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The sliding mechanics of the subcutaneous structures in man
Illustration of a functional unit: the microvacuoles

J.C.GUIMBERTEAU
INSTITUT AQUITAIN DE LA MAIN

Abstract
The mobility of our body structures is so intrinsic and natural to us that we tend to take it for granted.
The very fact of being able to pinch your skin and lift it, then let it go and see it return to its initial shape and texture in just a few seconds may seem banal enough until you begin to think of all the elements involved. The same is true when you bend your fingers and think of the movement of the flexor tendon across the palm without external translation.
For decades, scientists thought that the skin was simply an elastic structure with loose connective tissue and a more or less virtual space. However, in biomechanical terms, this explanation is very vague.
These old concepts, developed more than 50 years ago, have evolved thanks to the impact of research at the microscopic level, and the global, mesospheric concept has been abandoned.
And yet, surgical dissection in vivo demonstrates that there are only tissue connections, simply a histological continuum without any clear separation between skin and hypodermis, the vessels, the aponeurosis and the muscles. In fact, visible everywhere are structures which ensure a gliding movement between the aponeurosis, the fat structures and the dermis.
As they studied this system of gliding between the various organs, in particular at the level of the tendons, the authors noted the existence of a type of system composed of cables and veil-like structures that they term the Multimicrovacuolar Collagen Dynamic Absorption System (MCDAS).
This system looks totally chaotic in organization and seems to function in a manner far removed from traditional mechanical structures.
The functional unity of this sliding system is dependent upon a polyhedral three-dimensional crisscrossing in space of the microvacuoles, whose collagen envelope is type 1 or type 4 and whose content is made up of proteoglycoaminoglycans.
The dynamic of this multimicrovacuolar system allows all of the subtle movements that occur within the body, thanks to its pre-stressed nature and the molecular fusion-scission-dilacerations that it is capable of. In this way, the system is mobile, can move quickly and interdependently, and is able to adapt is plasticity.
This notion of microvacuoles is a fascinating one because it provides an explanation for the system's space-filling ability.
The matter is composed of elements: although they seem to be arranged in a haphazard manner, this is not the case. In fact, they occupy space in an optimal manner.
If we accept this notion of microvacuoles, then it becomes possible to explain certain pathologies occurring with age, such as edema, obesity, aging and inflammation.

This sliding system is to be found everywhere in the body and would seem to be the basic network of tissue organization. For this reason, it should be thought of in global terms.
Keywords: Living matter /Collagen / Glycoaminoglycans / Tendon / Carpal sheath / Sliding system / Tensegrity / Microvacuolar concept.

Introduction

We created 95 video recordings with sequential analyses of the living human organism during surgical operations.
The movement of the endoscope inevitably depends on the limits of the endoscopy itself, and a good quality vision depends on numerous factors. The quality of the documents is that produced by the digital technology, and the photos taken from these sequences are of good quality but this always depends on the pixels. Nevertheless, all attempts to return to reflex and analogue techniques have failed. Only the camera allows unique moments to be captured, and in the future the quality of the documents will improve, there is no doubt about that.
Finally, the stringent sterilisation protocols forbid us from using non-accredited material during operations, which complicates things further.
Immediately under the dermis and hypodermis lies a highly mobile tissue at an absolutely global level, distributed over the entire surface of the structures, covering every so-called surface oh detachment, encasing the fatty lobules and infiltrating between the muscle fibres. Not seeming a «noble» tissue, it has long been neglected, regarded simply as a filler. Also defined as connective and areolar (known as "paratendinous" around the tendons), it is this tissue which we will explore.
If grasped with tweezers, we discover a surprising manner of organisation, apparently haphazard, disorganised and vacuolar, in which the high degree of traction causes strange movements which are the bursting of small vacuoles at atmospheric pressure, showing the presence of hydraulic systems with a different pressure.
It is a system consisting of fibrillar filaments which go in all directions, with a highly chaotic distribution marking the boundaries of the interfibrillar spaces which we will call vacuoles, highly refractive.
This sliding system therefore allows an optimal level of gliding without jerking or stress on the peripheral tissues. We have called this tissue the Multimicrovacuolar Collagen Dynamic Absorption System - MCDAS, so as to correctly highlight its main role.

