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Viscoelastic or Viscoplastic Glucose Theory (VGT #102): 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 Biomedical Behaviors of 3 Postprandial Plasma Glucose from Glycemic Edge Using 3 Standard Datasets for Normal, Pre-T2D, and T2D Patients Based on GH-Method: Math-Physical Medicine (No. 692)

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Note: This article No. 692 (VGT #102) is an enhanced version of the author's previous article No. 581 (VGT #4).

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 strength of materials and theory of elasticity from undergraduate courses at the University of Iowa. He also conducted research work to earn a Master 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 study the interactions between US soldiers and their M16 automatic weapon during 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. At the same time, he took some other graduate courses at MIT including machine learning, fluid dynamics, thermodynamics, finite element method, etc.

Since 1970, the biomechanics field has made some visible advancements in a few application areas, especially body parts and tissues of the human limb which possess both elastic & 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, simple and straightforward 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 biomaterial properties. Although 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

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"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 excluding biology, chemistry or medicine. As a result, he can only investigate his observed biophysical phenomena to make meaningful biomedical interpretations and then try to derive some useful conclusions or hints for healthcare purposes using his ready-learned math-physical knowledge from his 39 years of college-level curriculums and self-studies 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), 360 mg/dL (peak at 1-hour), and 330 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 their energy influx which pushes them to become either overweight or obese conditions. Being overweight and obese indeed leads to many chronic diseases, including diabetes. 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. In addition, many types of processed food contain certain unhealthy ingredients, and harmful chemicals from our surrounding environment that are toxic to the bodies, which lead to the development of many other deadly diseases, including a variety of cancers.

The author has already investigated glucose behaviors over the past 8 years using linear elasticity theory and nonlinear plasticity theory and has written several hundred medical articles. 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 using these viscoplastic or viscoplastic analysis tools.

In this particular article, he uses a set of publicly available PPG waveforms for a normal case, pre-diabetes case (pre-T2D), and severe diabetes case (T2D) from Glycemic Edge (see Reference 2) to conduct his glucose stress-strain behavior analyses and to identify which glucose behavior category belongs to linear elastic, plastic, viscoelastic, or viscoplastic. More importantly, he could use both space-domain (SD) VGT analysis and wave theory with frequency-domain analysis to figure out estimated energy levels associated with different diabetes conditions.

The author utilizes the PPG value from a public source, GlycemicEdge, as the strain and the respective strain rate ($d\varepsilon/dt$) 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, therefore, he makes a bold assumption about the viscosity factor in this article by using the following carbs/sugar intake grams from his record as the corresponding viscosity factors (i.e. carbs/sugar intake amounts):

Normal:
119 meals at 109 mg/dL, 10.7 grams

Pre-T2D & mild T2D:
24 meals at 135 mg/dL, 20.1 grams

Severe T2D:
25 meals at 328 mg/dL, 88.8 grams

Their relative carbs/sugar ratios are 100%, 188%, and 830% if using the normal case as the base of 100%.

These 3 different carbs/sugar intake amounts are served as the viscosity factors (η) in the following defined stress and strain equations:

Stress σ
= viscosity factor * (present PPG - previous PPG) / 15
= η * (dε/dt)

Strain ε
= present PPG value

His research effort in this study includes the following three major parts, time-domain analysis, space-domain analysis, and frequency-domain analysis:

First, he investigates his collected time-domain data using elasticity and plasticity theories to examine PPG behavior with time. Second, he investigates his collected data via space-domain VGT (SD-VGT) tool using theories of viscoelasticity and viscoplasticity to draw the stress-strain curve, i.e. hysteresis loop, for his SD-energy estimation. Third, he investigates his calculated data of both the variable of PPG from TD and a newly defined variable of (strain*stress) from SD and then uses the wave theory and frequency-domain fast Fourier transform (FD-FFT) analysis to estimate his two sets of FD-energy.

Elastic vs. plastic glucose

The author has spent a considerable amount of his research effort during 2020 and 2021 to develop his 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 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 studies.

The analogy between 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 force or cause has no difference between elastic and plastic. Second, the deformation or strain in physics and engineering corresponds to the actual PPG level in medicine. The strain, i.e. symptom of glucose level, indeed has noticeable difference between elastic case and plastic 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 human body with its internal organs and body 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 different selected time windows. In other words, they are both time-dependent and specimen-dependent. Because of these fundamental differences, calculations of a cross-section of subject and calculation of bending moment of resistance, or shape-factors 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 elasticity, plasticity, viscoelasticity, or viscoplasticity to the understanding of the biophysical phenomena quantitatively is extremely useful for exploring deeper insights into predicting both normal and abnormal glucose behaviors and diabetes disease.

