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Viscoelastic or Viscoplastic Glucose Theory (VGT #101): Applying the Concept of Elasticity, Plasticity, Viscoelasticity, Viscoplasticity, Wave Theory and Frequency-Domain Analysis to Conduct a "Glucose Analogy" Study and Illustrate Certain Biophysical Characteristics and Behaviors of Postprandial Plasma Glucose (PPG) Using Collected Data of 4,525 Elastic Glucoses (<180 mg/dL) and 25 Plastic Glucoses (>180 mg/dL) Within a Period of 4+ Years from 5/8/2018 to 6/18/2022 Based on GH-Method: Math-Physical Medicine (No. 691)

Gerald C. Hsu*

eclaireMD Foundation, USA

Note: This article is an enhanced version of Paper No. 579 (VGT #2).

Keywords: Viscoelastic; Viscoplastic; Carbohydrates; Sugar; Walking k-steps; Body weight; Postprandial plasma glucose; Fasting plasma glucose; Type 2 diabetes; Fast Fourier transform

Abbreviations: FFT: fast Fourier transform; T2D: type 2 diabetes; PPG: postprandial plasma glucose; FPG: fasting plasma glucose; FD: frequency domain; SD: space domain; TD: time domain; MPM: math-physical medicine

1. INTRODUCTION

The author studied both strengths of materials and theory of elasticity from undergraduate courses at the University of Iowa. He also conducted research work to earn a master's degree in Biomechanics under Professor James Andrews at UI. He still remembers that he used a model with both spring and dashpot (similar to an oil-filled shock absorber) to simulate the behaviors of human bone (similar to spring), muscle, and tendon (similar to dashpot) to simulate the soldier-M16 interactions in Vietnam war. Later on, he went to MIT to pursue his Ph.D. study under Professor Norman Jones who taught him the theory of plasticity and dynamic plastic behaviors of various structural elements. Furthermore, he took some other graduate courses at MIT including machine learning, fluid dynamics, thermodynamics, etc.

Since 1970, the biomechanics field has made some visible advancements in a few application areas, especially tissues of the human body which possess viscoelastic characteristics, such as bone, muscle, cartilage, tendon (connect bone to muscle), ligament (connect bone to bone), fascia and skin. For example, the night splint dorsiflexes the forefoot on the rear foot increasing plantar fascia tension to offer stress-relaxation of plantar fascia pain. This muscles and tendons connecting the model of the lower-leg and foot are a kind of viscoelastic problem.

When we deal with human internal organs, it is not as easy as bones and muscles. For example, we cannot easily conduct live-body experiments in a medical laboratory to obtain some accurate and useful measurements of biomedical material properties. Although

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*Corresponding author: Gerald C. Hsu, eclaireMD Foundation, USA

blood itself is a viscous material which viscosity factor may sit between water and honey, syrup, or gel. But, the author's research subject is related to the "glucose" compound inside the blood vessel, i.e. the sugar amount inside of blood or carried by blood cells, not the blood itself. Therefore, it is near impossible to measure material geometry or figure out the engineering properties of "glucose". The best way he can do this is to apply the concept of elasticity, plasticity, viscoelasticity, and viscoplasticity to construct an "analogy" model of glucose to study the complex biophysical behaviors of glucose which are both nonlinear and dynamic, i.e. time-dependent.

The author's academic background covers mathematics, physics, and various engineering disciplines, but not including biology, chemistry, or medicine. As a result, he can only investigate his observed biophysical phenomena to make biomedical interpretations and then derive some useful conclusions for healthcare purposes using his ready-learned math-physical knowledge from his 17 years of college-level education in 10 different academic disciplines.

Based on other research papers (References 1 and 2), people without diabetes have PPG waveforms within a range between 80 mg/dL (start and end) and 120 mg/dL (peak). For pre-diabetes patients, their PPG waveforms range between 100 mg/dL (start and end) and 180 mg/dL (peak). For severe diabetes patients who indeed possess "plastic glucose" phenomena, their PPG waveforms range between 180 mg/dL (starting), 370 mg/dL (peak at 1-hour), and 325 mg/dL (ending at 3-hours) or 270 mg/dL (if ending at 5-hours).

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 obese lead to chronic diseases, including diabetes. In addition, many types of processed food adding in unhealthy ingredients and harmful chemicals from our surrounding environment that is toxic to the bodies, which lead to the development of many other deadly diseases, such as cancers. For example, there are ~85% of worldwide diabetes patients are overweight, and there are ~75% of patients with cardiac illnesses or surgeries have diabetes conditions.

The author has already investigated glucose behaviors for several years using linear elasticity theory and nonlinear plasticity theory and has written 100+ articles on his various medical research findings. In December of 2021, Professor Norman Jones, his advisor at MIT, wrote an email to him. He said, "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 emphasised the time-dependence of various behaviours in the body. Just a thought." His suggestion has triggered the author's interest and desire to investigate further more about glucose behaviors using the viscosity theory. Since then, he has written 100+ medical papers.

This particular article uses his collected 4,550 meals data, including his postprandial plasma glucose (PPG) values at every 15-minute interval via a sensor, carbohydrates, and sugar intake grams (carbs), and post-meal walking exercise k-steps (ksteps) during the past 4+ years from 5/8/2018 to 6/18/2022. Furthermore, he has segregated his collected PPG data into two families: the first family is his 4,525 meals with PPG<180 mg/dL (pre-diabetes), averaged carbs of 13.1 grams and 4.251 ksteps, and the second family is his 25 meals with PPG>180 mg/dL (hyperglycemia), averaged carbs of 90.0 grams and 3.429 k-steps.