Demonstrating the notion of the microvacuole

Following 30 years of surgical dissection, and above all 215 recorded and analysed (1, 2) observations by videoendoscope (163 with a tourniquet applied at the base of the limbs and 52 without a tourniquet, especially in chest and abdominal areas), we can confirm a total continuity of tissue between all the parts of an area of anatomy traditionally considered in a manner too fragmentary. When, for example, in larger movements, we think of the group of elements consisting of skin, arteries, veins, nerves, muscles and tendons which all move in the same direction, without breakage or haemorrhage and able to return instantly to their original position, we must provide an explanation which conforms to our observations and our current data, without settling for data more than a century old, gathered from cadavers and concluded before the time of the electronic microscope and the biomolecular era.
The very fact of being able to pinch the skin and lift it (Fig. 1), release it and observe it as it returns to its original position in the space of a few seconds certainly seems a banal and

simple gesture. Instead it is a fascinating world, if we think of all the elements which come into play. Such as when we close our fingers, if we think of the movement of the flexor tendon along the palm of the hand.
Moreover, surgical experience shows great differences in the quality of the structures we operate on: skin which is taut, wrinkled, thick, thin, damp or dry, fragile or tough.
For decades, scientific explanations limited themselves to the notion of elasticity or the existence of loose connective tissue with more or less a virtual space. In biomechanical terms, nevertheless, this explanation is rather vague.
Beyond these old concepts, scientific research has advanced to microscopic level over the last 50 years, abandoning the global, mesospheric concept.

Fig. 1

This is even more the case in this field of research, in which the cell - which seems to be the living, attractive, intelligent element, the organisational unit of living organisms with various important functions - has been the primary object of study. But the extracellular environment, often represented in medical books by way of a few fibres and a few strokes, has been gravely neglected. This scientific research has always been carried out using knowledge acquired through in vitro experiences, on organs removed from their natural environment, and the conclusions are too often two-dimensional.
The notions of fascia and aponeurosis are based on values recorded at the end of the XIX century (3); obsolete on a scientific level, they must be completely reviewed.
The main constituent, water, must be given back its proper role. Water is everywhere in our bodily structures; this can observed very well at subcutaneous level. It is not possible to study the organisation of the living material without including and exploring the elementary laws of fluid mechanics, including the concepts of osmotic pressure and surface tension.

Method

We first of all concentrated our studies on the sliding zones of the flexor tendons to the wrist in zone III (4, 5).
163 observations were carried out using a tourniquet, first applied tightly then gradually released, thus giving sufficient blood flow to fill the vascular structures but not enough to flood the operating area. A sterilised endoscope with a diameter of 19 mm and a magnification of 25x, connected to a minicamera with extemporary control on a video screen, was passed

under the skin.
In the case of dissection at wrist level, a vascular image was recorded; this image is simple to capture and highly instructive (Fig. 2). Curiously, the image changes during the bending and straightening movements of the fingers; an image similar to that of a car which refuels at a petrol station. The car is the tendon which comes and goes. The tube represents a longitudinal vascular image and another vascular image, in this case vertical, is represented by the petrol pump. The advantage of this simple analogy is that it clearly shows how, in terms of movements, the pump and the car do not move at the same speed, and that the tube bends and straightens. Moreover, the vessels around this “scene” also move at different speeds. For example, vessel no. 3 moves more quickly than the pump, but also faster than the car. Therefore there are different speeds of progression during a movement within a homogeneous area of tissue, continuous and non-hierarchical. How can we explain this simple observation?

