

The GH-Method

Viscoelastic Glucose Theory (VGT #3): Similarity and Difference of Two Stress-Strain Diagrams for Viscoelastic Glucose Behaviors from Continuous Glucose Monitor Sensor Measured and Perturbation Theory Produced Postprandial Plasma Glucoses with “Time-Dependent” Characteristics of a Synthesized Postprandial Plasma Glucose Waveform Generated from 4,115 Meals Over a 3.7-Year Period from 5/8/2018 to 1/18/2022 Based on GH-Method: Math-Physical Medicine (No. 580)

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Note: Readers who want to get a quick overview can read the abstract, results, and graphs.

Abstract

The author has studied strength of materials and theory of elasticity through his undergraduate courses at the University of Iowa. He also conducted research work to earn a master's degree in Biomechanics under Professor James Andrews. He remembers using the spring and dashpot models to simulate the behaviors of human joints, bones, muscles, and tendons in order to investigate the human-weapon interactions. Later, he went to MIT to pursue his PhD study under Professor Norman Jones, who taught him theory of plasticity and dynamic plastic behaviors of various structure elements. He also took additional graduate courses in the field of fluid dynamics and thermodynamics. Since then, many advancements have been made in a few application areas of biomechanics, especially tissues in the human body which possess viscoelastic characteristics, such as bones, muscles, cartilages, tendons (connect bone to muscle), ligaments (connect bone to bone), fascia, and skin. For example, the author suffered plantar fasciitis for many years. He understood that the night splint dorsiflexes forefoot, at the back of the foot, increases plantar fascia tension to offer stress-relaxation for the pain. This model of muscles and tendons connecting the lower leg and foot is a form of viscoelastic problem. However, when dealing with the human internal organs, it is not easy to conduct live experiments to obtain accurate measurements for the biomedical material properties. Although blood itself is a viscous (time-dependent) material, the viscosity factor may fall between water, honey, syrup, or

gel. However, the author's research subject is “glucose”, the carbohydrates and sugar amount in blood produced by liver and carried by red blood cells, not the blood itself. It is nearly impossible to measure material geometry or certain engineering properties of glucose, for example, to determine the viscosity of “glucose”. Therefore, the best he could do is to apply the “concept of viscoelasticity and/or viscoplasticity” to construct an analogy model of time-dependent glucose behaviors. The author's background includes mathematics, physics, and various engineering disciplines, not including biology and chemistry. As a result, he can only investigate the observed biomedical phenomena using his ready-learned math-physical tools. He studied both modern physics and quantum mechanics during his school days; therefore, he attempted to apply the theory of relativity on interactions among internal organs and perturbation theory on approximation of glucose level along with the glucose associated energy estimation, where he has published a few articles. In addition, he has conducted some investigations of glucose behaviors using elasticity theory and plasticity theory, which allowed to write a few articles on the research findings. In the elasticity and plasticity papers, he utilized the postprandial plasma glucose (PPG) value as the strain along with the combined effect of both carbs/sugar intake amount and post-meal exercise level as the stress. In a recent email from Professor Norman Jones, he said that: “I have wondered if the use of viscoelastic/viscoplastic materials might be of some value to your studies. These phenomena embrace time-dependent behaviour and I know

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that you have emphasized the time-dependence of various behaviours in the body. Just a thought.” His suggestion triggered the author’s interest and desire to research the subject of glucose behaviors further using viscosity theory. This particular article is a follow-up to his papers No. 578 and No. 579 which focus on certain generic characteristics of viscoelastic glucose behaviors and the comparison via stress-strain diagrams between viscoelastic glucose versus viscoplastic glucose. In this paper, he initially applies the perturbation theory to generate a perturbed PPG waveform (an approximated PPG curve). He then uses a relative glucose level (individual PPG - average PPG) for both of his measured PPG and perturbed PPG as the strain and the respective strain rate (de/dt) multiplied with the viscosity factor (η) as the stress. Since it is difficult for him to determine the viscosity factor (η) of glucose, not blood, he makes a bold assumption by using his average carbs/sugar intake amount (grams) as his viscosity factors, 13.9 grams for the measured PPG and his selected perturbation factor of 0.39 for the perturbed PPG. It should be noted that the ratio of 36 from $13.9/0.39$ has also appeared in two different diagram’s stress Y-axis scales comparison with a ratio of 36. One special note is that he ceased taking any diabetes medications since 12/08/2015. As a result, his research papers are “medication-free”. Once medication enters the body, it takes over the control of glucose outputs or symptoms. In most of his studies using the continuous glucose monitoring (CGM) sensor collected glucose data after 12/08/2015, the raw data he has collected are completely “free from any biochemical influences”. The only two influential forces or root-causes are the natural health of his organs (liver for glucose production and pancreatic beta cells for insulin production) and his lifestyle management (specifically, diet for energy influx and exercise for energy consumption). Elastic glucose vs. plastic glucose: The author has spent a considerable amount of research time during 2020 and 2021 to write 39 papers about his developed linear elastic glucose theory (LEGT). This LEGT can be expressed through the following linear elastic glucose equation: Predicted PPG = FPG * GH.f + (carbs&sugar grams) * GH.e + (post-meal walking k-steps * GH.w), where: GH.f-Modulus can estimate the starting PPG of a meal at 0-minute using FPG value during sleep; GH.e-Modulus can estimate the peak PPG level at 60-minutes after a meal using carbs&sugar grams; GH.w-Modulus can estimate the decreased PPG level at 180-minutes after a meal using post-meal walking k-steps. It should be pointed out that his synthesized PPG waveform appears to behave as an “elastic glucose”; therefore, the above-described linear elastic equation can be applied to the 4,092 meals carry with “elastic or viscoelastic glucose <180 mg/dL” behaviors (99.4% of total). With the synthesized PPG waveform from 4,115 meals, by combining all of the 4,092 elastic PPG curves and 23 plastic PPG curves together, they have also

