

Coplanar Capacitive Matrix Structures Used for Monitoring the Recovery of Burn Injuries

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Abstract – This paper presents a study regarding a coplanar capacitive matrix structure used for monitoring the burn injuries recovery process. The monitoring method presented can be applied for superficial burns (first degree) and partial thickness burns (second degree). The aim of this paper is to confirm the simulation results through a practical experiment. Constructive aspects regarding the coplanar capacitive structure are also presented. In order to predict the behavior of the implemented structure in the vicinity of a burn injury, several functional simulations were made. In this case, the electrical relative permittivity of the environment was changed according to different imposed conditions. Laboratory measurements were performed in order to reproduce as close as possible the real situations. The experimental results show that the presented method can be a viable alternative to actual methods used for monitoring the burn injuries, not necessarily by replacing them, but mostly to provide additional information to the medical staff.

Keywords – coplanar capacitor, capacitive matrix, burn injuries, capacitive monitoring, burn recovery.

I. INTRODUCTION

Monitoring the recovery of the burn injuries is an actual concern in medical research. It is very difficult to investigate how the injuries are healing, without removing the incrustation of the burn or by monitoring with complex imagistic procedures.

This paper presents the possibility to estimate and monitor the state of a burn injury in real time, using a coplanar capacitive matrix structure inserted in different patches, bandages or applied directly over the wound.

The implementation of the coplanar capacitive matrix structure is relatively simple in terms of its construction. The coplanar capacitive sensors in a matrix configuration allow the discretization of a certain surface and the tracking of the evolution of monitored parameters on individual small areas. In this way, without requiring the presence of a complex imaging device, the evolution of biological parameters can be monitored in real time.

Conventional methods of monitoring anisotropic media, such as ultrasound investigation, tomography scanning, and magnetic resonance imaging restrict the investigations at a laboratory level, limiting the subjects' mobility.

Using the coplanar capacitors for monitoring the parameters gives many advantages and solutions to the discussed problems. The small dimensions of those sensors and the simplicity of the conversion method from a nonelectric measure to a variation of capacitance are a real advantage compare to other methods of measurement.

II. RELATED RESULTS IN LITERATURE

Capacitive methods of measuring various parameters can give essential information in real time about: concentration of some reagents, the stored volume, the degree of alteration of substances, the dosage monitoring, the kinetics of chemical slow reaction, etc.

In 2012, a capacitive sensor used for measuring the complex permittivity of planar and cylindrical structures was presented in "Graduate Theses and Dissertations-12294" on "Iowa State University", USA. [1]

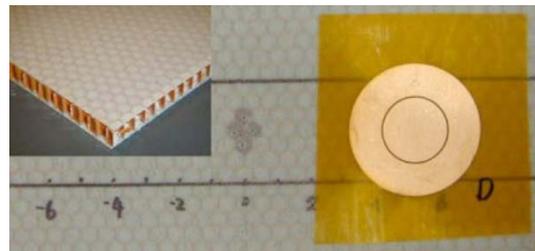


Fig. 1. Coplanar capacitive sensor used for measuring the permittivity of planar and cylindrical structures[1]

In order to analyze the water intrusion in random structures, water ingress experiments based on a sandwich structure were made.

Fig. 2 presents an optical micrograph of an epidermal hydration sensing system and the schematic illustration of a concentric coplanar capacitor from 3-D perspective view of the single-layered model, published in 2013 by a researcher group from "Northwestern University", Evanston, USA, "Tsinghua University", Beijing, China

and “University of Illinois”, USA. [2].

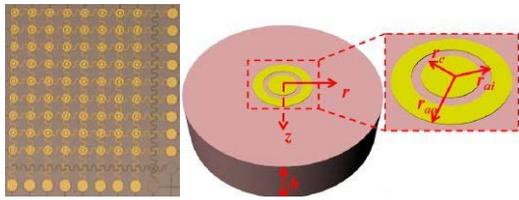


Fig. 2. Coplanar capacitive matrix structure used for epidermal hydration sensing [2]

This device can predict the hydration level of the tissue measuring either the capacitance or the impedance. The study also analyses the influences of motion-induced changes and provide analytical and simulation results that sustain the method.

