

# Viscoelastic and Viscoplastic Glucose Theory (VGT #20): Applying Theories of Viscoelasticity and Viscoplasticity from Engineering and Energy Theory from Physics for Two eAG Cases to Compare the Energy Loss in the Loading-Unloading Process through Two Hysteresis Loop Areas along with Comparing Two eAG Associated Energies from Time-Domain and Frequency-Domain Based on the GH-Method: Math-Physical Medicine (No. 599)

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## Abstract

Recently, the author applied theories of elasticity, plasticity, viscoelasticity, and viscoplasticity from engineering along with the theories of wave and energy from physics to conduct his research on output biomarkers (symptoms or behaviors) resulting from a suspected or identified input biomarkers (causes or stressors). As a result, he has written a series of 19 different articles. In this research, he studies two related topics of glucose energy utilizing a continuous glucose monitoring (CGM) sensor device that collected the estimated daily glucose (eAG) from 1,374 days for a period of 5/5/2018 to 2/7/2022. The first one is the energy loss of hysteresis loops via VGT analysis. The second one is the eAG associated relative energy level in time-domain (TD) and frequency-domain (FD) through wave theory and energy theory of physics. He then compares his two respective energies corresponding to 2 eAG cases which are divided by 2 different PPG ranges: PPG < 150 mg/dL, and PPG > 150 mg/dL.

The following two defined equations are used to construct his stress-strain diagram:

**strain** =  $\epsilon$   
= individual output biomarker value (eAG) at present time

**Stress** =  $\sigma$   
=  $\eta * (d\epsilon/dt)$   
=  $\eta * (d\text{-strain}/d\text{-time})$   
= (viscosity factor  $\eta$ , i.e. input biomarker of carbs/sugar amount) \* ((output biomarker of eAG at present time - output biomarker of eAG at previous time) / (time duration = 15))

Where the time duration of 15 is chosen due to his eAG measurements are at 15-minute intervals.

After completing the steps from above, he generated the following useful information:

- (1) An organized data table that contains the input biomarker (viscosity factor  $\eta$ , carbs/sugar amount) and output biomarker (eAG) for each case to construct a time-domain (TD) waveform diagram.
- (2) A constructed stress-strain diagram in space-domain (SD) using the strain rate ( $d\epsilon/dt$ ), eAG changing rate, multiplied with the viscosity factor  $\eta$  (carbs/sugar amount), input biomarker, as the stress. eAG is the strain.
- (3) A calculation of the hysteresis loop area ratio for the comparison of the two energy losses in the loading-unloading process along with additional calculation of relative energies in TD and FD through the fast Fourier Transform (FFT) operation.

To offer a simple explanation to readers who do not have a physics or engineering background, the author includes a

brief excerpt from Wikipedia regarding the description of basic concepts for elasticity and plasticity theories, viscoelasticity and viscoplasticity theories from the disciplines of engineering and physics in the Method section.

In summary, the following three observations outline the findings of the two selected eAG cases according to the PPG ranges of either <150 mg/dL or >150 mg/dL:

(1) From the TD diagram, the two curves have different glucose values, but their waveforms (curve shapes) look similar to each other. The far left side of the fasting plasma glucose (FPG) during sleep hours (midnight to 7am) looks like two salad bowls with zig-zag edges. During the day (7am to 7pm), the peaks of the two eAG curves occur after lunch (around 2pm). The 2 eAG curves are trending downward in the evening (7pm to midnight). The observed TD phenomena confirm the important role of carbs/sugar intake to meals. This is why the author utilizes carbs/sugar amounts as the viscosity factor for his analysis.

(2) For both cases, even though the stress-strain diagrams look complicated at first glance, we can observe that they have viscoplastic behaviors with a big ratio of two hysteresis loop areas. This 132x (or 13,200%) area ratio indicates that the high-glucose hysteresis loop area (energy loss) is far greater than the low-glucose hysteresis loop area. The viscoelasticity or viscoplasticity behaviors can be determined by the two different glucose values between 00:00 and 23:45 as well as the existence of hysteresis loops.

(3) By using wave theory and energy theory with a FFT operation, the low-glucose case's (<150 mg/dL) energy is defined as 100%. Then, the high-glucose case's (>150 mg/dL) energy is 200% which is 2x higher than the low-glucose case.