possessed the viscoelastic glucose behavior pattern. However, if the author separates out the 23 hyperglycemia (high glucose level) meals, their synthesized PPG waveform would carry the “plastic or viscoplastic glucose >180 mg/dL” behaviors (0.6% of total). In the plastic glucose study of nonlinear plastic glucose theory (NPGT), he has developed the following simplified plastic glucose equation which produces two consecutive glucose peaks by the excessive intake amount of carbs/sugar: Predicted PPG = (carbs&sugar grams) * GH.e + (carbs&sugar grams) * GH.p + (post-meal walking k-steps * GH.w), where: GH.e-Modulus can estimate the first elastic peak PPG at 60-minutes after a meal using carbs&sugar grams; GH.p-Modulus can estimate the second elasto-plastic peak PPG at 120-minutes after a meal using the same value of carbs&sugar grams; GH.w-Modulus can estimate the decreased PPG at 180-minutes after a meal using post-meal walking k-steps. It should be noted that his plastic slope, GH.p-Modulus value of 0.254, is less than half or at the 43% level of his elastic slope, GH.e-Modulus value of 0.586. 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 viscoelasticity theory, viscoplasticity theory, and perturbation theory from the disciplines of engineering and physics in the Method section. The analogy between physics and medicine is twofold. First, the force or stress (σ) in physics and engineering (y-axis) corresponds to the influential force or load on our body for pushing PPG upward or downward in medicine, e.g. carbohydrates and sugar intake amount or post-meal walking exercise. This combined stress component has no difference between elastic and plastic. The only major influential factor of stress is the selection of viscosity factors (η). Second, the deformation or strain (ϵ) in physics and engineering (x-axis) corresponds to the actual PPG level in medicine. This strain component has a difference between elastic glucose (<180 mg/dL) and plastic glucose (>180 mg/dL). Therefore, the difference in “strain rate”, i.e. “change amount of PPG in certain amount of time duration”, between elastic state and plastic state will have further influence on stress value. Nevertheless, the medicine field is still quite different from the engineering field, where the engineering materials such as steel, copper, concrete, and aluminum are inorganic in most cases. These material properties do not change significantly over their expected lifespans. However, in medicine, the body with its organs and cells are organic and go through many distinct stages over their natural lifespans, such as birth, splitting, growth, mutation, development, repair, sickness, and death. Therefore, the biomedical properties are “moving targets” which vary with the individual person, severity of diabetes, and selected different time-windows. In another word, they are both time-dependent and specimen-

dependent. Because of these fundamental characteristics, calculations of cross-section of subject, bending moment of resistance, or the shape-factors in solid mechanics are not applicable in this biomedical glucose analogy study of elasticity/plasticity or viscoelasticity/viscoplasticity. The most important part, in the author's opinion, is that by applying the concept of elasticity/plasticity theory or viscoelasticity/viscoplasticity theory on understanding the biomedical phenomena is extremely useful for exploring deep insights for predicting overall glucose behaviors, particularly for understanding and be able to predicting hyperglycemia situations (or severe diabetes cases) in order to help the 100+ million diabetes patients or 1.3% of the world population of 7.9 billion who are currently suffering from hyperglycemia (i.e., high glucose level > 180 mg/dL). Energy theory: After declaring the analogy of elasticity and plasticity theories on glucose, the energy theory in physics must be brought into context. The human body and organs are composed of different organic cells that require energy infusion from glucose (i.e. nutrition) carried by red blood cells and energy consumption from labor-work or exercise. Incidentally, approximately 70% of energy inputs are consumed by our brain functions. When the residual energy resulting from a plastic glucose scenario is stored in the body, it will cause damage to many internal organs. According to the physics principle, energies associated with the residual glucose waves are proportional to the square of the residual glucose amplitude. The residual energies from elevated glucoses are then circulating inside the body via red blood cells inside blood vessels which then impact all of the internal organs to cause varying degrees of damage and develop into different diabetic complications, for example heart diseases, stroke, kidney problems, retinopathy, neuropathy. The author has applied Fast Fourier Transform (FFT) operations to convert the glucose wave from a time-domain into a frequency-domain. The y-axis amplitude values in the frequency-domain indicate the proportional energy levels associated with each different frequency component for the glucose occurrence. Furthermore, he has modified the famous equation of theory of relativity invented by Albert Einstein, $E=mc^2$, into his energy estimation equation of $E = na^2$, where n is number of frequency and a is the amplitude of glucose, and the a^2 , i.e. a square, is the Y-axis amplitude of frequency domain. Actually, this na^2 value indicates the area underneath the frequency amplitude curve in frequency domain diagram. This simple transformation can provide another quick estimation of the relative energy level of excessive glucose from hyperglycemia situations. Currently, many people live a sedentary lifestyle and lack sufficient exercise to burn off the energy influx which causes them to become overweight or obese. Being overweight and/or having obesity can

