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The Liquid Crystalline Organism and Biological Water

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Abstract

The organism is a dynamic liquid crystalline continuum with coherent motions on every scale. Evidence is presented that biological (interfacial) water, aligned and moving coherently with the macromolecular matrix, is integral to the liquid crystallinity of the organism; and that the liquid crystalline continuum facilitates rapid intercommunication throughout the body, enabling it to function as a perfectly coherent whole.

Key words
Liquid crystalline continuum, coherence, birefringence, nonlinear optics, delayed luminescence, bound water, free water, collagen, proton-conduction, intercommunication, body consciousness

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1. The liquid crystalline organism

More than ten years ago, we discovered what living organisms look like under the polarized light microscope that geologists use for examining rock crystals (Ho and Lawrence, 1993; Ho and Saunders, 1994). They give brilliant dynamic liquid crystal displays in colours of the rainbow (see Fig. 1). The colours depend on the coherent alignment of molecular dipoles in liquid crystal mesophases. But how can a living, breathing, squirming worm appear crystalline?

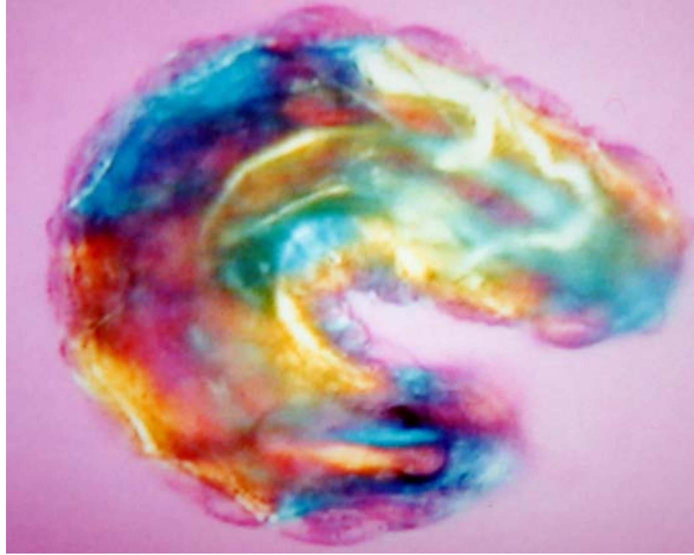

Figure 1. The rainbow worm: a freshly hatched fruitly larva.

It is because all the molecular dipoles in the tissues are not only aligned, but also moving coherently together. Visible light vibrates at 10^{14} cycles per second, much faster than the coherent molecular motions in the organism, which is why the molecules look statically aligned and ordered to the light passing through.

Not only are the molecular dipoles in the tissues aligned, they are aligned in *all* the tissues, and aligned globally from head to tail. The antero-posterior axis is the optic axis, so when that axis is laid out straight at the correct angle (45°) to the optics, each tissue takes on a more or less uniform colour: blue, orange, red, or green. But when that axis is rotated 90°, blue changes to red, green to orange and *vice versa*, as characteristic of interference colours.

The fruit fly larva has neatly demonstrated the colour changes for us by making a circle with its flexi-liquid crystalline body. The most active parts of the organism have the brightest colours; the brighter the colours, the more coherent the molecular motions (see later).

One more thing about the rainbow worm; the colours are not just a function of the coherent motions of all the molecules in the tissues, they are the result of the accompanying coherent motions of the 70% by weight of biological water that enables the molecules to be mobile and flexible, which is why the worm, and we too, are flexible and mobile.

Imagine all the biological water dancing together with the molecules in the entire body, creating a quantum jazz of life that's improvised from moment to moment. This technique involves a small modification of that used for examining rock crystals which happens to greatly improve colour contrasts for the range of small birefringences found in biological liquid crystals, and can give high resolution images.

In the live recording of the adult brine shrimp, gently held in a cavity slide under a cover slip just heavy enough to prevent it darting about, you can see giant solitary waves or solitons, both stationary and mobile, passing down the gut.

The organism is a liquid crystalline continuum, coherent beyond our wildest dreams, perhaps even quantum coherent (Ho, 1993; 1998). We thought we made a new discovery but Joseph Needham had anticipated that and a lot more of what this paper is about in his book, *Order and Life* (1935). The properties of 'protoplasm' preoccupied many physical-minded biologists since the end of the 19th century, and fortunately for some of us, well into the 20th

century (see Ling, 2001). Needham, who died a few years short of this century, proposed that all the remarkable properties of protoplasm could really be accounted for in terms of liquid crystals. Indeed, he suggested that living systems actually are liquid crystals.