**In conclusion, the higher eAG values present higher PPG values, which result in more relative energy associated with the hyperglycemic conditions. This would cause severe damage to the internal organs.**

## Introduction

Recently, the author applied theories of elasticity, plasticity, viscoelasticity, and viscoplasticity from engineering along with the theories of wave and energy from physics to conduct his research on output biomarkers (symptoms or behaviors) resulting from a suspected or identified input biomarkers (causes or stressors). As a result, he has written a series of 19 different articles. In this research, he studies two related topics of glucose energy utilizing a continuous glucose monitoring (CGM) sensor device that collected the estimated daily glucose (eAG) from 1,374 days for a period of 5/5/2018 to 2/7/2022. The first one is the energy loss of hysteresis loops via VGT analysis. The second one is the eAG associated relative energy level in time-domain (TD) and frequency-domain (FD) through wave theory and energy theory of physics. He then compares his two respective energies corresponding to 2 eAG cases which are divided by 2 different PPG ranges: PPG < 150 mg/dL, and PPG >150 mg/dL.

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(3) A calculation of the hysteresis loop area ratio for the comparison of the two energy losses in the loading-unloading process along with additional calculation of relative energies in TD and FD through the fast Fourier Transform (FFT) operation.

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## Methods

### Brief introduction of math-physical medicine (MPM) research

The author has collected ~3 million data regarding his health condition and lifestyle details over the past 12 years. He spent the entire year of 2014 to develop a metabolism index (MI) model using topology concept, nonlinear algebra, algebraic geometry, and finite element method. This MI model contains various measured biomarkers and recorded lifestyle details along with their induced new biomedical variables for an additional ~1.5 million data. Detailed data of his body weight, glucose, blood pressure, heart rate, blood lipids, body temperature, and blood oxygen level, along with important lifestyle details, including diet, exercise, sleep, stress, water intake, and daily life routines are included in his MI database. His developed MI model has a total of 10 categories covering approximately 500 detailed elements that constitute his defined "metabolism model" which are the building blocks or root causes for diabetes and other chronic disease complications, including but not limited to cardiovascu-

lar disease (CVD), chronic heart disease (CHD), stroke, chronic kidney disease (CKD), retinopathy, neuropathy, foot ulcer, and hypothyroidism. The end result of the MI development work is a combined MI value within any selected time period with 73.5% as its dividing line between a healthy and unhealthy state. The MI serves as the foundation to many of his follow-up medical research work.

During the period from 2015 to 2017, he focused his research on type 2 diabetes (T2D), especially glucoses, including fasting plasma glucose (FPG), postprandial plasma glucose (PPG), estimated average glucose (eAG), and hemoglobin A1C (HbA1C). During the following period from 2018 to 2022, he concentrated on researching medical complications resulting from diabetes, chronic diseases, and metabolic disorders which include heart problems, stroke, kidney problems, retinopathy, neuropathy, foot ulcer, diabetic skin fungal infection, hypothyroidism, and diabetic constipation, cancer, and dementia. He also developed a few mathematical risk models to calculate the probability percentages of developing various diabetic complications.

From his previous medical research work, he has identified and learned that the association with the energy of hyperglycemic conditions is the primary source for causing many diabetic complications which lead to death. Therefore, a thorough knowledge of these energies is important for achieving a better understanding of those dangerous complications.

### **Elasticity, Plasticity, Viscoelasticity and Viscoplasticity** **The Difference Between Elastic Materials and Viscoelastic Materials** (from "Soborthans, innovating shock and vibration solutions")

#### **What are Elastic Materials?**

Elasticity is the tendency of solid materials to return to their original shape after forces are applied on them. When the forces are removed, the object will return to its initial shape and size if the material is elastic.

#### **What are Viscous Materials?**

Viscosity is a measure of a fluid's resistance to flow. A fluid with large viscosity resists motion. A fluid with low viscosity flows. For example, water flows more easily than syrup because it has a lower viscosity. High viscosity materials might include honey, syrups, or gels – generally things that resist flow. Water is a low viscosity material, as it flows readily. Viscous materials are thick or sticky or adhesive. Since heating reduces viscosity, these materials don't flow easily. For example, warm syrup flows more easily than cold.