In 2015, the researchers from “Faculty of Technical Sciences”, University of Novi Sad, Serbia, has investigated the possibility to conduct a non-invasive identification process of liquid samples packed in glass and polypropylene containers [3].



Fig. 3. Coplanar capacitor used for non-invasive identification process of liquids [3]

In Fig. 3 are presented two capacitive structures used for non-invasive liquid recognition based on interdigital capacitor.

In 2016, a study made by the “Department of Automation Measurement and Control Engineering”, Harbin Institute of Technology, China, analyses the segmented annular coplanar capacitive tilt sensors with increased sensitivity [4].

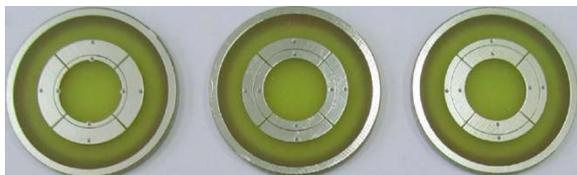


Fig. 4. Coplanar capacitive tilt sensors [4]

The results were focused on mathematical expression of the capacitance value and experimental results that confirm the utility of coplanar capacitors in various engineering fields.

Regarding the capacitive imaging methods, one of the most recent studies is provided by the “Department of Electronic and Electrical Engineering”, University of Strathclyde Technology, Glasgow, UK. [5]

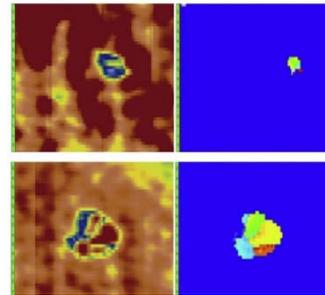


Fig. 5. Coplanar capacitive imaging method [5]

The results present the differences between ultrasonic scans (left) and capacitive non-destructive imaging (right) of impact damage in woven fiber using a coplanar capacitive sensor.

Even if in this paper only the significant results in the field were presented, many researchers are focused on developing measurement methods that use coplanar capacitors.

III. CONSTRUCTIVE ASPECTS

The presented method consists in determining the water concentration in a certain skin area, by measuring the variation of the capacitance of a coplanar structure.

Several coplanar capacitive matrix structures were built in order to analyze the behavior of those sensors in the vicinity of an environment that reproduces the real configuration of a burned area.

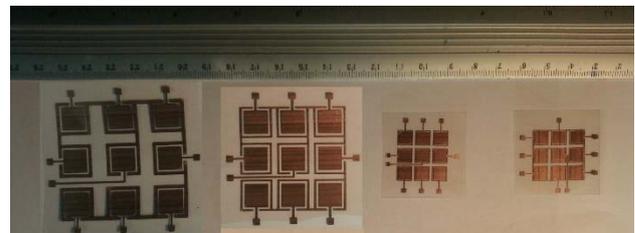


Fig. 6. Coplanar capacitive matrix structures

The development process of the presented coplanar capacitive structures contains several steps:

- choosing the geometry and dimensions in close connection with the monitoring area;
- printing the capacitive structure geometry to a copper layer through thermal transfer;
- lamination of the unprinted side of the copper layer with a polyethylene foil before the corrosion process;
- removing the unnecessary copper through a corrosion procedure;
- external terminals attachment;
- sealing the coplanar matrix through a second laminating process, on both sides, avoiding the situation that any external substance interacts with the capacitor.

IV. FUNCTIONAL SIMULATIONS

In order to predict the behavior of the analyzed structures, some simulations were performed using the COMSOL Multiphysics® software. The used module of this software was: „Electrostatics”.

The water concentration from the skin layers will be the principal factor that influences the electrical relative permittivity. The situations that involve the presence of a drug substance should be considered. [1]

In this condition, for the functional simulation, we considered the variation of the relative permittivity of the environment close to the values of the human skin: $\epsilon_r=20...50$. [1]

The basic idea of the model was the fact that the electrical capacitance is influenced by the variation of the electrical permittivity of the environment in which the capacitor is placed in. The simulation results will show if this variation is significant enough to be measured.

In the simulation, a matrix with nine capacitors was considered. Each capacitor has the same dimensions as the real structure used later for the experiments.

In order to simulate the structure of a burn injury, the environment under the coplanar capacitive matrix structure was divided in small cubes. Modifying the relative permittivity of those cubes, allows us to configure several cases that can be found in a real situation.