lead to chronic diseases, including diabetes. In addition, many types of processed food add unnecessary ingredients and harmful chemical components that are toxic to the bodies, which lead to the development of many other deadly diseases, such as cancer. For example, there are ~85% of worldwide diabetes patients, who are also overweight, and ~75% of them have cardiac issues or require surgeries due to diabetes conditions. In the engineering analysis, when the load is applied on the structure, it bends or twists becoming deformed; however, when the load is removed, it will either be restored back to its original shape (elastic) or remain in a permanent deformed shape (plastic). In its corresponding biomedical situation, after eating carbohydrates or sugar from food, our glucose level will increase; therefore, the sugar and carbohydrates function as the energy supply or energy influx. After having labor work or exercise, the glucose level will decrease. As a result, exercise burns off energy, which is similar to the load removal in the engineering case. But, in the biomedical case, the energy input and output process takes some time which is not as simple and quick as the structural load removal in the engineering case. Therefore, the glucose behaviors, for both elastic glucose and plastic glucose, are "dynamic" in nature which is time-dependent. Time-dependent strain (PPG) and time-dependent stress (viscosity factor * glucose change rate): The Hooke's law of linear elasticity is expressed as: Strain (ϵ : epsilon) = Stress (σ : sigma) / Young's modulus (E). For biomedical glucose application, his developed LEGT is expressed as: PPG (strain) = carbs/sugar (stress) * GH.p-Modulus (a positive number) + post-meal walking k-steps * GH.w-Modulus (a negative number), where GH.p-Modulus is reciprocal of Young's modulus E. In order to construct an "ellipse-like" diagram in a stress-strain space domain covering both positive and negative sides of the space, he has modified his definition of strain as follows: Strain = (PPG value at certain time instant) - (averaged PPG value). In summary, in this viscoelastic study, he defines his strain and stress as follows: strain = ϵ = (individual PPG - averaged PPG). Stress = $\sigma = \eta * (d\epsilon/dt) = \text{viscosity factor} * (d\text{-strain}/d\text{-time}) = \eta * (\text{PPG at next time instant} - \text{PPG at current time instant}) / 15$, where 15 indicates the 15-minute timespan of his CGM sensor Glucose measurement. He then uses 13.9 grams as the viscosity factor of viscoelastic case (<180 mg/dL) for measured PPG case; and 0.39 perturbation factor as the viscosity factor of viscoelastic case (<180 mg/dL) for perturbed PPG case, in their stress evaluations. In summary, the objective of this article is to explore similarity and difference between the measured PPG and the perturbed PPG. The following three concluding remarks have described the findings for similarities and differences of these two stress-strain diagrams from the measured PPG and perturbed PPG: (1) From the stress-strain diagram of the measured

PPG and perturbed PPG, these two hysteresis loops look similar to each other because both of them use strain rate as the stress component i.e., glucose change rate with time. (2) However, a closer look at the two similar stress-strain diagrams, we can clearly notice the differences from their corresponding time-domain curves between 0-minute to 60-minutes and 60-minutes to 120-minutes. These minor differences are a result from the deviation between measured PPG and perturbed PPG in the time-domain curves since the perturbation theory only provides an approximated PPG. (3) If we examine the y-axis scale of the stress-strain diagrams, then the

viscoelastic measured PPG's stress Y-axis scale is 36 times higher than the viscoelastic perturbed PPG's stress Y-axis scale. This observation is a direct result from the author using the carbs/sugar amount of 13.9 grams as his viscosity factor for measured PPG's stress (Y-axis), while using the perturbation factor of 0.39 as his viscosity factor for perturbed PPG's stress (Y-axis). The ratio of 13.9 over 0.36 is 36. Of course, he can also select a different perturbation factor for generating his perturbed PPG which will then produce a different stress (Y-axis) scale on its corresponding stress-strain diagram.

Keywords: Viscoelastic; Postprandial plasma glucose; Diabetes; Glucose

Abbreviations: PPG: postprandial plasma glucose; FPG: fasting plasma glucose; CGM: continuous glucose monitoring

1. INTRODUCTION

The author has studied strength of materials and theory of elasticity through his undergraduate courses at the University of Iowa. He also conducted research work to earn a master's degree in Biomechanics under Professor James Andrews. He remembers using the spring and dashpot models to simulate the behaviors of human joints, bones, muscles, and tendons in order to investigate the human-weapon interactions. Later, he went to MIT to pursue his PhD study under Professor Norman Jones, who taught him theory of plasticity and dynamic plastic behaviors of various structure elements. He also took additional graduate courses in the field of fluid dynamics and thermodynamics.

