Beams in Biology

Supurna Sinha
Raman Research Institute, Bangalore

This article gives a perspective on the connection between the elastic properties of polymers of biological origin and the functional roles they play, with a special focus on DNA. It is an edited version of an article that appeared in the September-October 2010 issue of Jantar Mantar.

If you have looked at a roof made of hay, you will definitely have seen the wooden beams or bamboo poles, the coils of ropes used in making a structure to hold the roof together. The entire support structure is called the scaffolding. The ropes and poles can be thought of as fibres and beams with different stiffness or flexibility: a rope is more flexible than a bamboo pole.

A similar idea works in the world of living creatures. The scaffolding of our bodies has various layers, each with a range of flexibility. Our skeletons are made of rigid bone structures so they are not flexible. But these are layered with softer structures of actin filaments in the muscles which we can flex. For instance, to pick things up, the actin filaments make it possible to flex the muscles in our hands, and so on.

As we go to smaller scales, we find that all these parts of our body, the various layers of its scaffolding, are made of polymers of different flexibilities. Polymers are large molecules composed of a chain of repetitive units known as monomers. Some polymers are as stiff as needles, others are as flexible as thread and still others are like twine, neither too stiff nor too floppy. Indeed, having these different polymers is vital to life.

The DNA Biopolymer

Polymers found in living organisms are termed biopolymers, of which DNA is an example. The DNA biopolymer, which carries the genetic code, is a semi-flexible polymer, a bio-beam, that can be found in the nucleus of each cell inside every living being.

The nucleus is a very small organelle, only a few microns in size [one micron equals 1/1000000 metres]. You need a microscope to see such a small object. A typical human DNA biopolymer, is about a metre long. Isn't it rather amazing that such a long molecule can be packed into a small box such as the cell nucleus, a few microns across?

This efficient packaging is somewhat like the way we pack our clothes into a very small suitcase before a journey! In a cell, the task is made even harder since a DNA molecule gets jiggled around in a cell nucleus that is maintained at a finite temperature. This is somewhat like the way clothes on a clothesline get buffeted around on a windy day. A finite temperature is essential for cellular activity just like when we add yeast to flour, we need to keep the yeast at a warm temperature for it to be effective.

The elasticity of DNA and other biopolymers such as proteins and cellulose play a functionally important role. This means that the functions they perform are determined by their elasticity. This is similar to the way a craftsman puts strands of rope together to form a variety of structures like mats, lampshades, bags which can serve different functions.

DNA assumes various different forms depending on the function it needs to perform. These are called conformations or conformational structures. It is essential to understand the interplay between the conformational structures and the functional roles they play. For example, DNA molecules form loops during gene expression. These loops are created by proteins binding to different regions of the DNA structure. The proteins are involved in gene expression.

Such a form is distinct from the tight packaging of DNA we usually find in a cell nucleus. The tightly packaged, super-coiled configuration, looks like coiled up telephone cords. This shape protects and preserves the DNA's genetic code intact till it is needed. DNA is unwound or uncoiled during replication so that the genetic code can be accessed and copied.

These distinct conformations (or distinct shapes) are related to the elasticity of DNA and other biopolymers.

Persistence Length

How do you characterise the stiffness of a rope or DNA strand? Intuitively you know that a rope is more flexible than a steel rod. You can capture the essence of this behaviour by the persistence length. This is the length over which the rope or DNA or any polymer can be thought to be straight. Immediately you see that the persistence length of a young plant stem is much less than that of a stiff twig from a tree.

At the cellular level, actin filaments that are present in the cytoskeleton of muscle cells (the scaffolding of a cell made up of different filaments of various rigidities) have a persistence length of about 16 microns. They are stiff in contrast to a more flexible bio-polymer like DNA, which has a persistence length of about 1/20-th of micron.

The persistence length scale is central to the study of biopolymer elasticity. When the bio-polymer or bio-beam is buffeted around inside the cell by temperature fluctuations, this is the length that decides how much it will bend due to the buffeting.