Viscoelasticity and viscoplasticity

For readers in the medical field who do not have sufficient background in physics, engineering, and mathematics, the author decides to describe the VGT approach step-by-step in the English language instead of equations or formulas.

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 (dε/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 dε/dt and η together. The "time-dependent input or cause equation" of "stress σ = strain change rate of dε/dt * viscosity η" 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" from SD as a newly defined variable for his follow-on calculations of another estimated 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 in the English language, the author would still like to list the following set of 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)
= η * (dε/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, carbs values remain constant for each case, i.e. they are time-independent within those 180-minute time frame of each meal's PPG variation.

Energy theory

After declaring the analogy of elasticity, plasticity, viscoelasticity, viscoplasticity, the energy theory and wave theory in physics can 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; the stored glucose can be used for energy consumption for labor work or exercise. According to physics, energies associated with the glucose waves are proportional to the square of the glucose amplitude. After eating and exercising, there are some "left-over" or "residual" energies from elevated glucoses still circulating inside the human body via blood which can 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 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 (strain amplitude in TD) and glucose fluctuation rate (the strain rate and strain frequency) are influencing the energy level (the Y-amplitude in FD).

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 concepts of elasticity, plasticity, viscoelasticity &, viscoplasticity, wave theory, and frequency-domain analysis method from the disciplines of engineering and physics in the method section.

1.1 Specific medical information

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 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.

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 causing force is applied to 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.

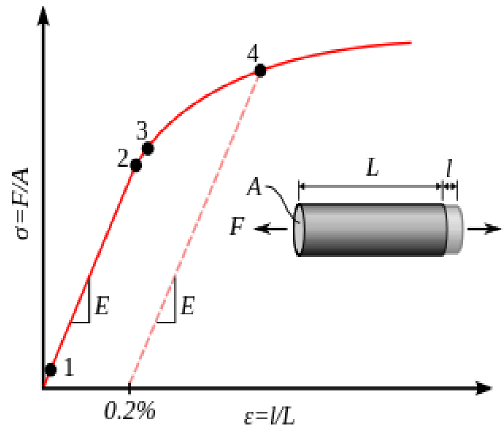
In engineering, the elasticity of a material is quantified by the elastic modulus such as the Young's modulus, bulk modulus or shear modulus which measure the amount of stress needed to achieve a unit of strain; a higher modulus indicates that the material is harder to deform. The material's elastic 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):

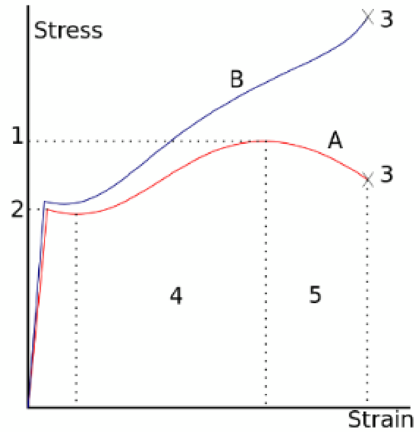
Deformation of a solid material undergoing non-reversible changes of shape in response to applied forces.

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.

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).

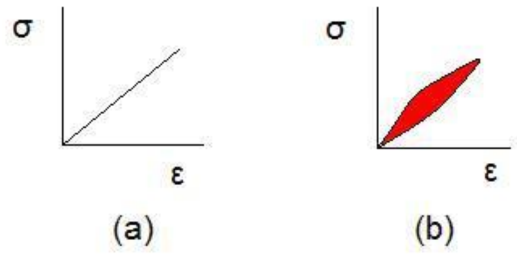
Depending on the change of strain rate versus stress inside a material, the viscosity can be categorized as having a linear, non-linear, or plastic response. In addition, when the stress is independent of this strain rate, the material exhibits plastic deformation. Many viscoelastic materials exhibit 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 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.

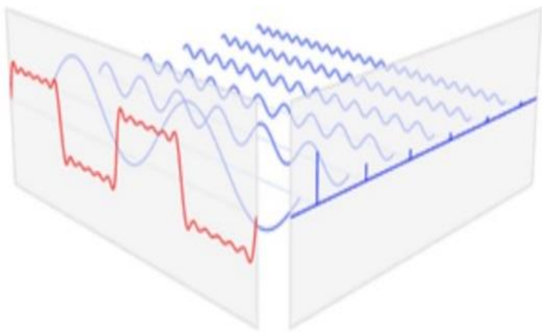
Medical analogy: In viscoelastic or viscoplastic analysis, the stress component equals the strain change rate of time multiplying with the viscosity factor, or

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 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 the data table of this analysis.

Figure 2 displays the PPG waveforms for both elastic glucose and plastic glucose.