The simulation’s purpose is to determine the capacitance variation in close connection to the variation of the electrical relative permittivity of the medium. Several domain and boundary conditions were imposed, as it is shown in Fig. 7 which represents a simplified sketch for one capacitor only.

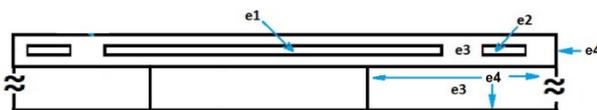


Fig. 7. Simple sketch of the computational domain

The domain conditions are: electric potential, $V=5V$ (e1 Fig. 7), for the capacitor’s voltage armature, zero voltage, $V=0$ (e2 Fig. 7), for the capacitor’s ground armature and charge conservation, $E = -\nabla V$ (e3 Fig. 7), for the rest of the domains.

The boundary conditions are similar to the domain condition for the armatures boundaries and continuity for all the remaining interior ones, (no other condition overwrites the interior boundary condition, so the software ensures continuity in the field variables across the interior boundaries). For the exterior boundaries the condition is zero charge, $-nD = 0$ (e4 Fig. 7), for the exterior ones, where n is number of charge carriers and D is the electric displacement field.

After the simulation conditions were imposed, the next step was to discretize the geometry.

The model was divided in tetrahedral volumes, the number of freedom degrees being around 350000 to

obtain a convergence under 10^{-5} .

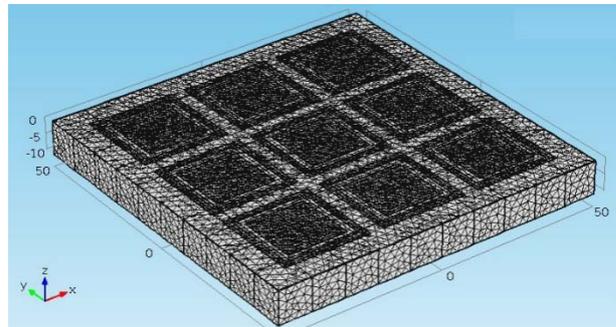


Fig. 8. The representation of the mesh for the analyzed model

For simplifying the simulation, the coplanar capacitive matrix structure does not include the external terminals. The influence of the terminals in final result is not relevant, being at least ten times smaller than the estimated variation of capacitance in any circumstances.

Fig. 9 presents the electric potential distribution in the computational domain in three different slices and the normalized electrical field in the central part of the model.

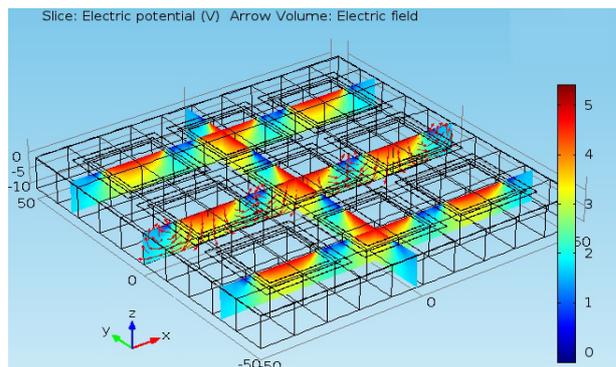


Fig. 9. Simulation result for the cubic environment with $\epsilon_r=50$

This representation was made for a stationary situation in which the relative permittivity of the small cubes was considered $\epsilon_r=50$, this value being used further as the permittivity of a healthy tissue.

The main idea of the functional simulation was to define several structures of a burn injury by imposing an initial value of relative permittivity for a certain area. The values will be close to the healthy tissue one as long it will be away from the center of the injury. Three layers were considered: 100%, 70% and 40% of the value of the healthy tissue. In that manner, an initial value of $\epsilon_r=20$ was considered for the most damaged tissue area. The parameters will vary continuously until all the analyzed domains will reach the value of $\epsilon_r=50$, this situation signifying that the burn injury has healed.

Several cases that can reproduce the real situations were analyzed. In this paper only three of them are presented.