#### **What is Viscoelastic?**

Viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. Synthetic polymers, wood, and human tissue, as well as metals at high temperature, display significant viscoelastic effects. In some applications, even a small viscoelastic response can be significant.

### **Elastic Behavior Versus Viscoelastic Behavior**

The difference between elastic materials and viscoelastic ma-

terials is that viscoelastic materials have a viscosity factor and the elastic ones don't. Because viscoelastic materials have the viscosity factor, they have a strain rate dependent on time. Purely elastic materials do not dissipate energy (heat) when a load is applied, then removed; however, a viscoelastic substance does.

**The following brief introductions are excerpts from Wikipedia:**

#### **"Elasticity (Physics)**

*Physical property when materials or objects return to original shape after deformation*

*In physics and materials science, **elasticity** is the ability of a body to resist a distorting influence and to return to its original size and shape when that influence or force is removed. Solid objects will deform when adequate loads are applied to them; if the material is elastic, the object will return to its initial shape and size after removal. This is in contrast to plasticity, in which the object fails to do so and instead remains in its deformed state.*

*The physical reasons for elastic behavior can be quite different for different materials. In metals, the atomic lattice changes size and shape when forces are applied (energy is added to the system). When forces are removed, the lattice goes back to the original lower energy state. For rubbers and other polymers, elasticity is caused by the stretching of polymer chains when forces are applied.*

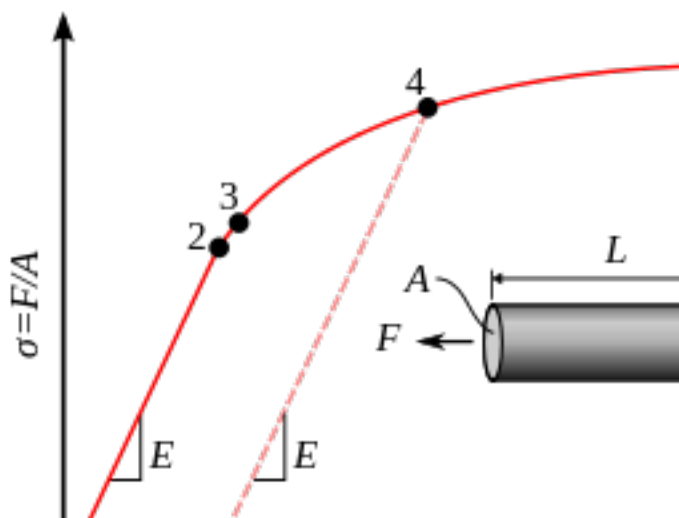
*Hooke's law states that the force required to deform elastic objects should be directly proportional to the distance of deformation, regardless of how large that distance becomes. This is known as perfect elasticity, in which a given object will return to its original shape no matter how strongly it is deformed. This is an ideal concept only; most materials which possess elasticity in practice remain purely elastic only up to very small deformations, after which plastic (permanent) deformation occurs.*

*In engineering, the elasticity of a material is quantified by the elastic modulus such as the Young's modulus, bulk modulus or shear modulus which measure the amount of stress needed to achieve a unit of strain; a higher modulus indicates that the material is harder to deform. The material's elastic limit or yield strength is the maximum stress that can arise before the onset of plastic deformation.*

#### **Plasticity (Physics)**

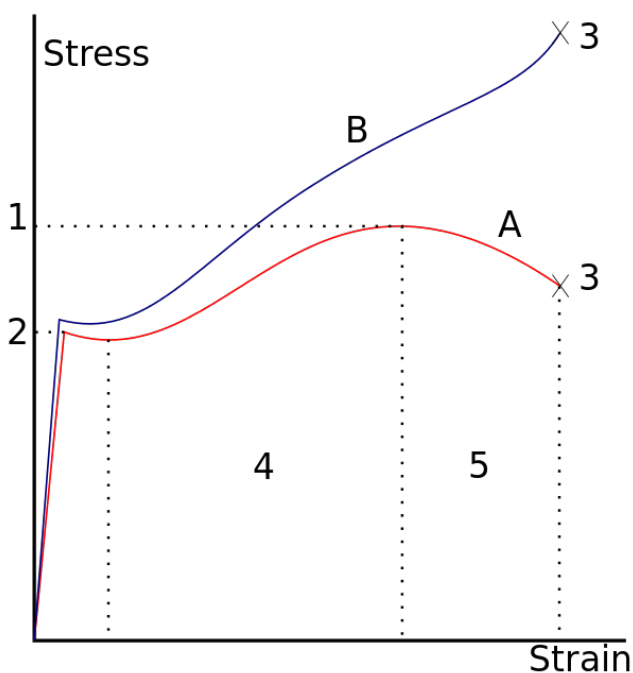
*Deformation of a solid material undergoing non-reversible changes of shape in response to applied forces.*