2. Rainbow worm optics

The optics of the rainbow worm is very straightforward. The organism is put between crossed polars in transmitted white light in series with a full wave plate that introduces a retardation of 560nm.

The colours are generated by interference when the plane-polarised light, doubly refracted by the birefringent crystals, is recombined on passing through the second polarizer; and depending on the wavelength of the light, there is either additive or destructive interference, so the white light becomes coloured.

The modification we introduced consist in placing the full wave plate at a very small angle of 7.5° to one of the polarizers, instead of 45° as is usually done.

We used the equation of Hartshorne and Stuart (1970) for two superposed birefringent crystals to represent the wave plate and the biological sample, to show why the colour contrast is so much better at the 7.5° angle than the 45° by plotting the intensity of the monochromatic wavelengths for red (700nm), blue (450nm) and green (560nm) respectively (Fig. 2). The effect of the small angle is to reduce the contributions of red and blue relative to green, and to increase the difference between the maximum and minimum intensities of all the colours at the +45° and –45° angle of rotation.

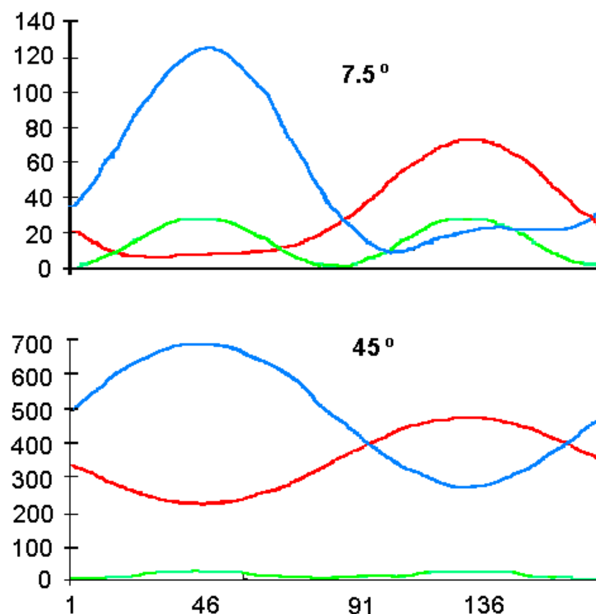

Figure 2. Intensity of red, green and blue light with angle of rotation.
(From Newton *et al*, 1995)

For small birefringences (retardation less than 50 nm), the intensity of light is approximately linearly related to retardation. We derived equations to relate the difference between maximum and minimum intensity of the red or the blue light to the retardation of

the sample. In practice, we determined the retardation of a sample relative to a mica standard for which the retardation has been measured exactly with monochromatic green light from a mercury lamp.

The next important result is mathematically quite involved and almost entirely the work of Zhou Yuming (2000). The detailed derivations are in a special chapter of his doctoral thesis. It says that birefringence is linearly related to the molecular alignment order parameter for nematic liquid crystals, which is a good first approximation to biological polymers. This is the reason for stating earlier that the most active parts of the organisms are the most coherent parts: the brightness of the colours is a direct measure of birefringence, and birefringence depends on coherence of molecular alignment. In fact, the linear relationship holds for both form and intrinsic birefringence, as Yuming showed in his thesis. But the distinction between form and intrinsic birefringence is extremely blurred; suggesting that biological water associated with proteins are all inseparably part of the intrinsic birefringence, and is perhaps the most important contribution to the liquid crystallinity of organisms.

These two main results - the linear variation in the intensity of the monochromatic red or blue light with birefringence, and the linear variation of birefringence with the molecular alignment order parameter - underpin a quantitative imaging technique that we have devised to determine the molecular alignment and the birefringence of liquid crystalline mesophases (see Fig. 3).