Evidence of the continuity of the material and the existence of a tissue connecting the various functional components

Previous explanations involved the concept of stratified levels which slid into or over one another, or the concept of virtual space, easier to imagine than to understand. Notions such as fascia, and synovial, visceral or membranous sheath abounded. And yet, whether it was a question of a surgical dissection unable to find a distinct surface between tendon and para tendon, or examinations carried out at the electronic microscope, our minute observations led us to re-affirm the notion of continuity of the matter between organ and sliding sheath (Fig. 3).
We were therefore faced by the inevitable need to pose the problem in terms of global dynamics, of continuous matter, of introducing the concept of tissue continuity. It was necessary to abandon the perception of a body consisting of different functional elements gathered together.
This evidence of a total continuity of living matter imposed new and inevitable constraints in terms of connection, organisation and behaviour. This vision, however, was a necessary one; it was not created simply to fall in with the global trends. I could not continue to accept these notions of fascia which separated the tissues into layers. It was a logical obligation.

Fig. 2

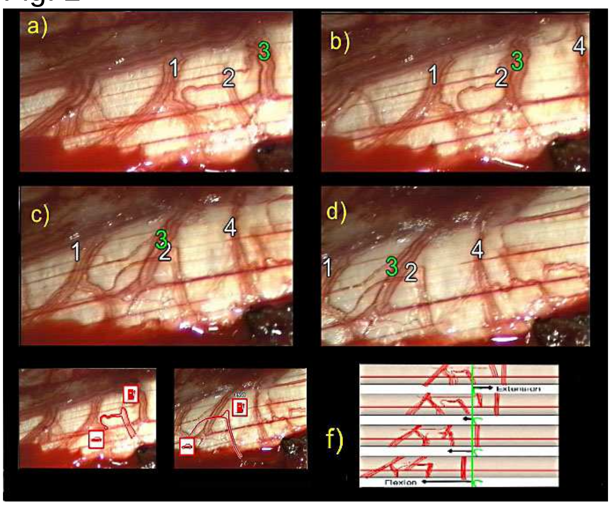
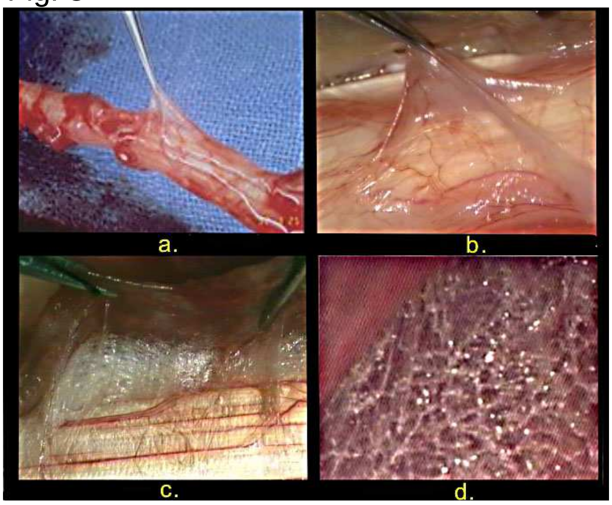


Fig. 3



Abandonment of the theory of lamellar, concentric and stratified spaces in favour of a continuous living material whose functional unit is the microvacuole

This tissue consists of billions of microvacuoles (Fig. 4), whose dimensions vary from several to several dozen microns, arranged in a chaotic manner with a fragmentary appearance, apparently similar but all unique. The vacuolar volume consisting of the intersecting of the fibres can only be conceived in the 3 dimensions of space. The vacuole is a volume with walls, a form, sides and a content.

The majority of the sequences show pseudogeometric forms with a polygonal distribution and differences in size based on dynamic role. A greater longitudinal movement is characterised by a finer and repeated vacuolar organisation, but the environment is always polyhedral and fibrillar in nature, containing a gel.

The costituents

The fibrillar structure (Fig. 5)

The fibres which make up the structure of each vacuole are linked to each other and consist essentially of collagens type 1 (70%), 3 and 4, but also elastin (circa 20%). There is also a high percentage of lipids (4%).

The fibres go in all directions with no preset pattern or logic, interconnecting and vibrating.

The fibres are several microns in diameter but excessively variable in length, giving a disordered and chaotic appearance, a series of bundles, a network of stems with intumescences. There is no point of geometric reference to be seen. The fibres intersect, very clearly or with unclear intermediate zones called “Plateau excrescences” (*bourrelet de Plateau*), veritable fixed nodules with a solid or mobile anchorage point and a sliding action brought about by the propelling force.