At first, he investigates his collected time-domain data using elasticity and plasticity theories to examine PPG behavior with time. Secondly, he then investigates his collected data via space-domain VGT (SD-VGT) tool using viscoelasticity and viscoplasticity theories to draw the stress-strain curve, i.e. hysteresis loop, for his SD-energy estimation. Thirdly, he investigates his calculated data of (strain*stress) using wave theory and frequency-domain fast Fourier transform (FD-FFT) analysis to estimate his FD-energy.

Elastic vs. plastic glucose

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

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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 around 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.

In his further plastic glucose study of non-linear plastic glucose theory (NPGT), he has developed the following simplified plastic glucose equation:

Predicted PPG
= FPG * GH.f + (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 around 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 elastic modulus and plastic Modulus are different from each other and they are also varying for different studied cases. For example, in this article, his plastic slope, i.e. GH.p-Modulus value, of 0.254, is less than half or at the 43% level, of his elastic slope, i.e. GH.e-Modulus value, of 0.586.

The analogy between physics or engineering and medicine are two-fold. First, the force or stress in physics and engineering corresponds to the influential force or cause on our body for pushing PPG upward or dragging PPG downward due to the combined effect of carbohydrates and sugar intake amount and post-meal walking exercise. This forces or causes have no differences between elastic and plastic. Second, the deformation or strain in physics and engineering corresponds to the actual PPG level in medicine. The strain component, i.e. symptom such as glucose, indeed has differences between elastic glucose case and plastic glucose case.

However, the medical field is still quite different from the engineering field, where the engineering materials such as steel, copper, concrete, and aluminum are inorganic material 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 material and go through many distinct stages over their lifespans, such as birth, split, growth, mutation, development, duplication, repair, sickness, and death. Therefore, the biomedical properties are “moving targets” which vary with the individual person, the severity of diabetes, and selected different time windows. In another word, they are both time-dependent and specimen-dependent. Because of these fundamentally different characteristics, calculations of a cross-section of subject and calculation of bending moment of resistance, or the shape-factors, etc. in solid mechanics are not applicable in this biomedical analogy studies using theories of elasticity, plasticity, viscoelasticity, or viscoplasticity. In his own opinion, the most important part is that applying the concept of plasticity theory or viscoelasticity theory to understanding biomedical phenomena is extremely useful for exploring deeper insights for predicting both normal and abnormal glucose behaviors quantitatively.

Viscoelasticity and viscoplasticity

The first step is to collect the output data or symptom (strain or ε) on a time scale. The second step is to calculate the output change rate with time ($d\varepsilon/dt$), i.e. the change rate of strain or symptom over each period. The third step is to gather the input data or cause (viscosity or η) on a time scale. The fourth step is to calculate the time-dependent input or cause (time-dependent stress or σ) by multiplying $d\varepsilon/dt$ and η together. The “time-dependent input or cause equation” of “stress σ = strain change rate of $d\varepsilon/dt$ * viscosity η”

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is the essential part of "time-dependency". The fifth step is to plot the input-output (i.e. stress-strain or cause-symptom) curve in a 2-dimensional space domain or SD (x-axis versus y-axis) with strain (output or symptom) on the x-axis and stresses (time-dependent inputs, causes, or stresses) on the y-axis. The sixth step is to calculate the total enclosed area within these stress-strain curves or input-output curves (i.e. the hysteresis loops), which is also an indicator of associated energies (either created energy or dissipated energy) of this input and output dataset. These energy values can also be considered as the degrees of influence on output by inputs.

The seventh step is to define a "hybrid input variable" by using "strain*stress" as the new variable which yields a more accurate estimation of energy. The eighth step is to present these hybrid models' results of (strain*stress) in TD and then perform the FFT operation to convert them into FD. The enclosed area of the FD curve (where the x-axis is the frequency and the y-axis is the amplitude of energy) can be used to estimate the total FD-FFT energy. The ninth step is to compare these two hybrid model results by using "strain*stress" in FD against the VGT results in SD.

After providing the above 9-step description, the author would still like to list the following VGT stress-strain mathematical equations in a 2-dimensional SD to address the unique "time-dependency characteristics" of selected medical variables:

Strain
= ε
= individual strain value at the present time duration

Stress
= σ (based on the change rate of strain multiplying with a chosen viscosity factor η)
= $\eta * (d\varepsilon/dt)$
= η * (d-strain/d-time)
= (viscosity factor η using individual viscosity factor at present time duration) * (strain at present quarter - strain at previous time duration)

Some of these inputs (causes or viscosity factors) are further normalized by dividing or multiplying them with the average number of viscosity or a certain established health standard, such as 6.0 for HbA1C, 120 mg/dL for glucose, 25 for body mass index (BMI), 4,000 steps after each meal, 10, 15, or 20 grams of carbs/sugar intake amount per meal, etc. If using the originally collected data, i.e. the non-normalized data would distort the numerical comparison of the hysteresis loop areas. Using this "normalization process", the author can remove the dependency of the individual unit or certain unique characteristics associated with each viscosity factor. This process allows him to convert the originally collected variables into a set of "dimensionless variables" for easier numerical comparison and result interpretation.

It should be mentioned here that, in this study, both carbs and k-steps are constants or fixed values, i.e. they are time-independent within the 180-minute time frames of each meal's PPG variation. He decides to use 10 grams as the normalization factor for carbs, i.e. carbs/10, and 4.0 k-steps as the normalization factor for k-steps, i.e. 4.0/k-steps.