A. Case 1: Most damaged area is in left lower corner

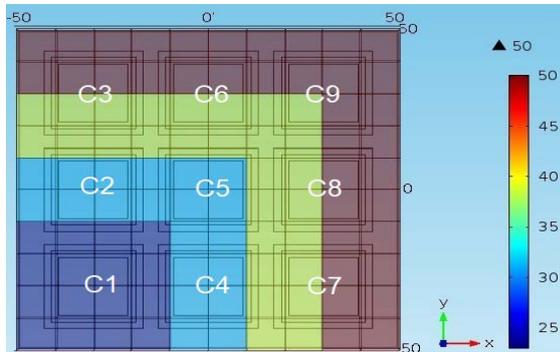


Fig. 10. The initial values for the electrical relative permittivity of the medium in analyzed case 1

As it is shown in Fig. 10, the capacitors have been numbered for an easier interpretation of the results.

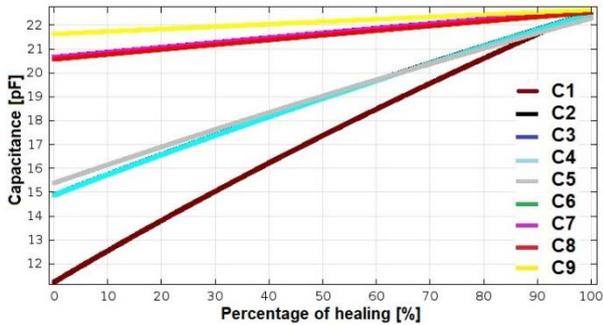


Fig. 11. The variation of the capacitance in the healing process for case 1

The variation of the capacitance under the most damaged area, C1, is around 11pF. The adjacent capacitors – C2, C4 and C5 have a variation about 7pF. The variation of the rest of the capacitors is insignificant in this case.

B. Case 2: Most damaged area is in left lateral middle

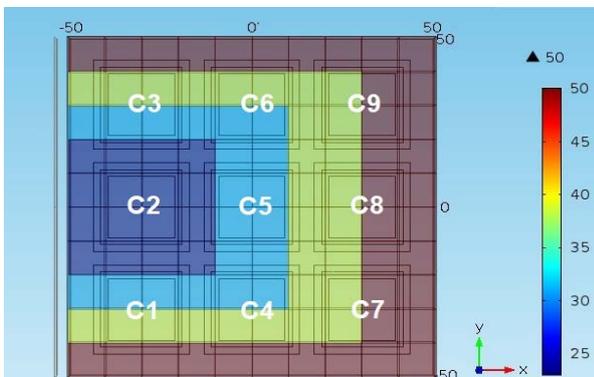


Fig. 12. The initial values for the electrical relative permittivity of the medium in analyzed case 2

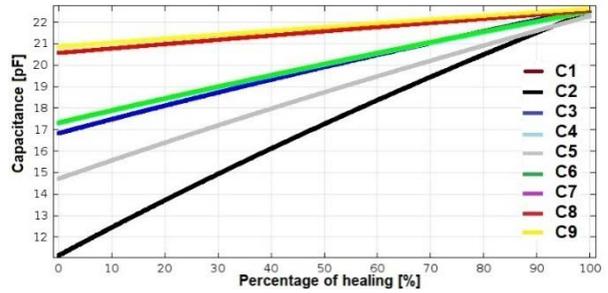


Fig. 13. The variation of the capacitance in the healing process for case 2

The variation of the capacitance under the most damaged area, C2, is around 11pF. The adjacent capacitors – C1, C3, C4 and C6 have a variation about 4pF. The capacitor C5 value -that includes three different areas- is around 6pF and the variation of the rest of the capacitors are insignificant in this case.

C. Case 3: Most damaged area is central

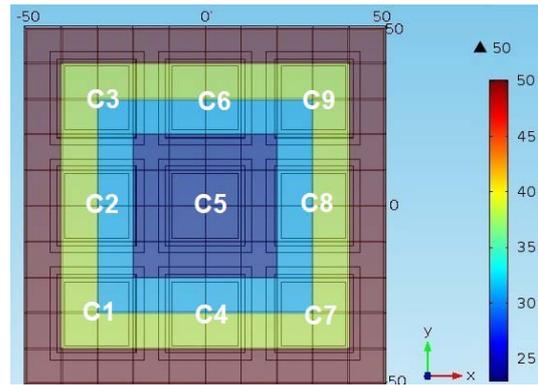


Fig. 14. The initial values for the electrical relative permittivity of the medium in analyzed case 3