A high degree of magnification reveals lateral variations on the collagens, suggesting that the proteoglycan chains are adhesive and bonded to the collagen.

The intravacuolar space

Difficult to analyse, these proteoglycans make up the intravacuolar part and represent a highly hydrophilic space in gel form, with a volume which is certainly constant but with a variable internal pressure.

They are proteins, such as decorin, glycosylated due to anionic covalent bonds with glycosaminoglycans, or sulfated polysaccharides.

The strong negative charges facilitate the ionic passage and draw the water molecules into the vacuole, explaining their ability to adapt to changes in volume and resistance to pressure, creating edema, filling the spaces and facilitating water retention.

The molecular bond between the fibrils of collagen I and the proteoglycans may consist of type IV collagen, threadlike and consisting of 2 globular sectors and a short triple helix, which join in a structure similar to a string of pearls.

Collagen I also interacts with the small proteoglycan decorin, as well as with non-sulfated glycosaminoglycans such as hyaluronan.

This intravacuolar whole provides a resistance to compression while the collagen or elastin fibres provide resistance to tension, developing abilities to stretch and bend under mechanical stress.

Form
This notion of the microvacuole is also fascinating for its polyvalent characteristics.
Indeed it allows us to better explain its space-filling ability. A living body is a space full of matter enclosed in skin, a shell or a film.

Fig. 4

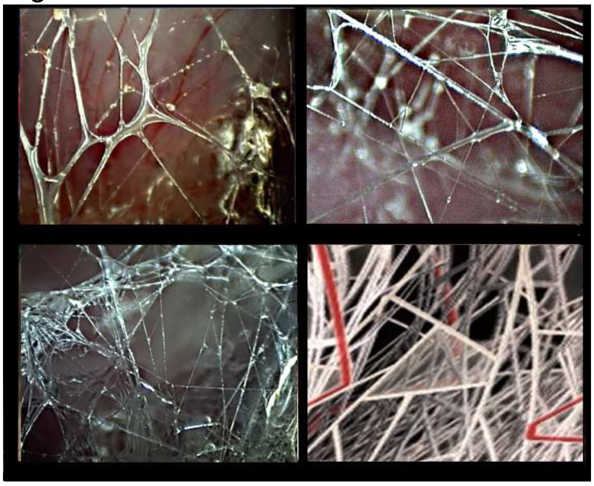
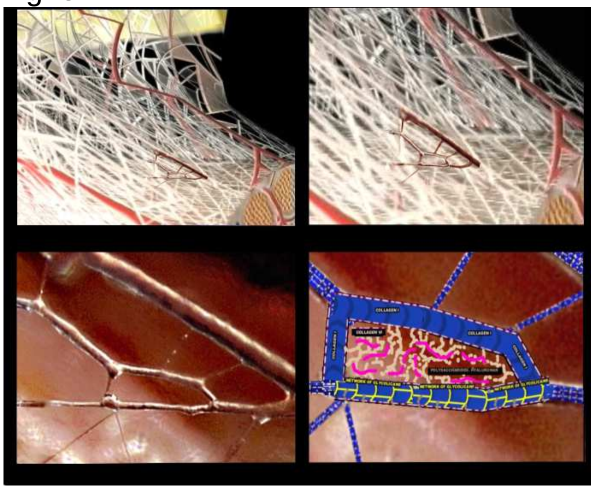