Since then, many advancements have been made in a few application areas of biomechanics, especially tissues in the human body which possess viscoelastic characteristics, such as bones, muscles, cartilages, tendons (connect bone to muscle), ligaments (connect bone to bone), fascia, and skin. For example, the author suffered plantar fasciitis for many years. He understood that the night splint dorsiflexes forefoot, at the back of the foot, increases plantar fascia tension to offer stress-relaxation for the pain. This model of muscles and tendons connecting the lower leg and foot is a form of viscoelastic problem. However, when dealing with the human internal organs, it is not easy to conduct live experiments to obtain accurate measurements for the biomedical material properties. Although blood itself is a viscous (time-dependent) material, the viscosity factor may fall between water, honey, syrup, or gel. However, the author's research subject is "glucose", the carbohydrates and sugar amount in blood produced by liver and carried by red blood cells, not the blood itself. It is nearly impossible to measure material geometry or certain engineering properties of glucose, for example, to determine the viscosity of "glucose". Therefore, the best he could do is to apply the "concept of viscoelasticity and/or viscoplasticity" to construct an analogy model of time-dependent glucose behaviors.

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In a recent email from Professor Norman Jones, he said that: "I have wondered if the use of viscoelastic/viscoplastic materials might be of some value to your studies. These phenomena embrace time-dependent behaviour and I know that you have emphasized the time-dependence of various behaviours in the body. Just a thought." His suggestion triggered the author's interest and desire to research the subject of glucose behaviors further using viscosity theory. This particular article is a follow-up to his papers No. 578 and No. 579 which focus on certain generic characteristics of viscoelastic glucose behaviors and the comparison via stress-strain diagrams between viscoelastic glucose versus viscoplastic glucose.

In this paper, he initially applies the perturbation theory to generate a perturbed PPG waveform (an approximated PPG curve). He then uses a relative glucose level (individual PPG - average PPG) for both of his measured PPG and perturbed PPG as the strain and the respective strain rate ($d\epsilon/dt$) multiplied with the viscosity factor (η) as the stress. Since it is difficult for him to determine the viscosity factor (η) of glucose, not blood, he makes a bold assumption by using his average carbs/sugar intake amount (grams) as his viscosity factors, 13.9 grams for the measured PPG and his selected perturbation factor of 0.39 for the perturbed

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1.1 Elastic glucose vs. plastic glucose

The author has spent a considerable amount of research time during 2020 and 2021 to write 39 papers about his developed linear elastic glucose theory (LEGT). This LEGT can be expressed through the following linear elastic glucose equation:

$$\text{Predicted PPG} = \text{FPG} * \text{GH.f} + (\text{carbs\&sugar grams}) * \text{GH.e} + (\text{post-meal walking k-steps} * \text{GH.w})$$

Where:

GH.f-Modulus can estimate the starting PPG of a meal at 0-minute using FPG value during sleep;

GH.e-Modulus can estimate the peak PPG level at 60-minutes after a meal using carbs&sugar grams;

GH.w-Modulus can estimate the decreased PPG level at 180-minutes after a meal using post-meal walking k-steps.

It should be pointed out that his synthesized PPG waveform appears to behave as an "elastic glucose"; therefore, the above-described linear elastic equation can be applied to the 4,092 meals carry with "elastic or viscoelastic glucose <180 mg/dL" behaviors (99.4% of total). With the synthesized PPG waveform from 4,115 meals, by combining all of the 4,092 elastic PPG curves and 23 plastic

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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 viscoelasticity theory, viscoplasticity theory, and perturbation theory from the disciplines of engineering and physics in the Method section.

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This combined stress component has no difference between elastic and plastic. The only major influential factor of stress is the selection of viscosity factors (η). Second, the deformation or strain (ϵ) in physics and engineering (x-axis) corresponds to the actual PPG level in medicine. This strain component has a difference between elastic glucose (<180 mg/dL) and plastic glucose (>180 mg/dL). Therefore, the difference in “strain rate”, i.e. “change amount of PPG in certain amount of time duration”, between elastic state and plastic state will have further influence on stress value.

Nevertheless, the medicine field is still quite different from the engineering field, where the engineering materials such as steel, copper, concrete, and aluminum are inorganic in most cases. These material properties do not change significantly over their expected lifespans. However, in medicine, the body with its organs and cells are organic and go through many distinct stages over their natural lifespans, such as birth, splitting, growth, mutation, development, repair, sickness, and death. Therefore, the biomedical properties are “moving targets” which vary with the individual person, severity of diabetes, and selected different time-windows. In another word, they are both time-dependent and specimen-dependent. Because of these fundamental characteristics, calculations of cross-section of subject, bending moment of resistance, or the shape-factors in solid mechanics are not applicable in this biomedical glucose analogy study of elasticity/plasticity or viscoelasticity/viscoplasticity. The most important part, in the author’s opinion, is that by applying the concept of elasticity/plasticity theory or viscoelasticity/viscoplasticity theory on understanding the biomedical phenomena is extremely useful for exploring deep insights for predicting overall glucose behaviors, particularly for understanding and be able to predicting hyperglycemia situations (or severe diabetes cases) in order to help the 100+ million diabetes patients or 1.3% of the world population of 7.9 billion who are currently suffering from hyperglycemia (i.e., high glucose level > 180 mg/dL).