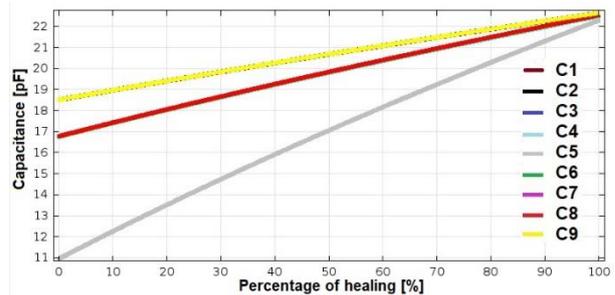


Fig. 15. The variation of the capacitance in the healing process for case 3

The variation of the capacitance under the most damaged area, C5, is around 11pF. All the capacitors from the corners have a variation about 3pF and the ones from the lateral middle around 5pF.

The modelling results show that the variation of the capacitances are significant and can be measured through usual laboratory instrumentation methods.

V. EXPERIMENTAL RESULTS

Because the medical devices testing procedures are regulated by a strict legislation, laboratory measurements were performed in order to reproduce as close as possible the real situations. The measurement method can be adapted for different practical situations.

Considering that each person has different hydration levels of the skin layers, it may be recommended that an initial measurement should be made on a healthy area. The measured values will be compared with ones obtained in an injured surface.

In order to gain a better perspective, a real time, direct comparison measurement is performed between two identical coplanar capacitive structures placed symmetrically on an injured and on a healthy area of the body. In order to decrease the experiments' time, a reverse procedure was performed. Starting with an empty porous material, a fixed volume of substance was injected into the substance layer until saturation occurs.

The experimental setup is presented in Fig.16 and contains: the coplanar capacitive matrix (1), the porous material support of the capacitive structure (2), the automatic syringe pump (3) and the digital RLC-meter (4).

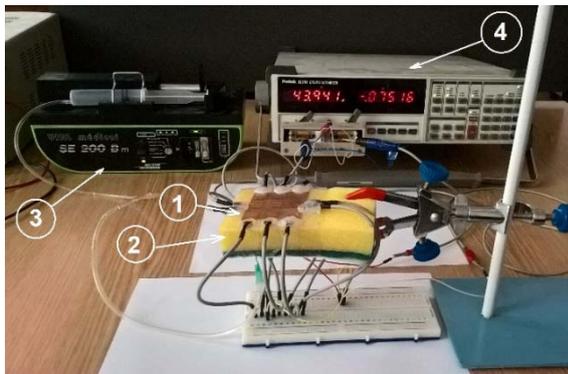


Fig. 16. The experimental setup used for capacitors testing

The presented structure allows the measurement of any individual small capacitor or in different series or parallel combinations.

In order to reproduce the cases that were simulated in the previous chapter three identical coplanar capacitive matrices (1) were used and same configuration of the porous support (2) as it is showed in Fig.17.

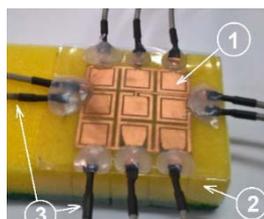


Fig. 17. The placement of the capacitive matrix on the porous material

The interior armature of each capacitor is a square with a surface of 1cm^2 . The wires (3) that connect the capacitive structure to the measurement circuit must be shielded to avoid external influences and additional parasitic capacitances.

The experimental procedure consists in injecting an amount of distilled water in different points of the porous support, under the capacitive structure and measuring the capacitance variation of each capacitor of the matrix. This reverse approach allows us to simulate the anisotropic environment created by different concentrations of substance.

The measurements were made with a 33pF capacitor in parallel to each small capacitor of the matrix. A volume of 5ml of liquid was injected continuously with the aid of an automatic syringe pump. The measurements were made every 0.5ml . The results present the difference between the initial values, when no liquid is present in the porous material and the capacitance at every step of the experiment.