Fig. 5



The matter consists of elements; although their distribution seems chaotic, these elements are not arranged at random, occupying the space in an optimal manner. The cell forms part of the space-filling structures but is not the only element. The vacuolar structures entirely surround and encase the cellular elements. Sometimes the cell makes up just a small part of the basic structural elements. There is a polyhedral-type vacuolar envelope with an optimal spatial arrangement, inside which the specialised cells group together to form the organ.
This vacuole must also be able to cope with all the demands of morphological change under the slightest stress, and the forms are various, basically round, triangular, rectangular, cylindrical or more chaotic. The dimensions too are very different, ranging from less than 10 microns around the tendons to, for example, 50 if not 100 microns in the abdominal area, yet we find a polyhedral pattern. Once formed, this form is subjected to all the internal and external pressures and stresses, adapting itself to the force as a consequence.
Movement is assisted by the mechanical adaptation, and in mathematical terms the icosahedral forms are the most suited to this purpose. From this point of view, the microvacuole satisfies this first requirement.
The fibrillar structure of the vacuole is pseudogeometric, polygonal (Fig. 6A, 6B).
It defines a volume in the space which must combine with the other vacuoles, meeting the chemical-physical needs to fill the space, thus seeking out surfaces defined as minimal areas in the arrangement. The spatial arrangement of the structures is a phenomenon which is not well-known as far as living matter is concerned. The whole has a chaotic appearance, with no apparent regularity. It is nevertheless interesting to note how the form of the vacuole is always to be found, often polygonal, triangular, pentagonal or hexagonal, with a chaotic and fragmentary distribution: an inevitable observation which must have an explanation. This relative homogeneity of the forms can be likened to the icosahedrals and other similar geometric forms.
The thermodynamic behaviour of these forms is certainly optimal; they have been selected to guarantee the best metabolism at the lowest expenditure of energy.
The selection of the form under the action of the physical forces was already underway.

Role of the microvacuolar structural network (Fig. 6)
Its behaviour must respect the basic principle: to ensure the total progression of the mobile part without any movement of the surrounding elements. The vacuolar structure must provide resistance, adapt itself to the basic physical stresses from outside and conserve its own architecture (6.). An absolutely dynamic role, therefore, and one of total shock absorption. Two combined roles, dynamically opposing with a return memory and thermodynamic efficiency, must therefore be carried out without interruption to the supply of information and energy.

Nutrition and information
These fibrils are used as supports, as a structure for the vessels; this explains the surprising variety of vascular forms. The vessels, thus united with the structure, adopt all changes in position thanks to the mobility of the MCDAS, without interruption to supply and without risk, for example, of traction and tissue fractures. The other carriers of nervous information can, for example, adopt the same network. The continuity of the tissues is always complete.

Mechanical behaviour and mobility of the structure (Fig. 7)
Certain facts are clear and must be taken into account to understand the biomechanical behaviour.
This organisational network, supporting life in equilibrium, cannot exist without rules of functioning.
Its role is two-fold; to ensure the complete progression of the organ and to preserve the stability of the other adjacent tissues at the same time.
In what way does MCDAS cope with this dilemma?

Fig. 6

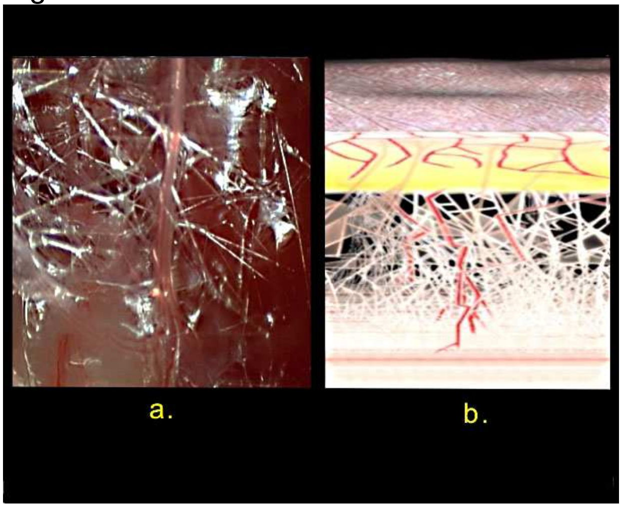
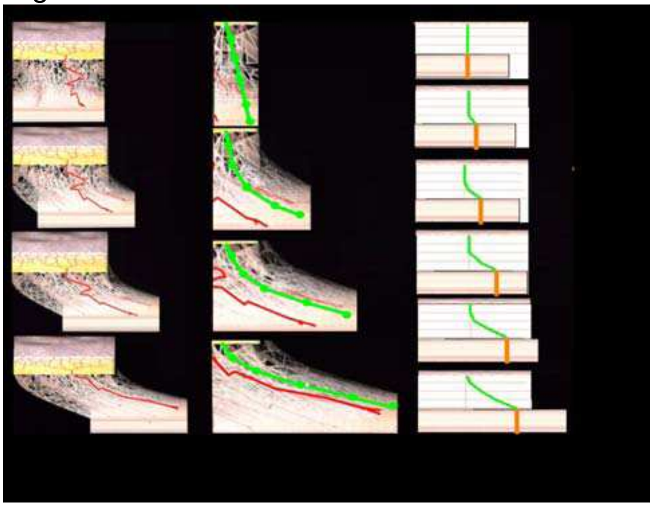