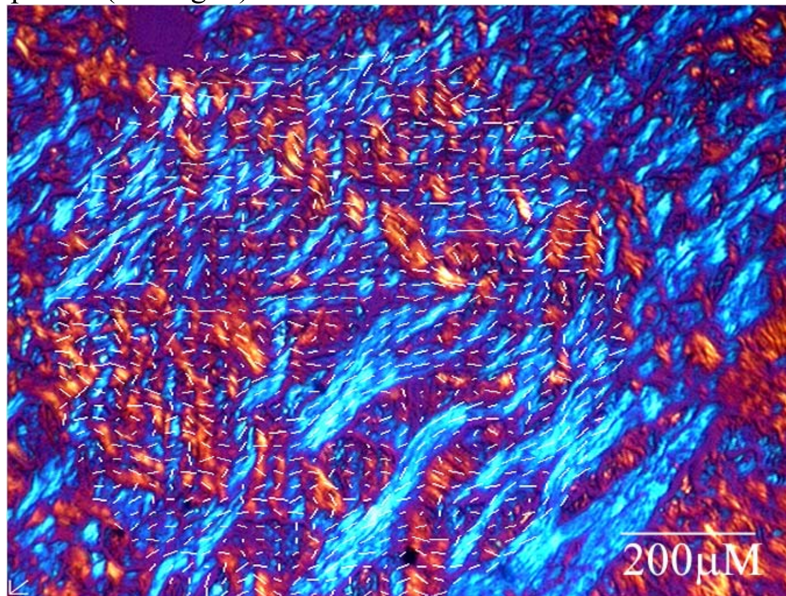

Figure 3. Section of pork skin with overlay of quantitative imaging.

The direction of the vector gives the direction of the molecular alignment at that point and its length is proportional to the retardation or the brightness. As can be seen, this technique is potentially very useful for working out the structure of soft tissues, bones, cartilage, other liquid crystalline composites, natural or self-assembled *in vitro*.

All sections and slides can be imaged directly in water without fixing or staining. As you shall see, water contributes a great deal to the birefringence. The details of this imaging technique and software are described in Ross et al (1997).

3. Collagen and the liquid crystalline living matrix

Collagen is the most abundant protein in the organism, and is known to form liquid crystalline mesophases, at least, *in vitro*. It is the main protein in the extracellular matrix and connective tissues and may thus account for the liquid crystallinity of living organisms as a whole, facilitating intercommunication throughout the body.

Type I collagen is the archetype of all collagens as well as the most abundant. It is found in tendons, skin, and bone. The polypeptide chain is made up of the repeating tripeptide unit, Gly-X-Y, where X are Y are usually proline and hydroxyproline respectively. Three peptide chains are wound into a triple left-handed helix molecule, with the glycine in the middle and a stagger of one amino acid between neighbouring chains. The helix has a pitch of about 9.5Å and 3.3 units per turn.

The molecules are assembled into fibrils, fibrils into fibres, and many different hierarchical structures. What makes collagen most interesting is its associated biological water. We used our quantitative imaging technique to investigate how water contributes to the birefringence of the rat-tail tendon (Zhou, 2000). We looked at all organisms and sections in water, because it was the most convenient and also because it gives the highest birefringence. But is that due to *form birefringence*, which results from a difference in refractive index between the sample and the medium rather than *intrinsic birefringence* due to polarisability of the biological molecules?

The retardation of a fixed, unstained tendon 5 micron thick section of rat tail tendon was measured in both the air-dry state, and embedded in histomount. The relative retardation in histomount was between two to three-fold that of the dry section. As the refractive index of histomount is 1.29, while that of collagen is around 1.47, the increase in relative retardation in histomount could be said to due to form birefringence, assuming that there is no interaction between histomount and collagen.

To investigate further, mixtures of water and glycerol were prepared in order to vary the refractive index between 1.333 for water and 1.471 for glycerol (see Fig. 4).

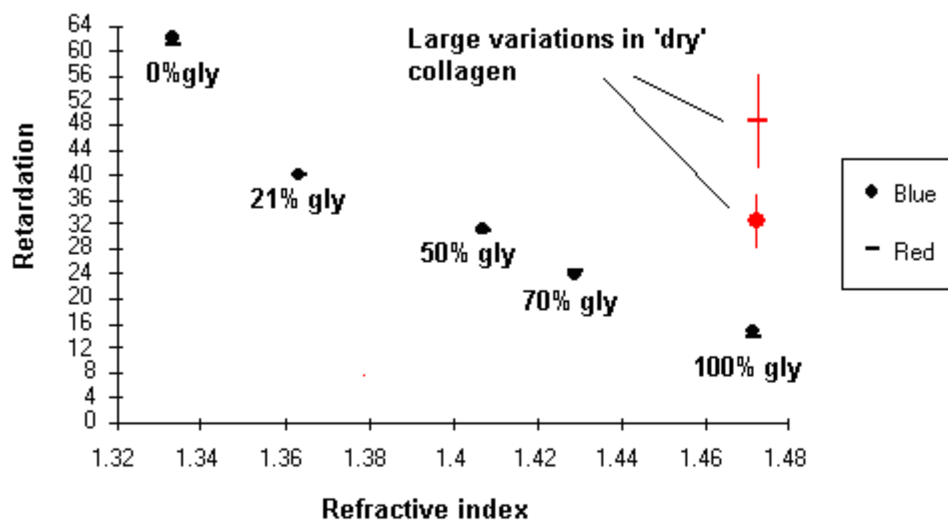

Figure 4. Relative retardation in increasing concentrations of glycerol in water.
(From Zhou, 2000)