A. Case 1: Liquid injected under the left lower corner

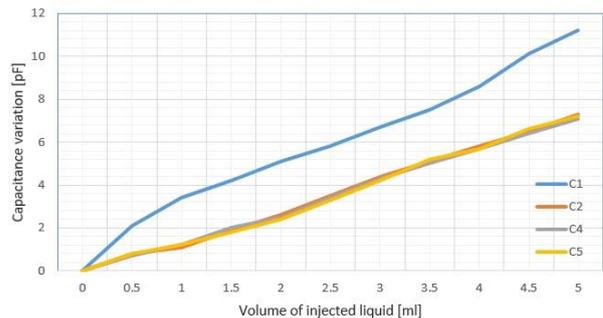


Fig. 18. The variation of the measured capacitance in case 1

The variation of the capacitance of the left lower corner capacitor, $C1$, where the concentration of the liquid is higher, was around 11 pF . The adjacent capacitors had variations around 7 pF .

B. Case 2: Liquid injected under the left lateral middle

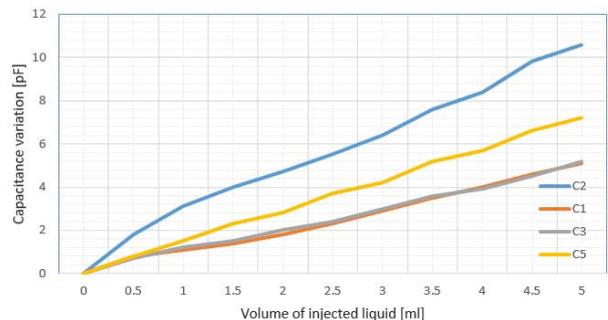


Fig. 19. The variation of the measured capacitance in case 2

The variation of the capacitance in the most influenced area, $C2$, was around 10 pF , the adjacent ones ranging from 5 pF to 7 pF .

C. Case 3: Liquid injected under the central capacitor

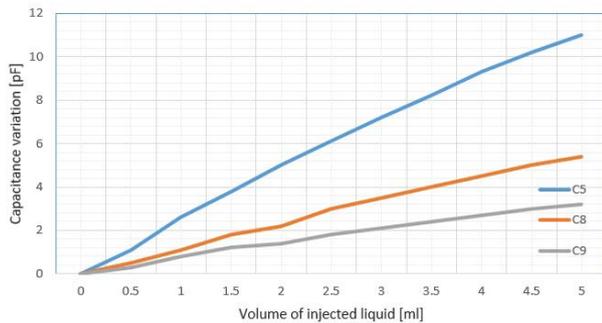


Fig. 20. The variation of the measured capacitance in case 3

In the case where the substance was injected in the center, the capacitance variation of the sensing element was around 10.5 pF, while the perpendicular adjacent capacitors varied with 5 pF and the diagonal ones with 2.5 pF.

Repetitive measurements were made, the results being relatively similar, in the interval of ± 0.5 pF.

VI. CONCLUSIONS

The variation of the capacitances obtained from measurements, even if they are relatively small (pF), are similar with the usual values commonly found in actual capacitive methods, such as: tactile sensorial systems, fingerprint readers, humidity sensors etc. The sensitivity and accuracy with which these simple elements detect the variation of the dielectric permittivity of a media in the proximity of the sensor, allows the integration of the capacitive elements in complex integrated structures. Moreover, the coplanar embodiment significantly reduces the size of the capacitors, the thickness of a sensing element being reduced to micrometres.

The matrix structures that are the subject of this paper allow a discretization of the interest surface, offering the possibility of local detection of the monitored parameters, compared to classical solutions on which a single sensing element with a large covering surface, integrates the effects on the specific area. The result will be a map of the surfaces, in terms of the monitored parameters, that will allow studying the variation in real time, limitations being introduced only by the size of the matrix structures being used.

The ability to control each individual capacitive element of the matrix is a major advantage over currently used methods. The geometry of the matrix structures proposed allows the use of a variable frequency measurement method, which facilitates in-depth area monitoring. The coplanar capacitive matrix structures can offer a solution as a response to many limitations of the actual technical implementations. The accuracy of the results compared to the constructive patterns simplicity, adaptability to various circumstances required, ability to

accurately determine some parameters of an anisotropic media, the small dimensions and low production price are the advantages of these devices and the differences from actual sensing methods.

VII. ACKNOWLEDGMENT

This work was supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CNCS-UEFISCDI, project number PN-II-RU-TE-2014-4-2196.

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