Energy theory

After declaring the analogy of elasticity, plasticity, viscoelasticity, viscoplasticity theories, the energy theory and wave 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 carried by red blood cells; and energy consumption from labor-work or exercise. According to physics, energies associated with the glucose waves are proportional to the square of the glucose amplitude. The residual energies from elevated glucoses are circulating inside the human body via blood vessels which then impact all the internal organs to cause different degrees of damage, i.e. diabetic complications.

The author has applied Fast Fourier Transform (FFT) operations to convert the glucose wave from a TD into FD. The y-axis amplitude values in the FD indicate the proportional energy levels associated with each different frequency component of glucose occurrence. Actually, both glucose value (i.e. strain amplitude in TD) and glucose fluctuation rate (i.e. the strain rate and strain frequency) are influencing the energy level (i.e. the Y-amplitude in FD).

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To offer a simpler explanation to readers who do not have a physics or engineering background, the author includes a brief excerpt from Wikipedia regarding the description of the basic concept of elasticity, plasticity, viscoelasticity &, viscoplasticity theory, wave theory, and FD analysis method from the disciplines of engineering and physics in the method section.

1.1 Specific medical information

Sub-cellular pathology pathways

In chapter 10 of the published book "Metabolical" written by Dr. Robert H. Lustig, there are 8 sub-cellular pathologies that are related to chronic diseases, particularly diabetes:

1. Glycation
2. Oxidative stress
3. Mitochondrial dysfunction
4. Insulin resistance
5. Membrane integrity
6. Inflammation
7. Epigenetics
8. Autophagy

All of these 8 physiology-pathological pathways are related to chronic diseases, and also related to each other and food; however, only 5 of them are responsive to exercise. Based on these 8 physiology-pathological pathways, a rough estimation of the degree of influence on diabetes between food and exercise is 8:5 = 1.6.

The author's case of diabetes

The author has been a severe T2D patient since 1996. He weighed 220 lb. (100 kg, BMI 32.5) at that time. By 2010, he still weighed 198 lb. (BMI 29.2) with average daily glucose of 250 mg/dL (HbA1C of 10%). During that year, his triglycerides reached 1161 and albumin-creatinine ratio (ACR) at 116. He also suffered from five cardiac episodes within a decade. In 2010, three independent physicians warned him regarding his need for kidney dialysis treatment and his future high risk of dying from his severe diabetic complications. Other than the cerebrovascular disease (stroke), he has suffered most of the known diabetic complications, including both macro-vascular and micro-vascular complications.

In 2010, he decided to launch his self-study on endocrinology, diabetes, and food nutrition to save his own life. During 2015 and 2016, he developed four prediction models related to diabetes conditions: weight, PPG, fasting plasma glucose (FPG), and A1C. As a result, from using his developed mathematical metabolism index (MI) model in 2014 and the four prediction tools, by end of 2016, his weight was reduced from 220 lbs. (100 kg, BMI 32.5) to 176 lbs. (89 kg, BMI 26.0), waistline from 44 inches (112 cm) to 33 inches (84 cm), average finger glucose reading from 250 mg/dL to 120 mg/dL, and lab-tested A1C from 10% to ~6.5%. One of his major accomplishments is that he no longer takes any diabetes medications as of 12/8/2015.

In 2017, he has achieved excellent results on all fronts, especially glucose control. However, during the pre-COVID period of 2018 and 2019, he traveled to approximately 50+ international cities to attend 65+ medical conferences and made ~120 oral presentations. This hectic schedule inflicted damage to his diabetes control, through dining out frequently, post-meal exercise disruption, jet lag, and along with the overall metabolic impact due to his irregular life patterns through a busy travel schedule; therefore, his glucose control and overall metabolism state were somewhat affected during this two-year heavier traveling period.

Since 2020, living in a COVID-19 quarantined lifestyle, not only has he published 400+ medical papers in 100+ journals, but he has also reached his best health conditions in the past 26 years. By the beginning of 2022, his weight was further reduced to 168 lbs. (BMI 24.8) along with a 5.8% A1C value (beginning level of pre-diabetes), without having any medication interventions or insulin injections. These good results are due to his non-traveling, low-stress, and regular daily life routines. Of course, his knowledge of chronic diseases, practical lifestyle management experiences, and development of various high-tech tools contribute to his excellent health status since 1/19/2020, the beginning date of his self-quarantined life.

On 5/5/2018, he applied a continuous glucose monitoring (CGM) sensor device on his upper arm and checks his glucose measurements every 5 minutes for a total of ~288 times each

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day. He has maintained the same measurement pattern to the present day. In his research work, he uses his CGM sensor glucose at a time interval of 15 minutes (96 data per day). Incidentally, the difference in average sensor glucoses between 5-minute intervals and 15-minute intervals is only 0.7% (average glucose of 112.15 mg/dL for 5-minutes and average glucose of 111.33 mg/dL for 15-minutes with a correlation of 96% between these two sensor glucose curves) during the period from 2/19/20- to 5/9/22.

Therefore, over the past 13 years, he could study and analyze the collected ~3 million data regarding his health status, medical conditions, and lifestyle details. He applies his knowledge, models, and tools from mathematics, physics, engineering, and computer science to conduct his medical research work. His research is based on the aims of achieving both "high precision" with "quantitative proof" in the medical findings.

The following timetable provides a rough sketch of the emphasis in his medical research during each stage:

2000-2013: Self-study diabetes and food nutrition, developing a data collection and analysis software.

2014: Develop a mathematical model of metabolism, using engineering modeling and advanced mathematics.