As can be seen, increasing glycerol concentration increases the refractive index, but concentrations greater than 21% also begins to reduce the birefringence to below the level of ‘dry collagen’ (left overnight in a dessicator with silica gel). It is quite likely that this ‘dry’ collagen is actually hydrated to some degree (see next Section), and the effect of high concentrations of glycerol may involve dehydrating the collagen further.

It suggests that the role of water is not just an embedding medium, and introduces more than form birefringence. As water interacts extensively with collagen through hydrogen bonds, it would be expected to alter the intrinsic birefringence of the protein. One way to investigate the effects of hydrogen-bonding is to introduce solvents that perturb this hydrogen bonding.

Two series of mixtures of solvents were prepared, a glycerol in water mixture from 0%to 21%, and a series with matching refractive index of different concentrations of ethanol in methanol. The idea was that glycerol may be more ‘water-like’ in that it does not have the hydrophobic side-chain of the alcohols. The results are shown in figure 5.

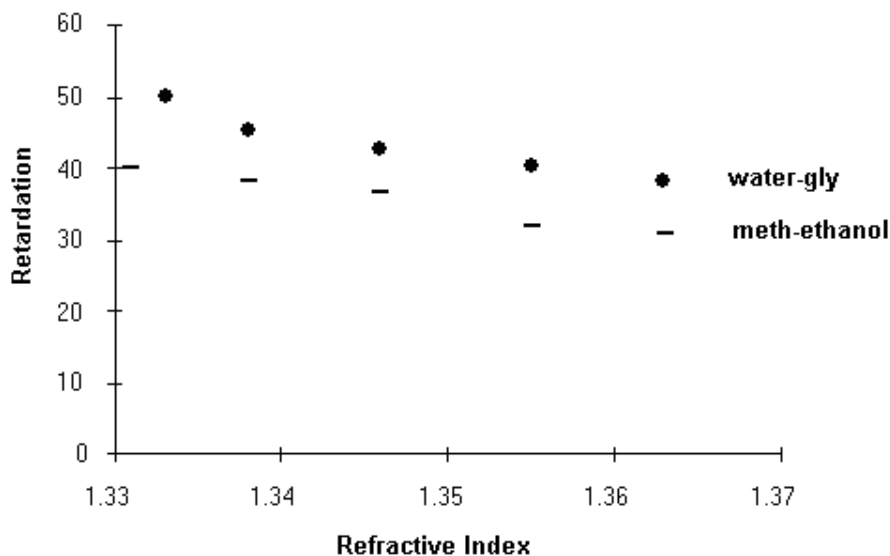

Figure 5. Retardation in water-glycerol mixtures vs methanol-ethanol mixtures in fixed rat tail tendon. (From Zhou, 2000)

It can be seen that alcoholic solvents reduce birefringence by about 20% at all refractive index values.

The difference was more pronounced in unfixed tendon sections of the same thickness (see Fig. 6). Here the birefringence in the aqueous solution was much stronger than in fixed sections, hence the difference between the aqueous and the alcohol solutions is correspondingly greater, while the change with refractive index was much less. This suggests that in unfixed sections, most of the total birefringence is intrinsic birefringence in both aqueous solutions and alcohol solutions. However, intrinsic birefringence also

differs by more than 70% between the solvents, probably on account of large changes in molecular order, or protein conformation, or both.

These experiments show that biological water contributes a great deal to the intrinsic birefringence and liquid crystallinity of biological polymers.

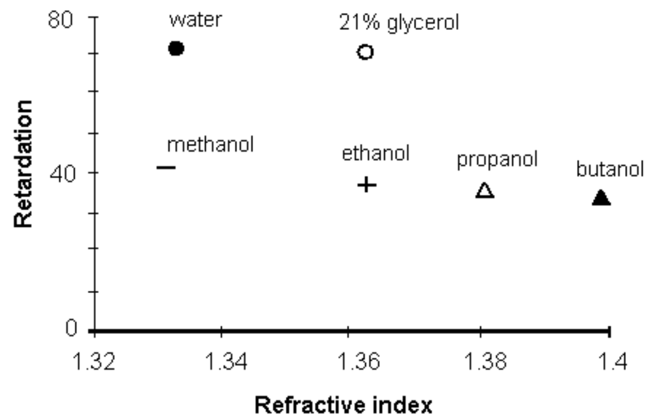

Figure 5. Retardation in water, 21% glycerol and various alcohols in fresh rat tail tendon. (From Zhou, 2000)

4. Collagen is richly hydrated

The hydration of proteins has been measured with dielectric relaxation and many other techniques.