1.2 Energy theory

After declaring the analogy of elasticity and plasticity theories on glucose, the energy theory in physics must be brought into context. The human body and organs are composed of different organic cells that require energy infusion from glucose (i.e. nutrition) carried by red blood cells and energy consumption from labor-work or exercise. Incidentally, approximately 70% of energy inputs are consumed by our brain functions. When the residual energy resulting from a plastic glucose scenario is stored in the body, it will cause damage to many internal organs. According to the physics principle, energies associated with the residual glucose waves are proportional to the square of the residual glucose amplitude. The residual energies from elevated glucoses are then circulating inside the body via red blood cells inside blood vessels which then impact all of the internal organs to cause varying degrees of damage and develop into different diabetic complications, for example heart diseases, stroke, kidney problems, retinopathy, neuropathy. The author has applied Fast Fourier Transform (FFT) operations to convert the glucose wave from a time-domain into a frequency-domain. The y-axis amplitude values in the frequency-domain indicate the proportional energy levels associated with each different frequency component for the glucose occurrence.

Furthermore, he has modified the famous equation of theory of relativity invented by Albert Einstein, $E=mc^2$, into his energy estimation equation of $E = na^2$, where n is number of frequency and a is the amplitude of glucose, and the a^2 , i.e. a square, is the Y-axis amplitude of frequency domain. Actually, this na^2 value indicates the area underneath the frequency amplitude curve in frequency domain diagram. This simple transformation can provide another quick estimation of the relative energy level of excessive glucose from hyperglycemia situations.

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unnecessary ingredients and harmful chemical components that are toxic to the bodies, which lead to the development of many other deadly diseases, such as cancer. For example, there are ~85% of worldwide diabetes patients, who are also overweight, and ~75% of them have cardiac issues or require surgeries due to diabetes conditions.

In the engineering analysis, when the load is applied on the structure, it bends or twists becoming deformed; however, when the load is removed, it will either be restored back to its original shape (elastic) or remain in a permanent deformed shape (plastic). In its corresponding biomedical situation, after eating carbohydrates or sugar from food, our glucose level will increase; therefore, the sugar and carbohydrates function as the energy supply or energy influx. After having labor work or exercise, the glucose level will decrease. As a result, exercise burns off energy, which is similar to the load removal in the engineering case. But, in the biomedical case, the energy input and output process takes some time which is not as simple and quick as the structural load removal in the engineering case. Therefore, the glucose behaviors, for both elastic glucose and plastic glucose, are “dynamic” in nature which is time-dependent.

1.3 Time-dependent strain (PPG) and time-dependent stress (viscosity factor * glucose change rate)

The Hooke’s law of linear elasticity is expressed as:

$$\text{Strain } (\varepsilon: \text{epsilon}) \\ = \text{Stress } (\sigma: \text{sigma}) / \text{Young's modulus } (E)$$

For biomedical glucose application, his developed LEGT is expressed as:

$$\text{PPG (strain)} \\ = \text{carbs/sugar (stress)} * \text{GH.p-Modulus (a positive number)} + \text{post-meal walking k-steps} \\ * \text{GH.w-Modulus (a negative number)}$$

Where GH.p-Modulus is reciprocal of Young’s modulus E.

In order to construct an “ellipse-like” diagram in a stress-strain space domain covering both positive and negative sides of the space, he has modified his definition of strain as follows:

$$\text{Strain} \\ = (\text{PPG value at certain time instant}) - \\ (\text{averaged PPG value})$$

In summary, in this viscoelastic study, he defines his strain and stress as follows:

$$\text{Strain} \\ = \varepsilon \\ = (\text{individual PPG} - \text{averaged PPG})$$

$$\text{Stress} \\ = \sigma \\ = \eta * (d\varepsilon/dt) \\ = \text{viscosity factor} * (d\text{-strain}/d\text{-time}) \\ = \eta * (\text{PPG at next time instant} - \text{PPG at} \\ \text{current time instant}) / 15$$

Where 15 indicates the 15-minute timespan of his CGM sensor Glucose measurement.

He then uses 13.9 grams as the viscosity factor of viscoelastic case (<180 mg/dL) for measured PPG case; and 0.39 perturbation factor as the viscosity factor of viscoelastic case (<180 mg/dL) for perturbed PPG case, in their stress evaluations.

2. METHODS

2.1 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 materials 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.