2015: Weight & FPG prediction models, using neuroscience.

2016: PPG & HbA1C prediction models, using optical physics, artificial intelligence (AI), and neuroscience.

2017: Complications due to macro-vascular research, such as cardiovascular disease (CVD), coronary heart diseases (CHD), and stroke, using pattern analysis and segmentation analysis.

2018: Complications due to micro-vascular research such as kidney (CKD), bladder, foot, and eye issues (DR).

2019: CGM big data analysis, using wave theory, energy theory, frequency domain analysis, quantum mechanics, and AI.

2020: Cancer, dementia, longevity, geriatrics, DR, hypothyroidism, diabetic foot, diabetic fungal infection, and linkage between metabolism and immunity, learning about certain infectious diseases, such as COVID-19.

2021: Applications of linear elastic glucose theory (LEGT) and perturbation theory from quantum mechanics on medical research subjects, such as chronic diseases and their complications, cancer, and dementia.

2022: Applications of viscoelastic/viscoplastic glucose theory (LEGT) on 92 biomedical research cases and 4 economics research cases.

Again, to date, he has spent around 40,000 hours self-studying and researching medicine. He has collected and calculated more than three million pieces of data regarding his medical conditions and lifestyle details. In addition, he has written nearly 700 medical research notes and published 600+ papers in 100+ various medical and engineering journals. Moreover, he has also given ~120 presentations at ~65 international medical conferences. He has continuously dedicated his time (11-12 hours per day and work each day of a year, without rest) and efforts to his medical research work and shared his findings and learnings with other patients worldwide.

2. METHODS

2.1 MPM background

To learn more about his developed GH-Method: Math-Physical Medicine or MPM methodology, readers can select the following three articles from the 400+ published medical papers.

The first paper, No. 386, describes his MPM methodology in a general conceptual format. The second paper, No. 387, outlines the history of his personalized diabetes research, various application tools, and the differences between the biochemical medicine (BCM) approach versus the MPM approach. The third paper, No. 397, depicts a general flow diagram containing ~10 key MPM research methods and different tools.

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All of the listed papers in the Reference section are his written and published medical research papers.

2.2 Elasticity, plasticity, viscoelasticity, and viscoplasticity (LEGT & VGT)

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.

Medical analogy: The medical application is when cause or risk factors are reduced or removed, the symptoms of certain disease would be improved or ceased.

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.

Medical analogy: Viscoelastic behavior means material has "time-dependent" characters. Biomedical data, i.e. biomarkers, are time-dependent due to body cells are organic which changes with time constantly.

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.

Medical analogy: Most of the biomarkers display time-dependency; therefore they have both change-rate of time and viscosity factor behaviors. Viscoelastic biomarkers do dissipate energy when a cause force is applied on it.

The following brief introductions are excerpts from Wikipedia:

"Elasticity (physics):

The physical property is when materials or objects return to their 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.

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 that 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

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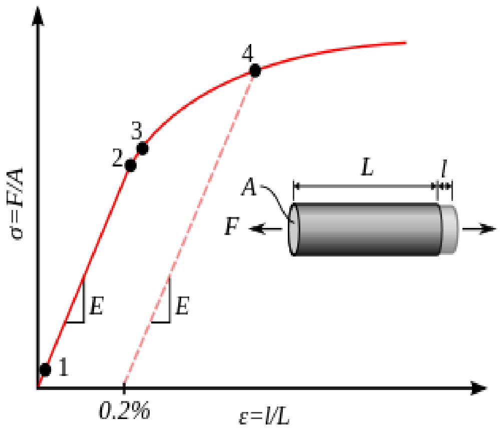
modulus indicates that the material is harder to deform. The material's elastic limit or yield strength is the maximum stress that can arise before the onset of plastic deformation.

Medical analogy: The elastic behavior analogy in medicine can be expressed by the metal rod analogy for the postprandial plasma glucose (PPG). Consuming carbohydrates and/or sugar acts like a tensile force to stretch a metal rod longer, while post-meal exercise acts like a compressive force to suppress a metal rod shorter. If lacking food consumption and exercise, the metal rod (analogy of PPG) will remain its original length, for a non-diabetes or less severe type 2 diabetes (T2D) patient.

Plasticity (physics):

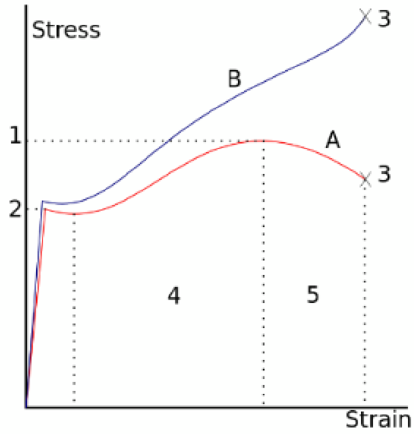
Deformation of a solid material undergoing non-reversible changes of shape in response to applied forces.

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



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 is 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/A0)
- B: Actual stress (F/A)

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.

Medical analogy: A plastic behavior analogy in medicine is the PPG level of a severe T2D patient. Even consuming a smaller amount of carbs/sugar, the patient's PPG will rise sharply which cannot be totally brought down to a healthy PPG level even with a significant amount of exercise. This means the PPG level has exceeded its "elastic limit" and entering into a "plastic range".

Viscoelasticity:

Property of materials with both viscous and elastic characteristics under deformation.

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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).