In dielectric relaxation measurements, the sample is subjected to alternating electric fields of different frequencies. As the frequency of the applied field increases, the dipole moments of the molecules are unable to orient fast enough to keep up alignment with the applied electric field and the total polarization falls. This fall, with its related reduction of permittivity and energy absorption, is referred to as dielectric relaxation or dispersion. A complex permittivity ε^* describes the dielectric relaxation, the real part of which, ε' represents the permittivity of the medium and the imaginary component ε'' is the loss of the medium (Cole, 1975).

The frequency-dependent dielectric constant of the combined protein-water system can be written as a sum of four dispersion terms for the protein, bound water, free water and bulk water respectively (Pethig, 1992). The dielectric relaxation time for bulk water is about 8.3ps, for free water, 40ps, and for bound water 10 ns, compared to the typical protein myoglobin, which is 74ns.

Three populations of biological water have been identified in tendon, which is almost all type I collagen, by means of NMR (Peto *et al*, 1990), dielectric measurements and sorption experiments (Grigera and Berendsen, 1979). The most tightly bound fraction consists of 2 water molecules for every three amino acid residues and provides water bridges between the three strands of the collagen molecule, linking backbone carbonyl groups. This represents 0.125gwater /g collagen. A second, less tightly bound fraction is localized in the interstices of

the quasi-hexagonal packing arrangement, which takes a further 0.35g/g, and consists of hydrogen-bonded chains of water molecules (Hoeve and Tata, 1978). A third population of more loosely bound water can be absorbed in the 'ground substance' in which the collagen fibrils are embedded. But considering the complicated hierarchical structure of most collagen structures, there are likely to be many different populations of water that are to varying extents 'restricted' in motion compared with bulk water (cf Fullerton, this volume).

Middendorf et al (1995) reported that some 0.06g of water/g collagen remained in completely desiccated collagen, representing the most tightly bound fraction. This is about one molecule of water per triplet and is similar to that reported for the desiccated (Pro-Pro-Gly)$_{10}$ peptide (Sakakibara et al, 1972), in which the water molecule forms a H-bond between glycine and the second proline in the triplet. Thus, the 'tightly bound' fraction of water probably consists of at least two populations of water molecules.

While the relaxation time of bulk water is about 8.3ps, the relaxation times of "free water" for collagen was reported to range from about 12 to 40 ps (Hayashi *et al*, 2002), indicating a rather uniform dynamical structure of water around the collagen triple helix.

Collagen is unusual among proteins in that there are very few direct H-bonds either within the chain or between chains. There is only one direct H-bond in each Gly-X-Y unit, the imide group of the Gly to the carbonyl group of the X residue in the adjacent chain. This leaves the carbonyl group of the glycine residues and the carbonyl of the Y residues with no amide H-bonding partner. In addition, the OH group of hydroxyproline points out from the triple helix and cannot directly H-bond to any other group within the molecule.

A detailed X-ray diffraction analysis was carried out by Bella *et al* (1995) on the ordered water molecules in a collagen-like peptide with ten repeating units of Gly-Pro-Hyp and a single substitution of a Gly by an Ala residue in the middle of the peptide. The analysis showed that all available groups of the peptide backbone and the Hyp are involved in binding water molecules. In other words, most of the H-bonds in collagen structure are water mediated.

Water chains mediate H-bonding between carbonyl groups on the same chain as well as between different chains in the triple helix, and between the OH group of hydroxyproline with carbonyl groups in the same or different chains. The number of water molecules involved in bridging two groups appears to vary along the helix. On average, the carbonyl groups of Gly residues are bonded to one water molecule, while that of Hyp are bonded to two. The OH group of Hyp can bind two water molecules at two distinct sites, but not all positions are fully occupied (Brodsky and Ramshaw, 1997). Water bridges are also critical in connecting adjacent triple-helices and maintaining the molecular spacing (Bella *et al*, 1995). Local hydrogen-bonding network was observed in the interstitial waters. Some water molecules link up to four other water molecules, illustrating the three-dimensional hydrogen-bonded network of water around the collagens.