*In physics and materials science, plasticity, also known as plastic deformation, is the ability of a solid material to undergo permanent deformation, a non-reversible change of shape in response to applied forces. For example, a solid piece of metal being bent or pounded into a new shape displays plasticity as permanent changes occur within the material itself. In engineering, the transition from elastic behavior to plastic behavior is known as yielding.*



Stress–strain curve showing typical yield behavior for nonferrous alloys.

1. True elastic limit
2. Proportionality limit
3. Elastic limit
4. Offset yield strength



A stress–strain curve typical of structural steel.

- 1: Ultimate strength
- 2: Yield strength (yield point)
- 3: Rupture
- 4: Strain hardening region
- 5: Necking region
- A: Apparent stress ( $F/A_0$ )
- B: Actual stress ( $F/A$ )

Plastic deformation is observed in most materials, particularly metals, soils, rocks, concrete, and foams. However, the physical

mechanisms that cause plastic deformation can vary widely. At a crystalline scale, plasticity in metals is usually a consequence of dislocations. Such defects are relatively rare in most crystalline materials, but are numerous in some and part of their crystal structure; in such cases, plastic crystallinity can result. In brittle materials such as rock, concrete and bone, plasticity is caused predominantly by slip at microcracks. In cellular materials such as liquid foams or biological tissues, plasticity is mainly a consequence of bubble or cell rearrangements, notably TI processes.

For many ductile metals, tensile loading applied to a sample will cause it to behave in an elastic manner. Each increment of load is accompanied by a proportional increment in extension. When the load is removed, the piece returns to its original size. However, once the load exceeds a threshold – the yield strength – the extension increases more rapidly than in the elastic region; now when the load is removed, some degree of extension will remain.

Elastic deformation, however, is an approximation and its quality depends on the time frame considered and loading speed. If, as indicated in the graph opposite, the deformation includes elastic deformation, it is also often referred to as "elasto-plastic deformation" or "elastic-plastic deformation".

Perfect plasticity is a property of materials to undergo irreversible deformation without any increase in stresses or loads. Plastic materials that have been hardened by prior deformation, such as cold forming, may need increasingly higher stresses to deform further. Generally, plastic deformation is also dependent on the deformation speed, i.e. higher stresses usually have to be applied to increase the rate of deformation. Such materials are said to deform visco-plastically."

### Viscoelasticity

Property of materials with both viscous and elastic characteristics under deformation

In materials science and continuum mechanics, viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. Viscous materials, like water, resist shear flow and strain linearly with time when a stress is applied. Elastic materials strain when stretched and immediately return to their original state once the stress is removed.

Viscoelastic materials have elements of both of these properties and, as such, exhibit time-dependent strain. Whereas elasticity is usually the result of bond stretching along crystallographic planes in an ordered solid, viscosity is the result of the diffusion of atoms or molecules inside an amorphous material.

In the nineteenth century, physicists such as Maxwell, Boltzmann, and Kelvin researched and experimented with creep and recovery of glasses, metals, and rubbers. Viscoelasticity was further examined in the late twentieth century when synthetic polymers were engineered and used in a variety of applications. Viscoelasticity calculations depend heavily on the viscosity variable,  $\eta$ . The inverse of  $\eta$  is also known as fluidity,  $\phi$ . The value of either can be derived as a function of temperature or as a given

value (i.e. for a dashpot).