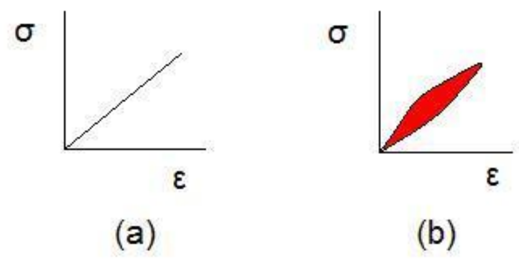
Depending on the change of strain rate versus stress inside a material, the viscosity can be categorized as having a linear, non-linear, or plastic response. In addition, when the stress is independent of this strain rate, the material exhibits plastic deformation. Many viscoelastic materials exhibit rubber-like behaviors 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
- 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 $\oint \sigma d\varepsilon$ where σ is stress and ε is strain. In other words, the hysteresis loop area represents the amount of energy during the loading and unloading process.

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.

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

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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.

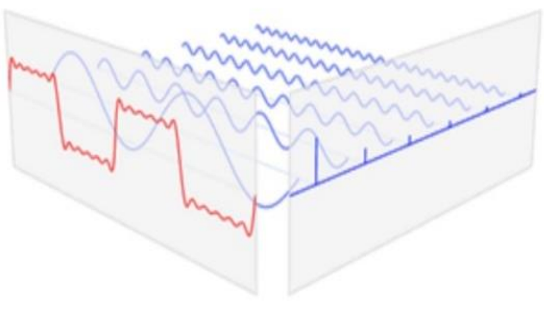
Medical analogy: In viscoelastic or viscoplastic analysis, the stress component equals the strain change rate of time multiplying with the viscosity factor, or

Stress (σ)
= strain (ε) change rate * viscosity factor (η)
= dε/dt * η

The hysteresis loop area
= the integrated area of stress (σ) and strain (ε) curve
= $\oint \sigma d\varepsilon$

2.3 From time-domain to frequency domain via Fourier transform

In physics, electronics, control systems engineering, and statistics, the frequency domain refers to the analysis of mathematical functions or signals concerning frequency, rather than time.[1] Put simply, a time-domain graph shows how a signal changes over time, whereas a frequency-domain graph shows how much of the signal lies within each given frequency band over a range of frequencies. A frequency-domain representation can also include information on the phase shift that must be applied to each sinusoid to be able to recombine the frequency components to recover the original time signal.



The Fourier transform converts the function's time-domain representation, shown in red, to the function's frequency-domain representation, shown in blue. The component frequencies, spread across the frequency spectrum, are represented as peaks in the frequency domain.

A given function or signal can be converted between the time and frequency domains with a pair of mathematical operators called transforms. An example is the Fourier transform, which converts a time function into a complex-valued sum or integral of sine waves of different frequencies, with amplitudes and phases, each of which represents a frequency component. The "spectrum" of frequency components is the frequency-domain representation of the signal. The inverse Fourier transform converts the frequency-domain function back to the time-domain function. A spectrum analyzer is a tool commonly used to visualize electronic signals in the frequency domain.

Advantages

One of the main reasons for using a frequency-domain representation of a problem is to simplify the mathematical analysis. For mathematical systems governed by linear differential equations, a very important class of systems with many real-world applications, converting the description of the system from the time domain to a frequency domain converts the differential equations to algebraic equations, which are much easier to solve.

In addition, looking at a system from the point of view of frequency can often give an intuitive understanding of the qualitative behavior of the system, and a revealing scientific nomenclature has grown up to describe it, characterizing the behavior of physical systems to time-varying inputs using terms such as bandwidth, frequency response, gain, phase shift, resonant frequencies, time constant, resonance width, damping factor, Q factor, harmonics, spectrum, power spectral density, eigenvalues, poles, and zeros.

An example of a field in which frequency-domain analysis gives a better understanding than the time domain is music; the theory of operation of musical instruments and the musical notation used to record and discuss pieces of music is implicitly based on the breaking down of complex sounds into their

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separate component frequencies (musical notes).

Magnitude and phase

In using the Laplace, Z-, or Fourier transforms, a signal is described by a complex function of frequency: the component of the signal at any given frequency is given by a complex number. The modulus of the number is the amplitude of that component, and the argument is the relative phase of the wave. For example, using the Fourier transform, a sound wave, such as human speech, can be broken down into its component tones of different frequencies, each represented by a sine wave of different amplitude and phase. The response of a system, as a function of frequency, can also be described by a complex function. In many applications, phase information is not important. By discarding the phase information, it is possible to simplify the information in a frequency-domain representation to generate a frequency spectrum or spectral density. A spectrum analyzer is a device that displays the spectrum, while the time-domain signal can be seen on an oscilloscope.

Types

Although "the" frequency domain is spoken of in the singular, there are several different mathematical transforms that are used to analyze time-domain functions and are referred to as "frequency domain" methods. These are the most common transforms and the fields in which they are used:

- Fourier series – periodic signals, oscillating systems.
- Fourier transform – aperiodic signals, transients.
- Laplace transform – electronic circuits and control systems.
- Z transform – discrete-time signals, digital signal processing.
- Wavelet transform — image analysis, data compression.

More generally, one can speak of the transform domain for any transform. The above transforms can be interpreted as capturing some form of frequency, and hence the transform domain is referred to as a frequency domain.

Discrete frequency domain

The Fourier transform of a periodic signal has energy only at a base frequency and its harmonics. Another way of saying this is that a periodic signal can be analyzed using a discrete frequency domain. Dually, a discrete-time signal gives rise to a periodic frequency spectrum. Combining these two, if we start with a time signal which is both discrete and periodic, we get a frequency spectrum which is also both discrete and periodic. This is the usual context for a discrete Fourier transform.