There is little or no direct contact between neighbouring collagen triple helices, suggesting that a uniform cylinder of water surrounds each triple helix.

There is disagreement over the role of Hyp and hydration in stabilizing the collagen triple-helix. In the computer simulation of the three-dimensional hydration structure of (Pro-Pro-Gly)$_{10}$ (Gough *et al*, 1998) which has no Hyp, and consequently, no water bridge between a side-chain group and a backbone group, the triple helical structure of the peptide was found to be very similar to native collagen. The water bridges between the carbonyl groups are all interchain, and quite different from the results obtained by Bella *et al* (1995). Instead, hydration is determined by the geometry of the backbone carbonyl groups and steric crowding

surrounding them. Prolines on different chains are stacked against each other in the triple helix, regardless of whether the molecule is hydrated or not. These close contacts prevent hydration molecules from entering, and are the stabilizing factor in solution. All Hyp-containing triple-helices known to-date form direct hydrogen bonding interactions between Hyp hydroxyl groups of adjacent triple helices (Berisio *et al*, 2001).

A high resolution X-ray diffraction study of $(Pro\text{-}Pro\text{-}Gly)_{10}$ (Berisio *et al*, 2002) found a thick cylinder of hydration, composed of as many as 352 water molecules surrounding the two triple helices in the asymmetric unit. These water sites occupy two hydration shells with equal population of the two shells. This is about 2 water molecules per amino acid, and includes the 'loosely bound' fraction identified from other studies.

5. Probing biological water of collagen with delayed luminescence

Bovine Achilles tendon has a very elaborate fractal structure of microfibrils, subfibrils, fibrils, fibres, and fibre-bundles (cf Fullerton, this volume); and we decided to use delayed luminescence to probe the different populations of biological water associated with it.

Delayed luminescence (DL) is the re-emission of ultraweak intensity light with delay time of milliseconds to minutes from all living organisms and cells on being stimulated with light.

Where does DL in living systems come from? When solid-state systems are excited by light, "excitons" are generated which propagate within the system, some of which then decay radiatively back to the ground state over long time scales. A similar phenomenon occurs in the living system stimulated by light. The excitation is delocalized over the whole system, and cannot be assigned to specific 'chromophores', or specific molecular species that are excited. As distinct from stimulated emission from chromophores, DL from living cells and organisms typically covers a broad spectrum of frequencies, indicating the collective excitation of many coupled modes; all of which remarkably, decay hyperbolically back to the 'ground' according to the same hyperbolic decay equation (Musumeci *et al*, 1992),

$$I(t) = I_0 / (1 + t/t_0)^m$$

where the parameters I_0, t_0 and m, are fitted using a non-linear least squares procedure. These parameters are very sensitive to the physiological states of the cell or organism, and have been used successfully to assess food quality, for example.

We were quite surprised to find that these parameters are also very sensitive to the degree of hydration (Figure 7).

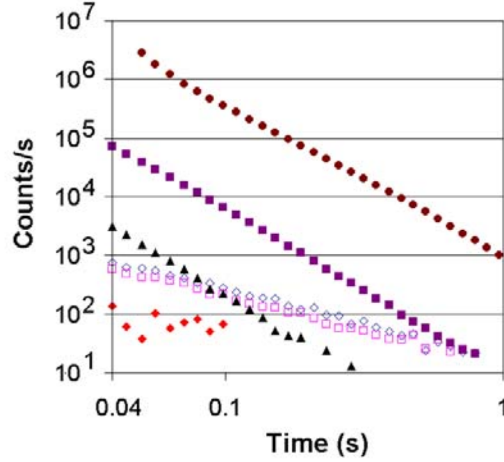

Figure 5. DL kinetics of bovine Achilles tendon at different hydration. (◇) Native sample, (□)1.6g/g, (◆)0.7g/g, (▲)0.4g/g. (■)0.2g/g, (●) fully dehydrated.
(From Ho *et al*, 2003)

We decided to use alternative parameters that enable us to relate the characteristics of DL more directly to the energy status of the system, as we have previously done (Ho *et al*, 1998; 2002). The total number of photon count, N, is connected to the total number of photons re-emitted, or the collective electronic levels excited that decay in a radiative way,

$$N = \int_{t_s}^{\infty} I(t)\, dt$$

where t_s is the start time of DL recording, and the probability of decay per excited level $P(t')$, expressed as,

$$P(t') = \frac{I(t')}{\int_{t'}^{\infty} I(t)\, dt}$$

In our condition, $t_0 \sim 0$, so the above equation becomes,

$$P_t(t') = \frac{I(t')}{\int_{t'}^{\infty} I(t)\, dt} = \frac{Rp}{t}$$

As the parameter N represents an extensive quantity, its values were normalized to the maximum value achieved by every sample in order to compare values from different samples. The resulting parameter is denoted the relative number of excited states Rn. Similarly, we use the parameter, Rp, the slope of $P(t)$ trend vs $1/t$.