Fig. 7



We believe that our structures are in a pre-stressed condition, and the tissues therefore develop a state of tension. This tension is evident in surgical operations: when we cut the skin or an aponeurosis, the edges immediately move apart by a few millimetres. A global inter-tissue tension does therefore exist, distributed throughout all structures which make up living matter and the fibrillar network of the MCDAS in particular.

The notion of combined transmitted stress and multifunctional and multidirectional adapted response

The vacuolar structures close or connected to the mobile part will undergo the greatest movement. The rheologic relationship of the elastin and collagen fibres cannot be linear and unlimited, as the mobile part would drag the peripheral tissues. Nor can it be a behaviour of the plastic type, which would allow the traction but cause a blockage *(en plateau)* and a sudden breakage beyond certain limits. The behaviour must be of a « rubber » type, permitting the traction of the fibrils and progressively involving the other nearby fibres, distributing the stress and preventing fibrillar fracture. The absorption of the stress occurs along the entire network. In this way, the vacuole nearest the mobile part carries out its plastic role to the greatest degree, as opposed to those farthest away and less involved.

The fibres as a whole prepare to respond to the local stress, immediately adopting the most suitable dynamic solution, subjecting the collagen structure to local compression, varying the vacuolar forms, compressing the volumes, showing the resistance experienced, progressive and increasing over time, and suggesting a correlation between the density of the fibres which respond to the stress and the resistance experienced.

The global tension which therefore spreads through the sliding system along the fibres is exhausted, gradually diminishing as the mobile part moves away; in this way the most distant structures remain immobile.

This is what we will call “combined transmitted stress”: each element of the fibre is connected to the next by way of a loose bond. When this bond is put under tension, the successive element is subjected to a decreasing tension until the relative deformation takes place. All constituent elements turn to move in the greatest number in the direction of the applied force, permitting its execution but controlling it to prevent breakage.

But these mechanistic explanations form part of a two-dimensional vision, remaining rather far from the observations made in videoanalysis.

We must imagine the movement in 3D.

There are other behaviours in addition to the general pattern of orientation of the fibres.

This apparent disorganisation and irregularity of the forms expresses an as yet unexplored complexity and forces us to re-think their functioning in a different manner.

The notion of an equilibrium of the forces within the structure is inevitable, like the ability to adapt to stress

i) We have observed that the stressed fibril responds first of all by lengthening, a sign of a molecular reorganisation with an instantaneous capacity to return to its initial form. For minimal degrees of tension, it would seem that there is initially a condition of internal pre-stress, such as for a spring.

ii) The fibres under mechanical stress can divide, in an apparently non-abrupt manner in the space, into many other fibrils which disperse, allowing them to distribute the forces and absorb them effectively.

iii) The fibres can glide together on a mobile and mutual point along the entire length of one of the two fibres.