6/20/2022 (avg. carbs)	Strain	Strain Rate	10.7 g	Strain=epsi	Stress=sig		Area	epsi*sig
GlycemicEdge PPG	Normal	PPG Rate	Viscosity	PPG	Stress	Height	Area	epsi*sig
First-Bite	80	0.0	10.7	80	0.0	0.000	0.0	0
15 min	88	0.5	10.7	88	5.4	2.675	1.3	468
30 min	95	0.5	10.7	95	5.4	5.350	2.7	508
45 min	103	0.5	10.7	103	5.4	5.350	2.7	548
60 min	110	0.5	10.7	110	5.4	5.350	2.7	589
75 min	120	0.7	10.7	120	7.1	6.242	4.2	856
90 min	110	-0.7	10.7	110	-7.1	0.000	0.0	-785
105 min	100	-0.7	10.7	100	-7.1	-7.133	4.8	-713
120 min	90	-0.7	10.7	90	-7.1	-7.133	4.8	-642
135 min	88	-0.2	10.7	88	-1.8	-4.458	0.7	-156
150 min	85	-0.2	10.7	85	-1.8	-1.783	0.3	-152
165 min	83	-0.2	10.7	83	-1.8	-1.783	0.3	-147
180 min	80	-0.2	10.7	80	-1.8	-1.783	0.3	-143
SD area & FD energy							25	4
Area Ratio to Normal							1	1

6/20/2022 (avg. carbs)	20.1 g	Strain Rate	20.1 g	Strain=epsi	Stress=sig		Area	epsi*sig
GlycemicEdge	Pre-T2D	PPG Rate	Viscosity	PPG	Stress	Height	Area	epsi*sig
First-Bite	95	0.0	20.1	95	0.0	0.000	0	0
15 min	111	1.1	20.1	111	21.8	10.888	12	2422
30 min	128	1.1	20.1	128	21.8	21.775	24	2776
45 min	144	1.1	20.1	144	21.8	21.775	24	3130
60 min	160	1.1	20.1	160	21.8	21.775	24	3484
75 min	185	1.7	20.1	185	33.5	27.638	46	6198
90 min	173	-0.8	20.1	173	-15.6	8.933	-7	-2710
105 min	162	-0.8	20.1	162	-15.6	-15.633	12	-2527
120 min	150	-0.8	20.1	150	-15.6	-15.633	12	-2345
135 min	140	-0.7	20.1	140	-13.4	-14.517	10	-1876
150 min	130	-0.7	20.1	130	-13.4	-13.400	9	-1742
165 min	105	-1.7	20.1	105	-33.5	-23.450	39	-3518
180 min	80	-1.7	20.1	80	-33.5	-33.500	56	-2680
SD area & FD energy							260	129
Area Ratio to Normal							11	34

6/20/2022 (avg. carbs)	88.8 g	Strain Rate	88.8 g	Strain=epsi	Stress=sig		Area	epsi*sig
GlycemicEdge	T2D	PPG Rate	Viscosity	PPG	Stress	Height	Area	epsi*sig
First-Bite	180	0.0	88.8	180	0.0	0.000	0	0
15 min	225	3.0	88.8	225	266.4	133.200	400	59940
30 min	270	3.0	88.8	270	266.4	266.400	799	71928
45 min	315	3.0	88.8	315	266.4	266.400	799	83916
60 min	360	3.0	88.8	360	266.4	266.400	799	95904
75 min	360	0.0	88.8	360	0.0	133.200	0	0
90 min	357	-0.2	88.8	357	-19.7	-9.867	2	-7038
105 min	353	-0.2	88.8	353	-19.7	-19.733	4	-6972
120 min	350	-0.2	88.8	350	-19.7	-19.733	4	-6907
135 min	345	-0.3	88.8	345	-29.6	-24.667	8	-10212
150 min	340	-0.3	88.8	340	-29.6	-29.600	10	-10064
165 min	335	-0.3	88.8	335	-29.6	-29.600	10	-9916
180 min	330	-0.3	88.8	330	-29.6	-29.600	10	-9768
SD area & FD energy							2846	22438
Area Ratio to Normal							115	5953

Figure 1: Data table.

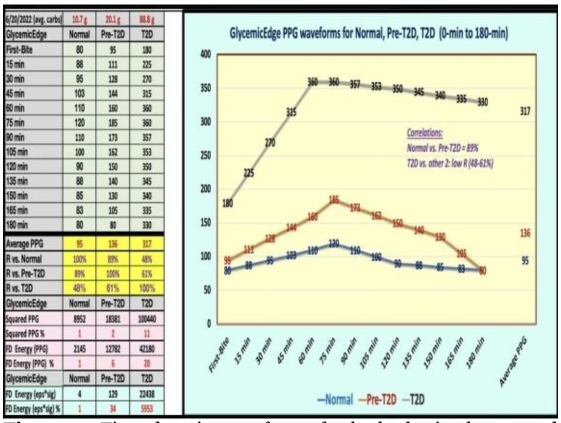


Figure 2: Time-domain waveforms for both elastic glucose and plastic glucose.