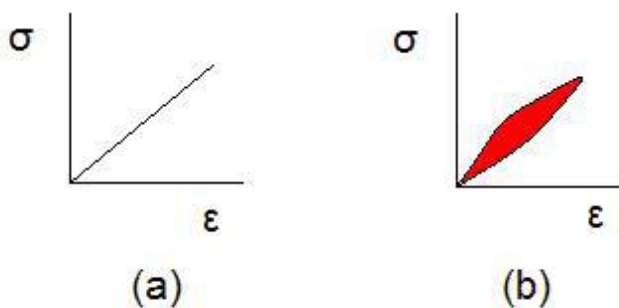
Depending on the change of strain rate versus stress inside a material, the viscosity can be categorized as having a linear, non-linear, or plastic response. When a material exhibits a linear response it is categorized as a Newtonian material. In this case the stress is linearly proportional to the strain rate. If the material exhibits a non-linear response to the strain rate, it is categorized as Non-Newtonian fluid. There is also an interesting case where the viscosity decreases as the shear/strain rate remains constant. A material which exhibits this type of behavior is known as thixotropic. In addition, when the stress is independent of this strain rate, the material exhibits plastic deformation. Many viscoelastic materials exhibit rubber-like behavior explained by the thermodynamic theory of polymer elasticity.

Cracking occurs when the strain is applied quickly and outside of the elastic limit. Ligaments and tendons are viscoelastic, so the extent of the potential damage to them depends both on the rate of the change of their length as well as on the force applied.

**A viscoelastic material has the following properties:**

- hysteresis is seen in the stress–strain curve
- stress relaxation occurs: step constant strain causes decreasing stress
- creep occurs: step constant stress causes increasing strain
- its stiffness depends on the strain rate or the stress rate.

#### Elastic Versus Viscoelastic Behavior



Stress–strain curves for a purely elastic material (a) and a viscoelastic material (b). The red area is a hysteresis loop and shows the amount of energy lost (as heat) in a loading and unloading cycle. It is equal to

$$\oint \sigma d\epsilon$$

where  $\sigma$  is stress and  $\epsilon$  is strain.

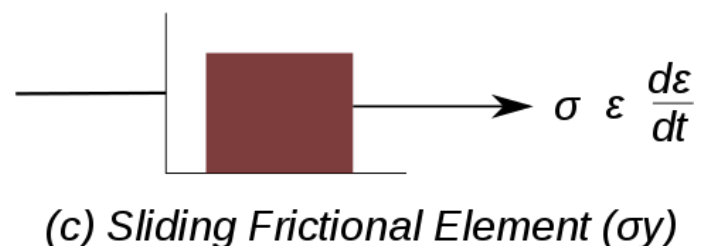
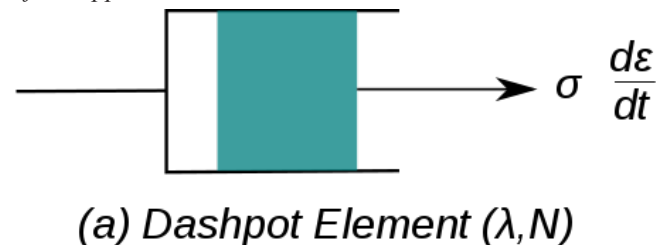
Unlike purely elastic substances, a viscoelastic substance has an elastic component and a viscous component. **The viscosity of a viscoelastic substance gives the substance a strain rate dependence on time.** Purely elastic materials do not dissipate energy (heat) when a load is applied, then removed. However, a viscoelastic substance dissipates energy when a load is **applied, then removed. Hysteresis is observed in the stress–strain curve, with the area of the loop being equal to the energy lost during the loading cycle.** Since viscosity is the resistance to thermally activated plastic deformation, a viscous material will lose ener-

gy through a loading cycle. Plastic deformation results in lost energy, which is uncharacteristic of a purely elastic material's reaction to a loading cycle.