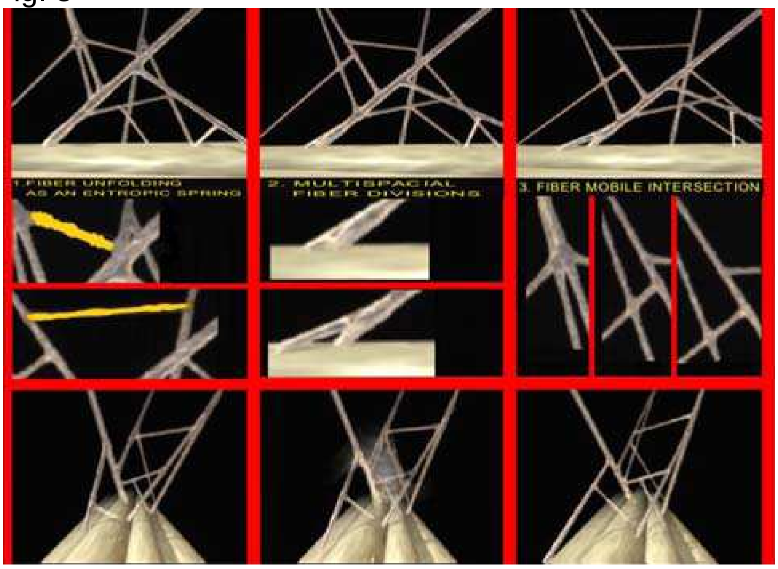
iiii) In their connection with others, the fibres often have the ability to combine or divide within a common gel, proof of a viscous fluidity capable of friction or attraction explicable by way of covalent bonds.

These fibrillar abilities as a whole, with their molecular abilities, offer an infinite number of ways of adapting to provide a response to the stress imposed.

This phenomenon can only be understood in the 3 dimensions of space (Fig. 8).

The elements must be pre-stressed and the stabilisation must be an equilibrium between opposing forces of tension and compression; this allows the conservation of form, solidity, multidirectional adaptability and independence from gravity. The role of gravity is therefore diminished, particularly during the phases of elaboration or growth. All the structures of the architecture distributed throughout the space are therefore reactive to the minimal tension increasing on one of the elements and transmitted to all the elements, even those which are distant. Any local compression changes the global tension. From the moment of its elaboration, the form cannot but be in equilibrium.

Fig. 8



The sequences of criscrossing, an entangling of fibrillar structures due to the recurring power of movements within movements, lie outside the standard analytical range, and require different physical rules based on non-linear mathematics. This complexity in the mathematical and mechanical approach is also accentuated by the fact that the structural elements - like the cables and “masts and yards” of a ship - add a further factor, the diversity of the material in terms of rigidity and resistance.

iiiii) Moreover, all of these observations and conclusions with regard to the fibrils - which offer an infinity of dynamic resources in response to stress - must not ignore the intravacuolar, interfibrillar volume. The conventional physical forces such as osmotic pressure, electrical gradients, surface tension and intermolecular tension all play their part. The proteoglycan gels certainly play a mechanical role in the response to traction, as well as one of nutrition and lubrication. The constant of the compressed volume and the different resulting forms provide great potential in terms of agility, but also in terms of resistance, with a rapid diffusion throughout the sliding system. Volume and structure cannot be separated.

These three movements as a whole allow the structures to execute an infinite number of movements in space, and here, for example, is a sequence recorded in vivo, showing the ability of a fibrillar whole to change form and adapt to a new stress, thus providing an explanation of everything we see daily in our surgical activities, in other words mobility, agility, the interdependence of the organs, and the mere fact of being able to explain the mobility of numerous tendons, one beside another with a complete functional disassociation, already appears reassuring. (Fig. 9)

This as far as the biomechanical explanation is concerned, as it seems to me that it can be proposed.

Physiopathology and evolutionary capacity of the MCDAS (Fig. 10)

The other interesting element to consider in this whole, this recognition of the body as an immense multifibrillar, chaotic and fragmentary network, is its evolution.
This tissue remains fragile in any case.
It can tear or deteriorate: the surgeon sees this deterioration in his daily life.
Let us take the case of a haematoma: when the surgeon cuts an old haematoma which has turned into serum, the surrounding metaplasia can clearly be seen, along with an inability of the surfaces to collaborate with each other.
The same can be said for the hygroma.
It would be like failing to compare a hygroma such as that which can be seen at the digital sheath of a long flexor, with that which can be seen here.
The multimicrovacuolar system can develop or adapt to create a megavacuole, which is another functioning system with the creation of an area of re-absorbent, secreting metaplasia on the periphery, and this allows me as a hand surgeon to explain for example the existence inside the hand of numerous types of rejoining, of various types of sliding in the zones 3 4 5; we can have a global multimicrovacuolar system with a metavacuolar system, half multimicrovacuolar and globally megavacuolar, such as in the digital canal.
This also makes it possible to explain how in the hand, at the level of the A1 pulley, we pass suddenly from a complete and natural multimicrovacuolar system to the area of the digital canal, where there is a total absence of microvacuoles.
But it is also possible to explain other elements such as edema, inflammation, obesity and ageing with relative ease.