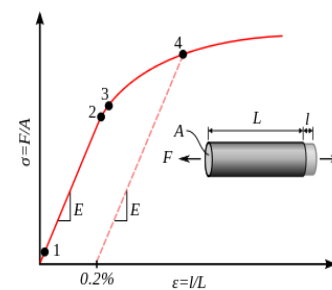
Hooke's law states that the force required to deform elastic objects should be directly proportional to the distance of deformation, regardless of how large that distance becomes. This is known as perfect elasticity, in which a given object will return to its original shape no matter how strongly it 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):

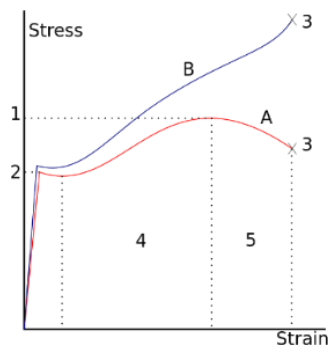
Deformation of a solid material undergoing non-reversible changes of shape in response to applied forces.

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.



A 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 T1 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 viscoplastically.”

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, η . The inverse of η is also known as fluidity, ϕ . 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-

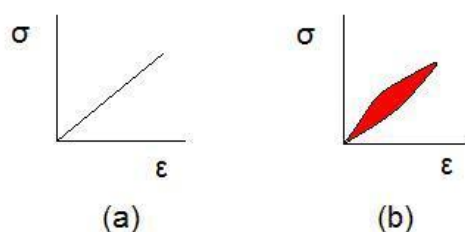
linear, or plastic response. When a material exhibits a linear response it is categorized as a Newtonian material. In this case the stress is linearly proportional to the strain rate. If the material exhibits a non-linear response to the strain rate, it is categorized as Non-Newtonian fluid. There is 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 σ is stress and ϵ 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 energy 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.

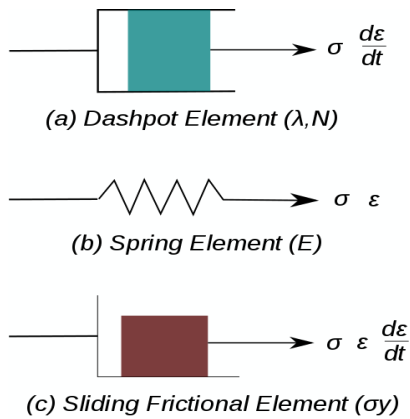


Figure 1. Elements used in one-dimensional models of viscoplastic materials.

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, λ is the viscosity parameter and N is a power-law type parameter that represents non-linear dashpot [$\sigma(d\epsilon/dt) = \sigma = \lambda(d\epsilon/dt)^{1/N}$]. The sliding element can have a yield stress (σ_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

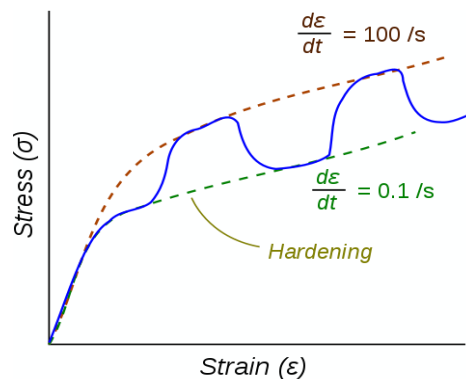


Figure 2. Stress–strain response of a viscoplastic material at different strain rates.

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 ε_e is the elastic strain and ε_{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.

2.2 Perturbation theory

This article is about perturbation theory as a general mathematical method. In mathematics and applied mathematics, perturbation theory comprises methods for finding an approximate solution to a problem, by starting from the exact solution of a related, simpler problem. A critical feature of the technique is a middle step that breaks the problem into "solvable" and "perturbative" parts. In perturbation theory, the solution is expressed as a power series in a small parameter ε . The first term is the known solution to the solvable problem. Successive terms in the series at higher powers of ε usually become smaller. An approximate 'perturbation solution' is obtained by truncating the series, usually by keeping only

the first two terms, the solution to the known problem and the 'first order' perturbation correction.

Perturbation theory is used in a wide range of fields, and reaches its most sophisticated and advanced forms in quantum field theory. Perturbation theory (quantum mechanics) describes the use of this method in quantum mechanics. The field in general remains actively and heavily researched across multiple disciplines.

Description:

Perturbation theory develops an expression for the desired solution in terms of a formal power series known as a perturbation series in some "small" parameter, that quantifies the deviation from the exactly solvable problem. The leading term in this power series is the solution of the exactly solvable problem, while further terms describe the deviation in the solution, due to the deviation from the initial problem. Formally, we have for the approximation to the full solution A , a series in the small parameter (here called ε), like the following:

$$A = A_0 + \varepsilon A_1 + \varepsilon^2 A_2 + \dots$$

In this example, A_0 would be the known solution to the exactly solvable initial problem and A_1, A_2, \dots represent the first-order, second-order and higher-order terms, which may be found iteratively by a mechanistic procedure. For small ε these higher-order terms in the series generally (but not always) become successively smaller. An approximate "perturbative solution" is obtained by truncating the series, often by keeping only the first two terms, expressing the final solution as a sum of the initial (exact) solution and the "first-order" perturbative correction