Single Molecule Experiments

Experimental studies of biopolymer molecules such as DNA have usually been done on samples containing a large numbers of molecules. This made it hard to probe the elastic properties of individual biopolymers. But this is the property that is of vital importance to biological processes such as protein-induced DNA bending.
In recent years, advanced technology has made it possible to probe the elasticity of single biopolymers (individual molecules) by pulling and twisting them.

Beams and Beams

The elasticity of a spring can be probed by loading it and measuring its extension. In a similar manner one can apply tiny forces to stretch a bio-beam like a DNA molecule to measure its elastic properties.

The little bio-beams are themselves studied with experimental beams of an Atomic Force Microscope. The experimental beams are cantilever beams - anchored at one end, with a sharp tip at the other end that is used to scan the surface of a specimen, a probe.

In a typical experiment, a polymer molecule is suspended between a fixed surface and a force sensor. The force sensor that can bind to such a small polymer is itself an object of wonder. A typical sensor is a bead in a laser trap or the flexible cantilever of the atomic force microscope.

The molecule is stretched between the fixed surface and the probe. The elastic properties are studied by measuring how much a polymer stretches due to an applied force. The elasticity and shape of a simple, coiled DNA, even a complicated globular protein with a unique three-dimensionally folded form can be studied in this manner.

Fig.2 shows linear polymer chains of length 0.2 microns. They have different shapes and folds. The polymer thickness is 0.0004 microns, much smaller than the length. The label “25 nm” in the figure refers to the scale below; 25 nm = 0.025 microns. The ends of the polymer can be tagged with fluorescent dye. Sometimes the polymer goes from a folded conformation to a stretched out (unfolded) one. By tagging the ends, it is possible to determine the variation of end-to-end distances.

Such experimental studies teach us a lot about biologically relevant mechanical properties of these polymers. These studies have opened up a vast area of exchange of ideas between biologists, chemists and physicists apart from teaching us a lot about how such biomolecules work.

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Rope Experiment

The experiment described below is designed to shed light on the elasticity of a small scale polymer like DNA. You can try this experiment with a rope. The rope can be viewed as a scaled up version of a DNA polymer.

Take a long, stout rope, as long as you can find. Chop it to make short as well as long segments. The long ones are more flexible and the short ones are not. These will therefore mimic rigid and flexible polymers.

Let the end you are going to hold be the 0 cm mark. On each piece of rope, mark off equal length segments of 10 cm, 20 cm, etc. from the 0 cm mark.

Drop these rope segments from a height of about 2 meters onto the floor. Make sure the rope doesn't touch the floor before you drop it.

Measure the distance between the 0 cm end and each one of the marks you have made along the rope. For example, if you look at Fig. 3 the distance from 0 cm to the 10 cm mark is 7 cm, from 0 to 20 cm mark is 10 cm, from 0 to 30 cm is 14 cm, from 0 to 40 is 20 cm, etc. You can see that because the rope coils, these distances are less than if the rope were rigid and straight. In particular, the separation between the two ends of the rope, when compared to the total length of the rope, gives a measure of the rigidity of the cord. Notice that for a rigid rope/filament the separation between the ends is large. In contrast, a floppy filament has a smaller separation between its ends. The distribution of the end to end separations that you measure thus tells you how elastic the rope is.

Now, take any mark of your choice, for instance, 30 cm. Then the distance between 0 cm and the 30cm mark is 14 cm. Drop this rope piece again. This time you may get a number slightly different from 14 cm for this measurement. Repeat many times, say 40 times.

Add the squares of each of these lengths, (14^2+...) and divide it by the total trials (say 40) to get what is called the root-mean-square length R^2.

Repeat this experiment for different lengths of rope. Do you get different results for R^2 depending on the length L of the rope?

On a graph paper, plot R^2 on the y-axis as a function of the full length L of the rope which is plotted on the x-axis. This will tell you how R^2 changes as the full length L increases from left to right on the x-axis. Is there a difference in the behaviour of rigid (short) and flexible (long) cords?

If you scale down back to DNA, think about how the flexibility of the DNA polymer can influence its shape.

["The shape of a randomly lying cord", by Don. S. Lemons and T. C. Lipscombe, American Journal Of Physics, Vol. 70, page 570 (2002).]