When we plotted *Rn* and *Rp* against hydration levels expressed as g water/g dry collagen (dried to constant weight at 39C in a desiccator with activated silica gel), we identified what appear to be four states of hydration, each with distinctive values of *Rp* and *Rn* (see Fig. 8). State 1, fully hydrated, has greater than 1.5g/g hydration (between 41 and 25.5 molecules of water per triplet, Gly-Pro-Pro, mw 305), and is characterized by low *Rn* and *Rp*; state 2, between 1.52g/g to about 0.53g/g (25.5 to 9 molecules of water per triplet) is characterized by such low levels of DL that it is not possible to calculate either *Rp* or *Rn* reliably; state 3, between 0.53g/g and 0.26g/g (9 to 4.5 molecule per triplet), is characterized by the highest *Rp* level while *Rn* levels remain almost as low as state 1; and finally, state 4, less than 0.26g/g (less than 4.5 molecule of water per triplet), has a broad range of high *Rn* values as well as a high *Rp*. The transitions between different states are apparently abrupt.

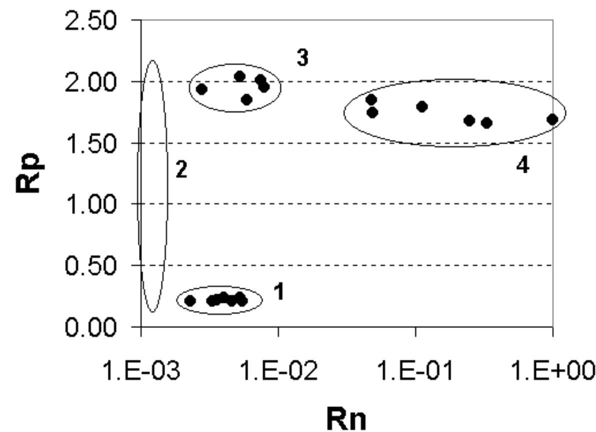

Figure 6. Plot of Rp versus Rn identifies four hydration states in bovine Achilles tendon. (From Ho *et al*, 2003)

State 4 corresponds to the tightly bound water, state 3, the loosely bound, and states 2 and 1 must therefore be different populations of 'free water'. The loss of each population of water involves what seems like a global phase transition, each 'state' being maintained until nearly all of the population of water is lost. Fullerton *et al* (this volume) have detected similar phase-transition like behaviour in their measurements of relaxation times of oriented bovine Achilles tendon using solid-state nmr - at hydrations of about 0.5, 0.26 and 0.06g/g - two of the values matching precisely those we obtain here.

Cell biologists have recently discovered a very interesting nonlinear optical phenomenon in collagen fibres, which enables the extracellular matrix and other collagenous material to be imaged without a fluorescent probe, using the multiphoton fluorescence microscope. Collagen, on absorbing simultaneously two low energy photons, generates second harmonic, frequency-doubled uv light, which stimulates it to fluoresce (Zipfel *et al*, 2003). We do not know whether the DL measured in bovine Achilles tendon is related to fluorescence, as we have been using a uv pulse laser (duration ≈ 5ns, λ= 337.1 nm), to stimulate DL.

One mechanism suggested for DL is the formation and subsequent radiative decay of excited Davydov (1994) solitons (Brizhik *et al*, 2002), which may be especially applicable to collagen. Optical solitons, induced in collagen, could act as waveguides giving rise to other nonlinear effects such as second harmonic generation. Salguerio *et al* (2004) have

described a mechanism for generating second harmonic wave in a vortex soliton waveguide.

It is clear that collagen liquid crystal mesophases have very exciting properties that could be responsible for ultrafast intercommunication within the body.

6. Water of hydration supports jump conduction of protons

There have been many suggestions for years that interfacial water adsorbed onto the surface of proteins and membranes could support a special kind of jump conduction of protons.

As mentioned earlier, a complex permittivity describes dielectric relaxation, consisting of a real part representing the permittivity of the medium, the dielectric constant, and an imaginary component representing the loss of the medium, or conductivity. For a long time, it has been known that both the dielectric constant and conductivity for biological polymers tend to increase strongly with the degree of hydration.