$$A \approx A_0 + \varepsilon A_1(\varepsilon \rightarrow 0)$$

Some authors use big O notation to indicate the order of the error in the approximate solution:

$$A = A_0 + \varepsilon A_1 + O(\varepsilon^2)$$

If the power series in ε converges with a nonzero radius of convergence, the perturbation problem is called a regular perturbation problem. In regular

perturbation problems, the asymptotic solution smoothly approaches the exact solution. However, the perturbation series can also diverge, and the truncated series can still be a good approximation to the true solution if it is truncated at a point at which its elements are minimum. This is called an asymptotic series. If the perturbation series is divergent or not a power series (e.g., the asymptotic expansion has non-integer powers $\epsilon^{1/2}$ or negative powers ϵ^{-2}) then the perturbation problem is called a singular perturbation problem. Many special techniques in perturbation theory have been developed to analyze singular perturbation problems.”

In this article, in order to select the parameter ϵ (the author calls it the perturbation factor), he defines the following:

Low carbs amount = 10 grams
 High carbs amount = 20 grams
 Selected carbs amount = 13.9 grams
 Calculated perturbation factor
 = (selected - low) / (high - low)
 = (13.9-10) / (20-10)
 = 0.39

Note: For a more detailed description, please refer to the “consolidated method” section which is given at the beginning of the special issue.

3. RESULTS

Figure 1 shows a data table of the input and output for this study. It contains both input data and stress / strain data ($\eta = 13.5$ for viscoelastic measured PPG & $\eta = 0.39$ for viscoelastic perturbed PPG).

Figure 2 depicts the time-domain of both measured and perturbed PPG waveforms. It is noted that these two waveforms have 100% of prediction accuracy in terms of averaged PPG values and 94% of correlation coefficient due to the nature of perturbation theory only proving an approximated answer.

Figure 3 reflects a space-domain for the stress-strain diagrams of these two cases. It is noted that the high degree of similarity of both diagrams and some insignificant difference on different time instances and an obvious difference on two stress Y-axis with a scale difference of 36 are noticeable.

1/20/22	4,115 meals	13.9 grams	4,281 k-steps	
5/5/18-1/19/22 PPG	Measured	1st-order Perturb		
0 min	122.97	122.97	High Carbs	20.0
15 min	125.26	123.86	Low Carbs	10.0
30 min	130.02	127.12	Selected Carbs	13.9
45 min	133.44	131.35	Perturbation Factor	0.39
60 min	133.57	133.49	Viscosity Factor	13.9
75 min	130.68	132.44		
90 min	127.94	129.61		
105 min	124.99	126.79		
120 min	122.81	124.14		
135 min	121.91	122.46		
150 min	122.10	121.98	High Carbs	20
165 min	122.85	122.39	Low Carbs	10
180 min	122.97	122.90	Selected Carbs	13.9
Average PPG	126.27	126.27	1st-order Perturbator	0.39
Correlation	94%			

Viscoelastic (VGT)	Viscosity+eta+carbs	13.9	Perturbation Theory	Perturbation Factor	0.39
Measured PPG	Strain: [e-avg.e]	VGT Stress: [13.9*de/dt]	Perturbed PPG	Strain: [e-avg.e]	Pert. Stress: [0.39*de/dt]
0 min	-3.30	0.00	0 min	-3.30	0.00
15 min	-2.01	2.12	15 min	-2.41	0.02
30 min	3.75	4.41	30 min	0.85	0.08
45 min	7.17	3.17	45 min	5.08	0.11
60 min	7.30	0.12	60 min	7.22	0.06
75 min	4.41	-2.68	75 min	6.17	-0.03
90 min	1.67	-2.54	90 min	3.34	-0.07
105 min	-1.28	-2.73	105 min	0.52	-0.07
120 min	-3.46	-2.02	120 min	-2.13	-0.07
135 min	-4.36	-0.83	135 min	-3.61	-0.04
150 min	-4.17	0.18	150 min	-4.29	-0.01
165 min	-3.42	0.70	165 min	-3.88	0.01
180 min	-3.30	0.11	180 min	-3.37	0.01
VGT Viscosity = Carbs =	13.9	Pert. Factor =	0.39	Viscosity / Pert. Factor =	36

Figure 1: Input data and stress / strain data ($\eta = 13.5$ for viscoelastic measured PPG & 0.39 for viscoelastic perturbed PPG).

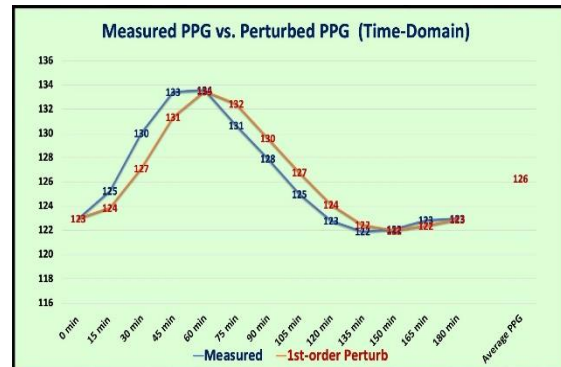


Figure 2: Time-domain of 2 PPG waveforms, measured PPG and perturbed PPG.