Conclusion

This perception of the body as a whole in terms of fibrillar structures, chaotic and fragmentary within a form, gives us a general vision of its agility, coherence and continuity.
Furthermore, as it presents itself, this organisation in its fragmentary, chaotic and global appearance with respect to the rest of the body as a whole obviously introduces other dimensions, those of the relationship with the other living forces - vegetables, the other animals - but also the non-animate system, and it is thus possible to approach the relationship between non-animate and inanimate structures if we keep this multimicrovacuolar organisation of living matter firmly in mind (7).

Fig. 9

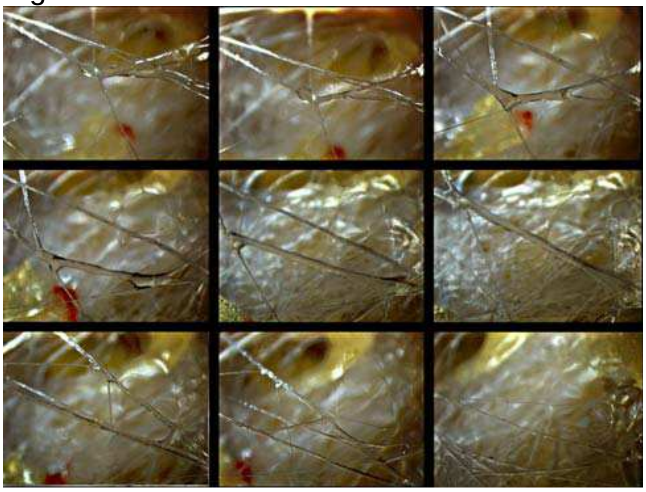
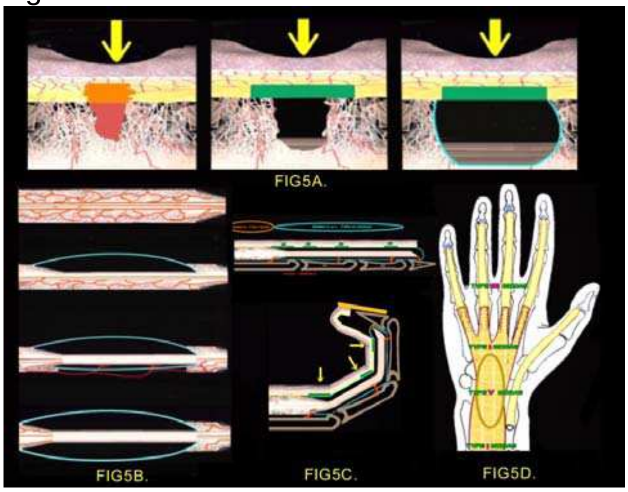


Fig. 10



Discussion

Contribution from Y Chapuis

We have just been exploring a fascinating world of living matter, collagen in particular.

Two questions:

- Is there a mathematical approach which governs this structure?
- Is it possible to imagine an industrial application?

Replies from JC Guimberteau

Question 1

Frankly the mathematical approach has not been clarified, given that the very notions of chaos and deterministic chaos have still not been completely accepted by the scientific community. Important ideas expressed in current language through the "butterfly" effect and translated into equations with non-linear functions only appeared towards the Sixties, and it was some time before they became established as acceptable ideas. And it will take some time to introduce the concepts of apparently disordered and unpredictable dynamic evolutions within living matter.

Question 2

For the moment, due to my medical training, I can only see the creation of a substitute matter – perhaps through genetic engineering – which has the same characteristics in terms of adaptive ability and which can be used in the treatment of tissue adhesions.