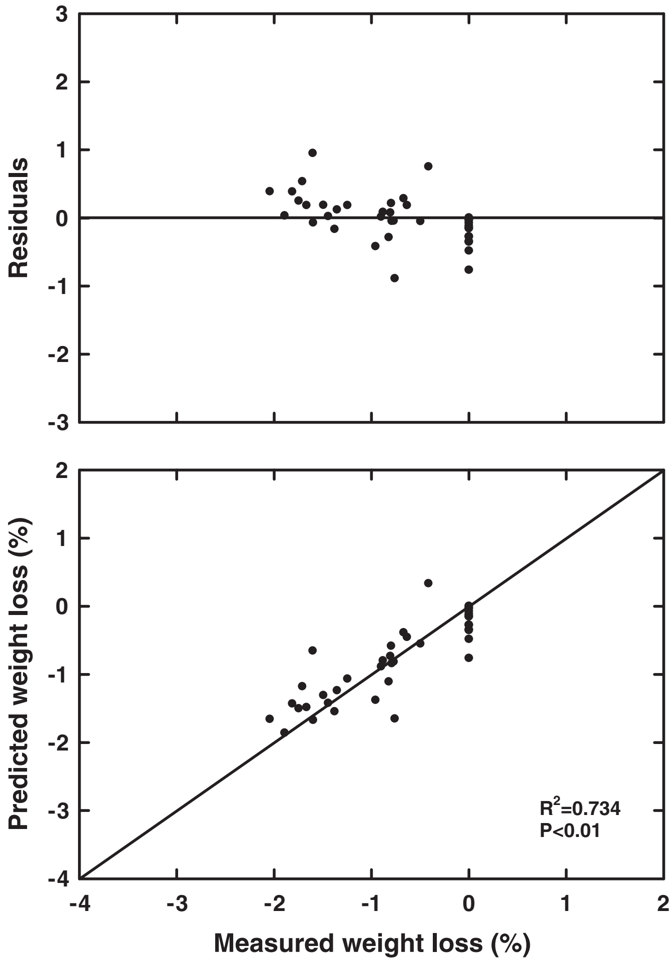

Figure 3. Comparison of predicted body weight loss (BWL) with measured BWL in euhydrated and hypohydrated subjects due to sweating (bottom panel) and residual scattergram (top panel).

0.01% of the whole body continuous exposure permitted by the American Conference of Governmental Industrial Hygienists (ACGIH 2000).

The exposure levels in improved versions of this device are expected to be considerably lower than that, due to much shorter exposure durations and considerably lower transmission power levels. It can thus be stated that the measurement process described in this study involves no RF radiation hazard according to prevailing safety standards (ICNIRP 1998).

This preliminary study presented, which was performed on young fit males, suggests an aid tool that can be used in the decision making process, especially for exercising individuals and physical workers who are at risk of hypohydration. However, because of this study design and the nature of the subjects tested in this study, further work regarding different levels of hypohydration (e.g., 3–5% body weight loss), body mass, gender, age, general physical condition of the examined persons, and environmental conditions (e.g., low external temperature) is needed for a fuller validation, extrapolation for other populations, and development of the present method.

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