Sasaki (1984) measured the dielectric dispersion of bovine Achilles tendon at several hydrations levels below 0.3 g water/g protein over the frequency range of 30 Hz to 100kHz. He found both the dielectric constant and conductivity increasing strongly with water content, especially in the lower frequency side. There was no dielectric absorption peaks within this range of frequencies. In the lower frequencies (< 1 kHz), ε'' varies as frequency, f, to the power $-n$.

$$\varepsilon'' \propto f^{-n}$$

This is apparently indicative of discontinuous jump of charge carriers between localized sites. The dielectric loss factor is proportional to the number of carrier jumps:

$$\varepsilon'' \propto \boldsymbol{J}_{\phi f}$$

where $\boldsymbol{J}_{\phi f}$ represents the number of jumps per unit volume performed by carriers within the period of oscillation of the external field and at the water content, ϕ. The charge carriers are presumed to be protons. There was a power-law relationship between conductivity σ and water content ϕ of the form,

$$\sigma(\phi) = X\,\phi^{Y}$$

where Y, the power of ϕ, is between 5.1 and 5.4, independent of the frequency of the electric field, and is thought to be related to the distance between ion-generating sites.

7. Proton-neural network

We have described some of the major findings suggesting that the main function of the liquid crystalline matrix in the body is to facilitate rapid intercommunication that makes organisms so perfectly coordinated, even organisms as large as whales or elephants. A substantial part of this intercommunication is associated with the biological

water (Ho, 1998), of which proton currents are the best understood, although other nonlinear optical and phonon effects such as solitons may also be important as mentioned earlier.

Welch and Berry (1985) suggested that a proton-neural network is involved in regulating enzyme reactions within the cell, where metabolic reactions are predominantly of a redox nature. Proton currents may well flow throughout the extracellular matrix, and linked into the interior of every single cell through proton channels. Proton currents could flow from the most local level within the cell to the most global level of the entire organism. Protons (reducing power) give a boost of energy where it is needed.

Structural studies carried out on proton pumps such as bacteriorhodopsin and cytochrome oxidase within the past ten years show that they typically form a channel through the cell membrane which is threaded by a chain of hydrogen-bonded water molecules from one side of the membrane to the other. There is now evidence that protons can flow directly along the membrane within the interfacial water layer, from proton pump to ATP synthase, both of which are embedded in the membranes (see Ho 2005).

A model of proton-conducting water chain or "proton-wire" has come from a further unexpected source: studies on carbon nanotubes.

Hummer *et al* (2001) showed in computer simulations that a single-wall nanotube 13.4 Å long and 8.1Å in diameter rapidly filled up with water from the surrounding reservoir, and remained occupied by a chain of about 5 water molecules on average during the entire 66ns of simulation.

Water molecules not only penetrate into the nanotubes, but are also conducted through them. During the 66 ns, 1 119 molecules of water entered the nanotube on one side and left on the other, about 17 molecules per ns. The measured water flow through the twice as long channel of the transmembrane water-conducting protein aquaporin-1 is about the same order of magnitude. Water conduction occurs in pulses, peaking at about 30 molecules per ns, reminiscent of single ion channel activity in the cell, and is a consequence of the tight H-bond inside the tube.

There is a weak attractive van der Waals force between the water molecules and the carbon atoms, of 0.114 kcal per mol. Reducing this by 0.05kcal per mol (less than 5%) turns out to drastically change the number of water molecules inside the nanotube. This fluctuates in sharp transitions between empty states (zero water molecule) and filled states, suggesting that changes in the conformation of enzyme proteins may control the transport of water from one side to another in the cell membrane.

Do such water-filled channels conduct protons? The answer is yes. If there is an excess of protons on one side of the channel, positive electricity will spirit down fast, in less than a picosecond, some 40 times faster than similar conduction of protons in bulk water (Hummer, 2003).

Collagen in connective tissues has a special role to play in coordinating the activities of each and every cell throughout the body. Giant collagen fibres and especially their associated biological water may be jump-conducting cables linking distant sites with one another.

Ho and Knight (1998) proposed that the system of ramifying water channels along aligned collagen fibres may be the basis of the acupuncture meridian system of Traditional Chinese Medicine.

The liquid crystalline continuum provides rapid intercommunication throughout the body, enabling the organism to function as a perfectly coordinated whole. This “body consciousness” is common to all cells and organisms; it precedes the “brain consciousness” of the nervous system in evolution and works in tandem with it. It is, remarkably, nothing more than a guided matrix of biological water.

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