History of term

The use of the terms "frequency domain" and "time domain" arose in communication engineering in the 1950s and early 1960s, with "frequency domain" appearing in 1953. See time domain: the origin of the term for details.

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 TD waveforms for both elastic glucose and plastic glucose.

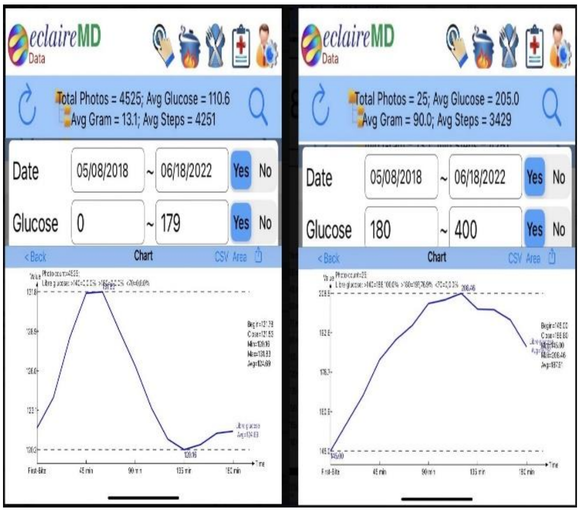

Figure 1: Time-domain waveforms for both elastic glucose and plastic glucose.

Figure 2 depicts the SD of the stress-strain diagram of both elastic glucose and plastic glucose using the VGT tool.

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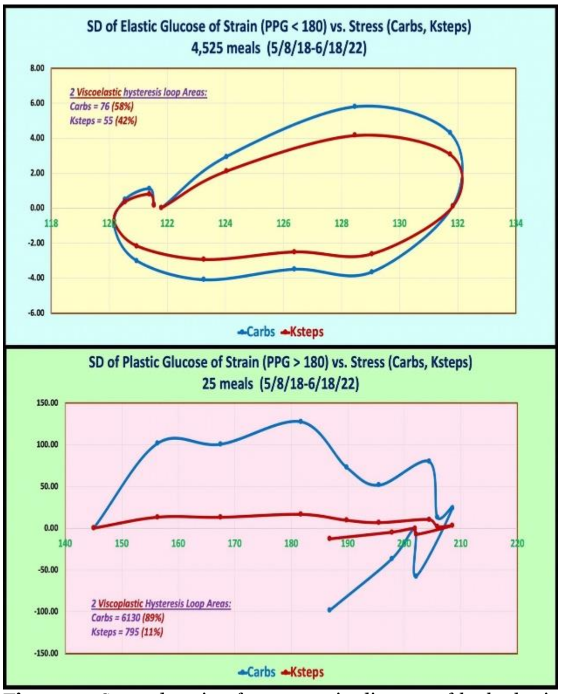

Figure 2: Space-domain of stress-strain diagram of both elastic glucose and plastic glucose using VGT tool.

Figure 3 reflects FD FFT analysis of both elastic glucose and plastic glucose.

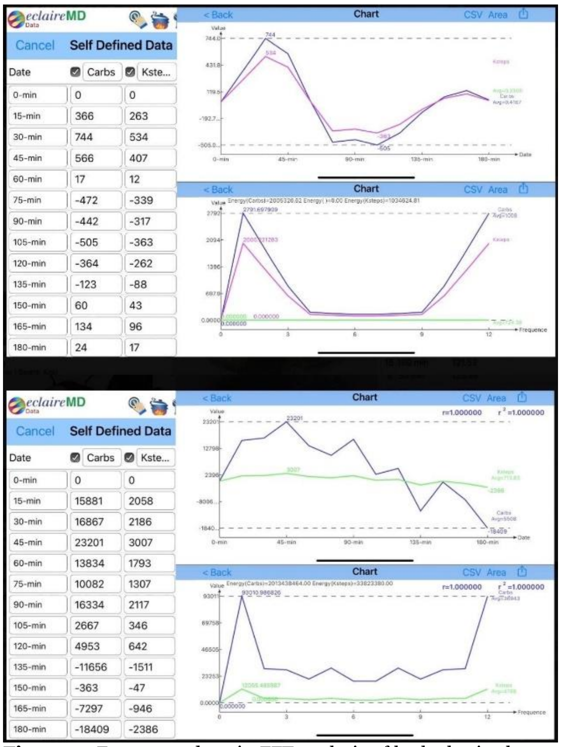

Figure 3: Frequency-domain FFT analysis of both elastic glucose and plastic glucose.

Figure 4 illustrates the comparison of both SD energy ratios and FD energy ratios for both pre-diabetes and hyperglycemia and the data table.

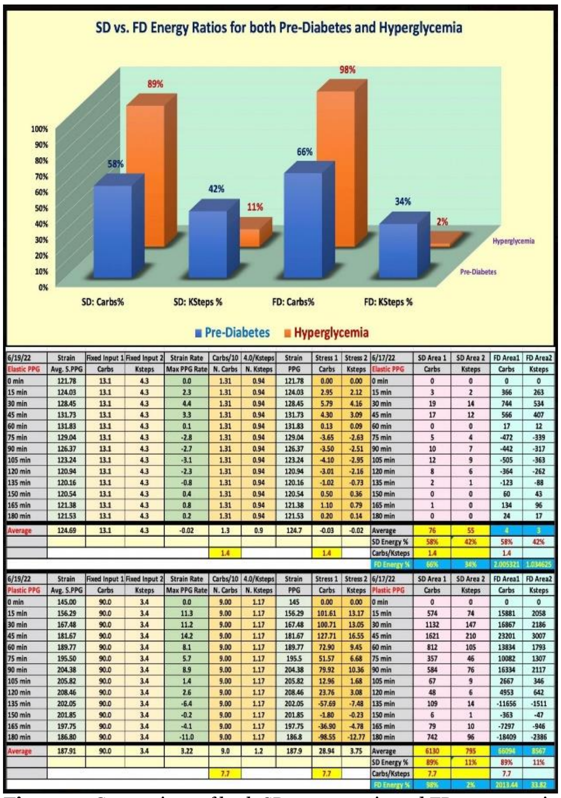

Figure 4: Comparison of both SD energy ratio and FD energy ratio for both pre-diabetes and hyperglycemia and data table.