Specifically, viscoelasticity is a molecular rearrangement. When a stress is applied to a viscoelastic material such as a polymer, parts of the long polymer chain change positions. This movement or rearrangement is called “creep”. Polymers remain a solid material even when these parts of their chains are rearranging in order to accompany the stress, and as this occurs, it creates a back stress in the material. When the back stress is the same magnitude as the applied stress, the material no longer creeps. When the original stress is taken away, the accumulated back stresses will cause the polymer to return to its original form. **The material creeps, which gives the prefix visco-, and the material fully recovers, which gives the suffix -elasticity.**

#### Viscoplasticity

Viscoplasticity is a theory in continuum mechanics that describes the rate-dependent inelastic behavior of solids. Rate-dependence in this context means that the deformation of the material depends on the rate at which loads are applied. The inelastic behavior that is the subject of viscoplasticity is plastic deformation which means that the material undergoes unrecoverable deformations when a load level is reached. Rate-dependent plasticity is important for transient plasticity calculations. The main difference between rate-independent plastic and viscoplastic material models is that the latter exhibit not only permanent deformations after the application of loads but continue to undergo a creep flow as a function of time under the influence of the applied load.



**Figure 1:** Elements used in one-dimensional models of viscoplastic materials.

The elastic response of viscoplastic materials can be represented in one-dimension by Hookean spring elements. Rate-dependence can be represented by nonlinear dashpot elements in a manner similar to viscoelasticity. Plasticity can be accounted for by adding sliding frictional elements as shown in Figure 1. In the figure  $E$  is the modulus of elasticity,  $\lambda$  is the viscosity parameter and  $N$  is a power-law type parameter that represents non-linear dashpot [ $\sigma(d\varepsilon/dt) = \sigma = \lambda(d\varepsilon/dt)^{1/N}$ ]. The sliding element can have a yield stress ( $\sigma_y$ ) that is strain rate dependent, or even constant, as shown in Figure 1c.

Viscoplasticity is usually modeled in three-dimensions using overstress models of the Perzyna or Duvaut-Lions types. In these models, the stress is allowed to increase beyond the rate-independent yield surface upon application of a load and then allowed to relax back to the yield surface over time. The yield surface is usually assumed not to be rate-dependent in such models. An alternative approach is to add a strain rate dependence to the yield stress and use the techniques of rate independent plasticity to calculate the response of a material.

For metals and alloys, viscoplasticity is the macroscopic behavior caused by a mechanism linked to the movement of dislocations in grains, with superposed effects of inter-crystalline gliding. The mechanism usually becomes dominant at temperatures greater than approximately one third of the absolute melting temperature. However, certain alloys exhibit viscoplasticity at room temperature (300K). For polymers, wood, and bitumen, the theory of viscoplasticity is required to describe behavior beyond the limit of elasticity or viscoelasticity.

In general, viscoplasticity theories are useful in areas such as

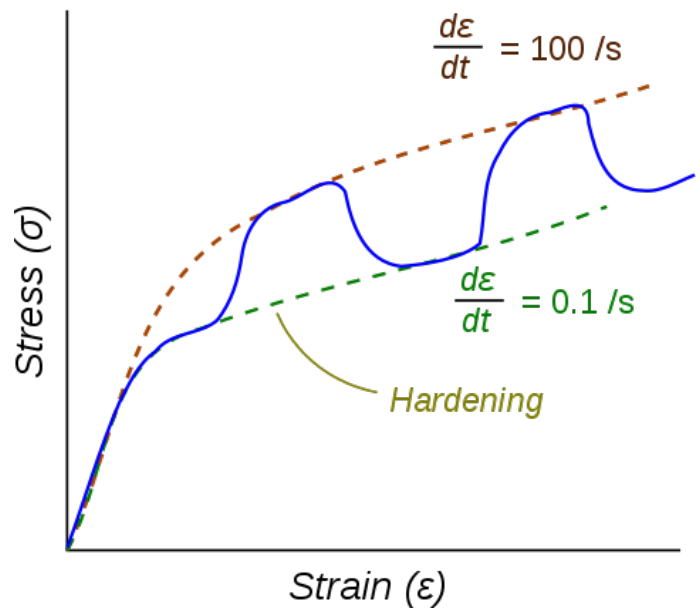
- the calculation of permanent deformations,
- the prediction of the plastic collapse of structures,
- the investigation of stability,
- crash simulations,
- systems exposed to high temperatures such as turbines in engines, e.g. a power plant,
- dynamic problems and systems exposed to high strain rates.