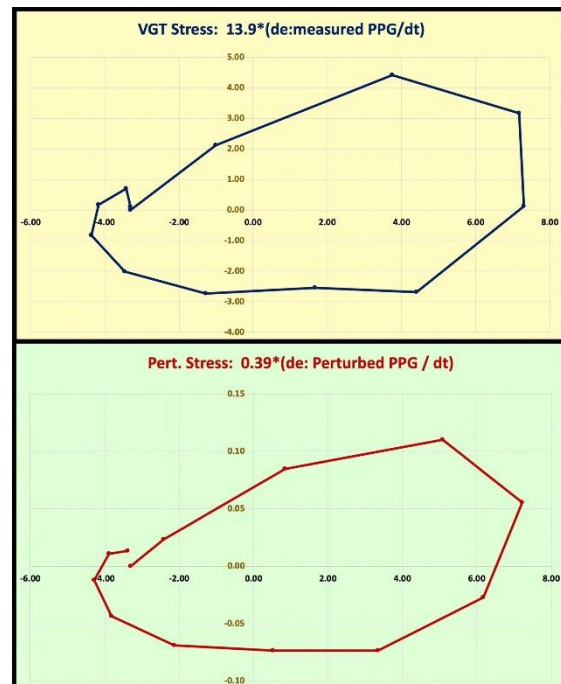


Figure 3: Space-domain of stress-strain diagrams for viscoelastic measured PPG (upper) and viscoelastic perturbed PPG (lower).

Figure 4 shows two stress-strain diagrams in the same scale for viscoelastic measured PPG (wide blue loop) and viscoelastic perturbed PPG (narrow green loop); their ratio in Y-scale is 36.

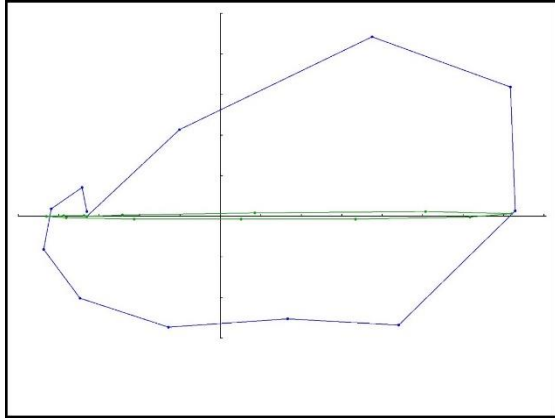


Figure 4: Two space-domain of stress-strain diagrams in the same scale for viscoelastic measured PPG (wide blue loop) and viscoelastic perturbed PPG (narrow green loop); ratio in Y-scale is 36.

4. CONCLUSION

In summary, the objective of this article is to explore similarity and difference between the measured PPG and the perturbed PPG. The following three concluding remarks have described the findings for similarities and differences of these two stress-strain diagrams from the measured PPG and perturbed PPG:

- (1) From the stress-strain diagram of the measured PPG and perturbed PPG, these two hysteresis loops look similar to each other because both of them use strain rate as the stress component i.e., glucose change rate with time.
- (2) However, a closer look at the two similar stress-strain diagrams, we can clearly notice the differences from their corresponding time-domain curves between 0-minute to 60-minutes and 60-minutes to 120-minutes. These minor differences are a result from the deviation between measured PPG and perturbed PPG in the time-domain curves since the perturbation theory only provides an approximated PPG.

(3) If we examine the y-axis scale of the stress-strain diagrams, then the viscoelastic measured PPG's stress Y-axis scale is 36 times higher than the viscoelastic perturbed PPG's stress Y-axis scale. This observation is a direct result from the author using the carbs/sugar amount of 13.9 grams as his viscosity factor for measured PPG's stress (Y-axis), while using the perturbation factor of 0.39 as his viscosity factor for perturbed PPG's stress (Y-axis). The ratio of 13.9 over 0.36 is 36. Of course, he can also select a different perturbation factor for generating his perturbed PPG which will then produce a different stress (Y-axis) scale on its corresponding stress-strain diagram.

5. ACKNOWLEDGMENT

Without Professor Norman Jones at MIT as his academic advisor, the author would not be able to conduct his medical research project and also published 500+ research papers. The author has never forgotten his advice to him that he should always enhance his strength on foundations, such as mathematics and physics, in order to make further improvement and advancement. Professor Jones has also provided him a personal example of doing outstanding teaching and research job with an excellent work attitude, extreme dedication, and ultimate commitment on advancing both science and engineering.

6. REFERENCES

For editing purposes, majority of the references in this paper, which are self-references, have been removed for this article. Only references from other authors' published sources remain. The bibliography of the author's original self-references can be viewed at www.eclaircmd.com.

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Viscoelastic and Viscoplastic Glucose Theory Application in Medicine

Gerald C. Hsu