4. CONCLUSION

In conclusion, the following four key observations are described as follows:

(1) In engineering analysis, when the load is applied on the structure, it bends or twists, i.e. deforms; however, when the load is removed, it will either be restored (elastic) or remain in a permanent deformed shape (plastic) with plastic hinges. In a corresponding biomedical analysis, after eating carbs or sugar from food, our glucose level will increase; therefore, the sugar and carbohydrates function as the energy supply. After having labor work or exercise, the glucose level will decrease. As a result, the exercise burns off the energy, which is similar to load removal in the engineering case; however, in the biomedical case, both processes of energy influx and energy consumption take some time which is not as simple and quick as the structural load removal in the engineering case. Therefore, the glucose behaviors, for elastic glucose and plastic glucose, are "dynamic" in nature, i.e. time-dependent. This time-dependent nature leads to a "visco-elastic or visco-plastic" situation. For the 4,525 "elastic glucose" case, it starts at 122 mg/dL at 0-minute, climbs up to 132 mg/dL at 60-minutes, and drops back

to 122 mg/dL again at 180-minutes, i.e. it returns to its original position similar to an elastic engineering material behavior. On the contrary, for the 25 "plastic glucose" case, it starts at 145 mg/dL at 0-minute, climbs up to 190 mg/dL at 60-minutes, and then continuously climbs further up to 209 mg/dL at 120-minutes and finally drops down to 187 mg/dL again at 180-minutes) - it never returns to its original position similar to a plastic engineering material behavior. This end-glucose value of 187 mg/dL is still 42 mg/dL higher than its initial-glucose position of 145 mg/dL. This type of "permanent deformation" or "residual glucose" value of 42 mg/dL is called "plastic" glucose or "elasto-plastic" glucose.

(2) Researching the variation of the VGT results, it can be seen that these 2 stress-train curves of carbs and ksteps have very similar waveform patterns due to using the same strain (PPG) rate. The ratios for the 2 average stress magnitudes, or 2 related normalized inputs, are 7.7 which is also reflected in the energy area ratio, i.e. hysteresis loop area ratio, 7.7 as well. It should be mentioned here that the normalization process for carbs is carbs/10 grams while the normalized ksteps is 4.0/ksteps. The most interesting findings are the two energy contribution % from these two SD-VGT inputs: For the pre-diabetes case, 76 (58%) from carbs and 55 (42%) from ksteps with an energy ratio of 1.4 (= 58/42); and for hyperglycemia case, 6130 (89%) from carbs and 795 (11%) from ksteps, with an energy ratio of 7.7 (= 89/11). From the Metabolical book written by Dr. Robert H. Lustig, the physiopathological pathways study indicates a medicine ratio of 8/5 = 1.6. Both conclusions have indicated that food (carbs) contributes more than exercise (ksteps), for both cases of pre-diabetes (PPG ~125 mg/dL) and hyperglycemia (~188 mg/dL).

(3) From frequency-domain analysis results, these two variables or areas of (strain*stress), i.e. (PPG * PPG change * stress of carbs) & (PPG * PPG change * stress of ksteps), the frequency-domain fast Fourier transform (FD-FFT) results have demonstrated that the two energy contribution % from these two FD-FFT inputs are: for the pre-diabetes case of Carbs energy = 66% and Ksteps energy = 34% with a ratio of 66:34 = 2.0; and for hyperglycemia case of Carbs energy = 98% and Ksteps energy = 2% with a ratio of 98:2 = 49. It is evident that the hyperglycemic case is resulted from a severely high carbs intake amount (~90 grams).

(4) The comparison of these 4 energy ratios are: For pre-diabetes case: SD energy ratio of 58%:42% = 1.4, and FD energy ratio of 66%:34% = 2.0; and For the hyperglycemic case: SD energy ratio of 89%:11% = 7.7, and FD energy ratio of 98%:2% = 49. Using a quote from a medical book of physio-pathological influence ratio of 8:5 = 1.6 between food and exercise.

This article has explained the relationship between PPG vs. influences from both carbs and ksteps using his collected big data of 4,550 meals between 5/8/2018 and 6/15/2022 (sensor PPG period). The quantitative findings from both TD, SD-VGT, and FD-FFT analysis results have revealed that severely high impact (7 times to 49 times higher damages) on his internal organs due to his hyperglycemic cases (average at 188 mg/dL) which further resulted mainly from the extremely high carbs intake amount (~90 grams) combined with a lesser-degree of post-meal exercise (15% less than 4 k-steps).