### Phenomenology

For a qualitative analysis, several characteristic tests are performed to describe the phenomenology of viscoplastic materials. Some examples of these tests are

1. hardening tests at constant stress or strain rate,
2. creep tests at constant force, and
3. stress relaxation at constant elongation.

### Strain Hardening Test



**Figure 2:** Stress–strain response of a viscoplastic material at different strain rates.

The dotted lines show the response if the strain-rate is held constant. The blue line shows the response when the strain rate is changed suddenly.

One consequence of yielding is that as plastic deformation proceeds, an increase in stress is required to produce additional strain. This phenomenon is known as Strain/Work hardening. For a viscoplastic material the hardening curves are not significantly different from those of rate-independent plastic material.

Nevertheless, three essential differences can be observed.

1. At the same strain, the higher the rate of strain the higher the stress
2. A change in the rate of strain during the test results in an immediate change in the stress–strain curve.
3. The concept of a plastic yield limit is no longer strictly applicable.

The hypothesis of partitioning the strains by decoupling the elastic and plastic parts is still applicable where the strains are small, i.e.,

$$\varepsilon = \varepsilon_e + \varepsilon_{vp}$$

where  $\varepsilon_e$  is the elastic strain and  $\varepsilon_{vp}$  is the viscoplastic strain. To obtain the stress–strain behavior shown in blue in the figure, the material is initially loaded at a strain rate of 0.1/s. The strain rate is then instantaneously raised to 100/s and held constant at that value for some time. At the end of that time period the strain rate is dropped instantaneously back to 0.1/s and the cycle is continued for increasing values of strain. There is clearly a lag between the strain-rate change and the stress response. This lag is modeled quite accurately by overstress models (such as the Perzyna model) but not by models of rate-independent plasticity that have a rate-dependent yield stress.

## Results

Figure 1 displays 2 eAG waveforms in TD for the following two cases in the format of (eAG at 00:00, Peak eAG, eAG at 23:45, average eAG):

- (1) < 150: (114, 136, 115, 118)
- (2) > 150: (115, 164, 119, 128)

It is noted that the eAG difference of >150 minus <150 at (00:00, peak, 23:45, average) are (1, 28, 4, 10).

Furthermore, by using the TD energy formula of:

$$TD \text{ energy} = \text{square of average eAG} * 96$$

The TD energies for these 2 cases are:

- (1) < 150 case: 1,336,704 (100%)
- (2) > 150 case: 1,572,864 (118%)

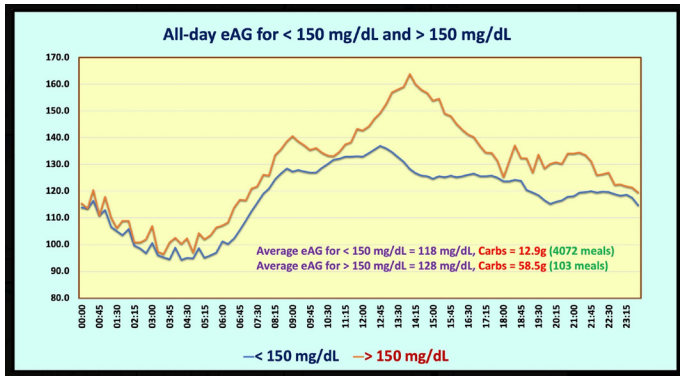


Figure 1: 2 eAG waveforms in TD

Figure 2 shows two stress-strain diagrams for two eAG cases. The viscosity factors used for these 2 cases are:

- (1) <150: Carbs/sugar 12.9 grams
- (2) >150: Carbs/sugar 58.5 grams

The ratio of energy loss via two hysteresis loops is 132 times higher for the case of >150 mg/dL than the case of <150 mg/dL.