The SD-VGT energy tool adopted from engineering and the wave theory with the FD-FFT energy tool adopted from physics have further provided some useful hints and realistic interpretations of complex biomedical results from hyper-PPG due to both high carbs/sugar consumption and less post-meal walking exercise. Diabetes control is a difficult task since this complex biophysical behavior of glucose requires deeper knowledge of mathematics and physics, more than depending on biology and chemistry alone. It has further proven that the energy ratios of carbs versus k-steps on PPG are comparable to each other regardless of which analysis method was used, the SD approach, FD approach, or physiology-pathology medical approach. The time-domain analysis results can only offer some limited and less quantitative information.

5. ACKNOWLEDGMENT

Without Professor Norman Jones at MIT as his academic advisor, the author would not be able to conduct this particular research project and also published nearly 700 medical research papers. The author has never forgotten his advice to him that he should always enhance his strength in foundations, such as mathematics and physics, to make further improvements and advancements. Professor Jones has also provided him with a personal example of doing outstanding teaching and research job with an excellent work attitude, extreme dedication, and ultimate commitment to advancing both science and engineering.

6. REFERENCES

For editing purposes, the 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.eclairemd.com.

Readers may use this article as long as the work is properly cited, their use is educational and not for profit, and the author's original work is not altered.

1) Freckmann G, Hagenlocher S, Baumstark A, et al. Continuous glucose profiles in healthy subjects under everyday life conditions and after different meals. J Diabetes Sci Technol. 2007;1(5):695-703.

2) Glycemic Edge.

To read more of the author's published VGT or FD analysis results on medical applications, here are three journals that published special editions:

(1) Special Issue. The GH-Method. (https://www.theghmethod.com)

(2) Journal of Applied Material Science & Engineering Research (contact: Catherine)

(3) Advances in Bioengineering and Biomedical Science Research (contact: Sonny Hazi).

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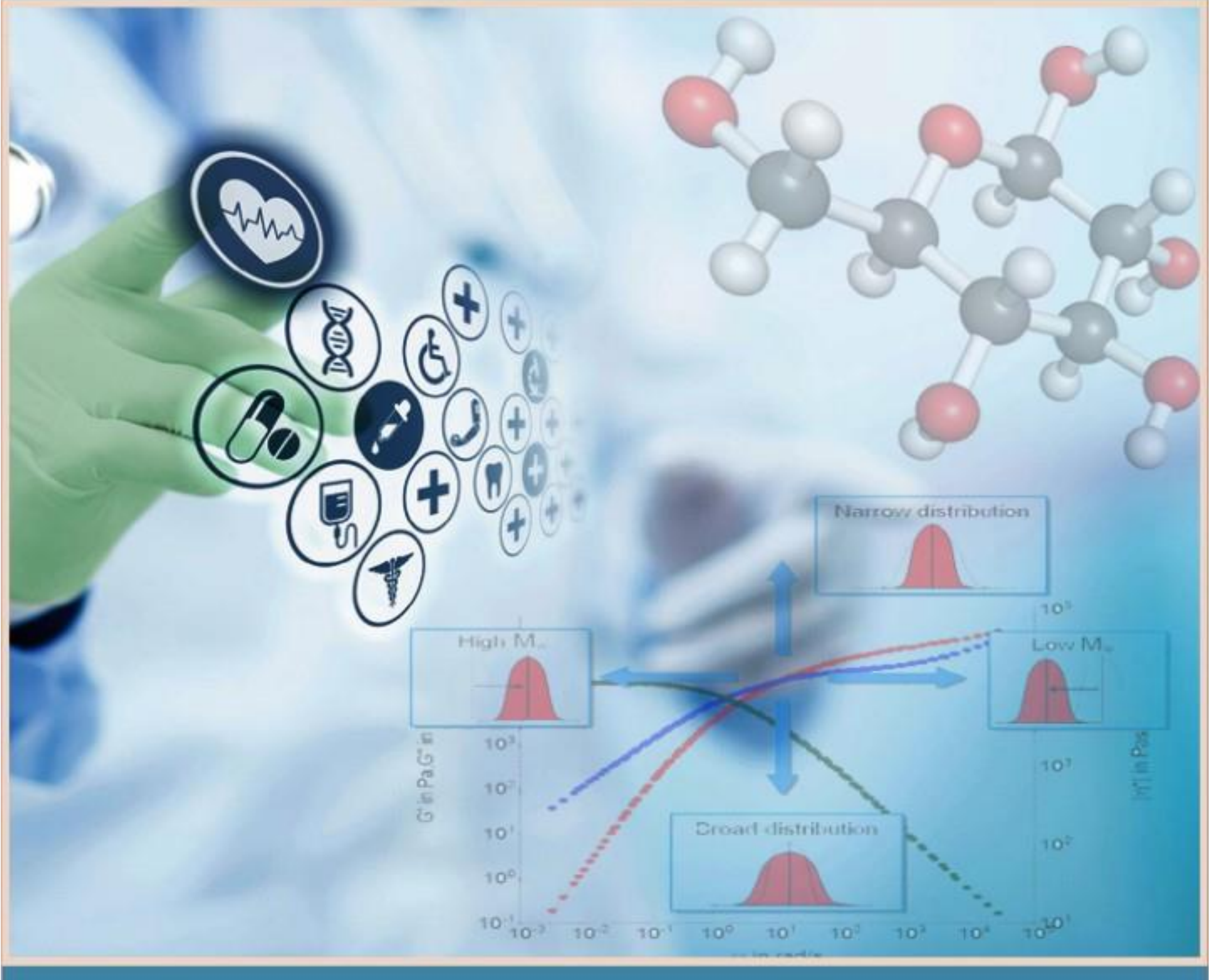
The GH-Method

Viscoelastic and Viscoplastic Glucose Theory Application in Medicine

Gerald C. Hsu



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