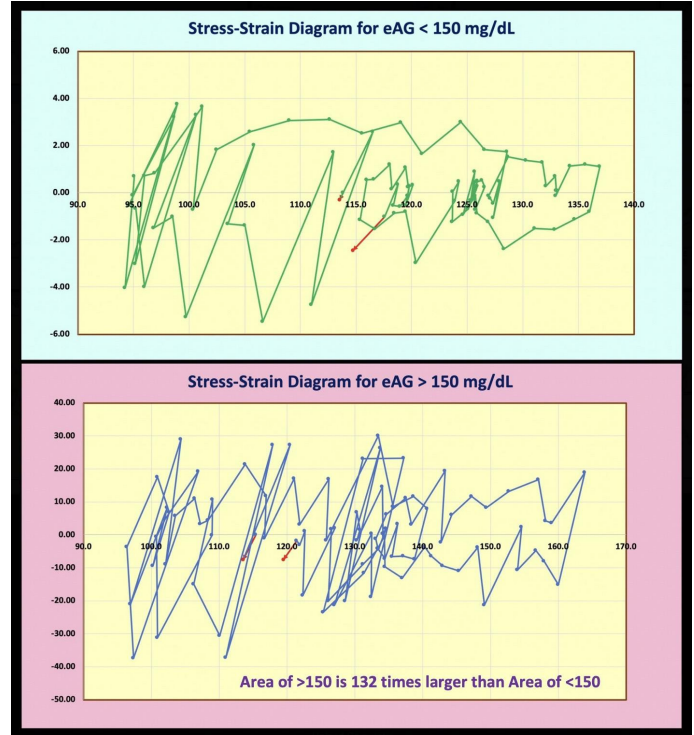


Figure 2: Comparison of stress-strain diagrams of 2 eAG cases

Figure 3 illustrates the comparison of two FD diagrams. The energy ratio between the high-glucose case of >150 mg/dL is two times (200%) of the low-glucose case of <150 mg/dL.

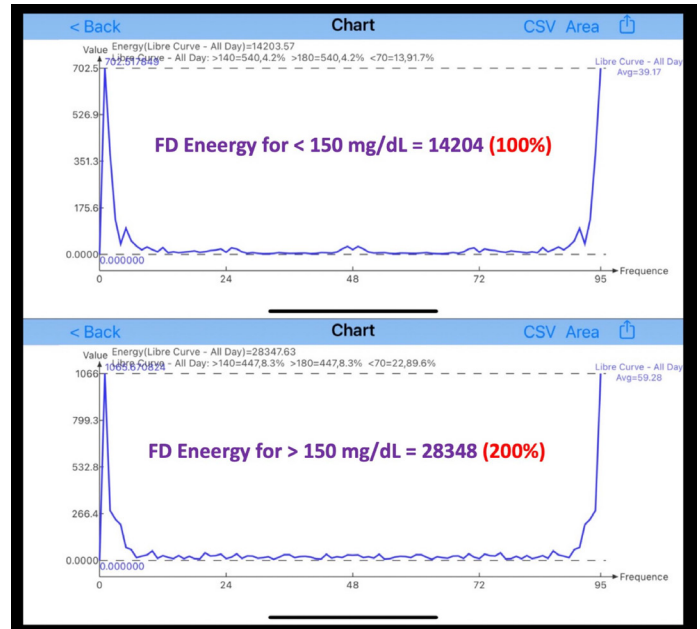


Figure 3: 2 FD energies

## Conclusion

In summary, the following three observations outline the findings of the two selected eAG cases according to the PPG ranges of either <150 mg/dL or >150 mg/dL:

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case values, but their waveforms (curve shapes) look similar to each other. The far left side of the fasting plasma glucose (FPG) during sleep hours (midnight to 7am) looks like two salad bowls with zig-zag edges. During the day (7am to 7pm), the peaks of the two eAG curves occur after lunch (around 2pm). The 2 eAG curves are trending downward in the evening (7pm to midnight). The observed TD phenomena confirm the important role of carbs/sugar intake to meals. This is why the author utilizes carbs/sugar amounts as the viscosity factor for his analysis.

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(3) By using wave theory and energy theory with a FFT operation, the low-glucose case's (<150 mg/dL) energy is defined as 100%. Then, the high-glucose case's (>150 mg/dL) energy is 200% which is 2x higher than the low-glucose case.

***In conclusion, the higher eAG values present higher PPG values, which result in more relative energy associated with the hyperglycemic conditions. This would cause severe damage to the internal organs.***

## References

For editing purposes, the majority of the references in this paper, which are self-references, have been removed. Only references from other authors' published sources remain. The bibliography of the author's original self-references can be viewed at [www.eclairermd.com](http://www.eclairermd.com).

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