Figure 3 depicts the SD of stress-strain diagram of both viscoelastic and viscoplastic behaviors using VGT tool.

Figure 4 reflects the FD-FFT analysis of 3 PPG cases.

Figure 5 illustrates the comparison of results from TD energy, SD energy, and FD energy for 3 PPG cases.

Figure 3: Space-domain of stress-strain VGT analysis of 3 cases.

Figure 4: Frequency-domain FFT analysis.

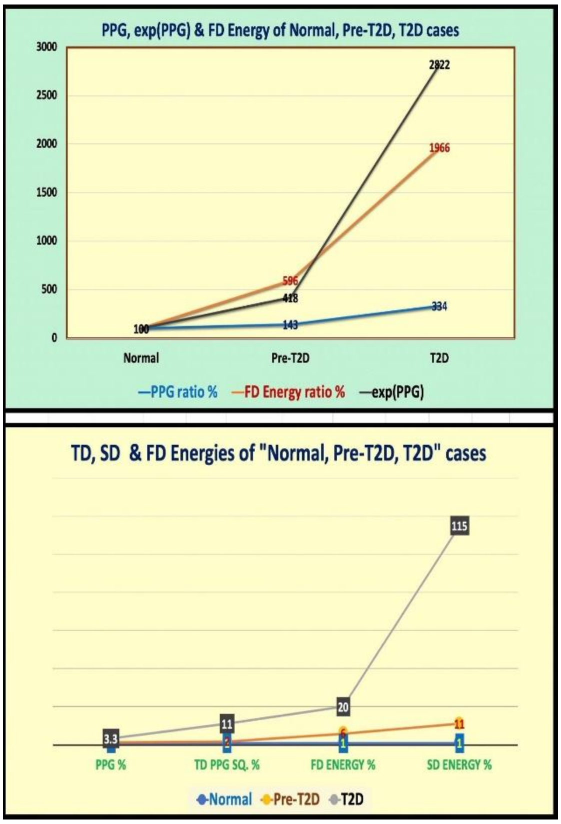


Figure 5: Comparison of TD (PPG square), SD energy ratio, and FD energy ratio.

4. CONCLUSION

In conclusion, there are four key observations described below:

(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 with plastic hinges (plastic). In a corresponding biomedical analysis, after eating carbs or sugar from food or meals, 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. But in the biomedical case, both processes of energy influx and energy consumption take some time which are not as simple and quick as the structural load removal in the engineering case. Therefore, the glucose behaviors in medicine, for both elastic glucose and plastic glucose, are “dynamic” in nature, i.e. time-dependent. This time-dependent nature leads into “visco-elastic or visco-plastic” situation. For both of the “Normal” & “pre-T2D” cases, they starts at 80 mg/dL and 95 mg/dL at 0-minute respectively, climbs up to 120 mg/dL for the normal case and 185 mg/dL for the pre-T2D case at 60-minutes respectively, and both cases drop down to 80 mg/dL again at 180-minutes, i.e. they return to their original position similar to an elastic engineering material behavior. On the contrary, for the more severe “T2D” case, it starts at 180 mg/dL at 0-minute, climbs up to 360 mg/dL at 60-minutes, and finally drops down to 330 mg/dL at 180-minutes, i.e. it never returns to its original position similar to a plastic engineering material behavior. This end-glucose value of 330 mg/dL is still 150 mg/dL higher than its initial-glucose position of 180 mg/dL. This type of “permanent deformation” or “residual glucose” value of 150 mg/dL is called “plastic” glucose or “elasto-plastic” glucose. In time-domain, the comparison of values of “square of PPG” are 1 : 2 : 11 which indicate the ration of PPG associated energy since the associated energy of a wave is directly proportional to the square of a wave’s amplitude.

(2) Researching the variation of the SD-VGT results, it can be seen that these 3 stress-train curves have similar waveform patterns due to using the same strain (PPG) rate. However, the T2D case has a huge gap between two end points which means “viscoplastic”. On the contrary, two end points of both normal case and pre-T2D case are in close proximity to each other which means “viscoelastic”. The ratios for these 3 hysteresis loop area are 25 (100%) : 260 (1100%) : 2846 (11500%). Therefore, this SD-VGT energy ratio of “ normal : pre-T2D : T2D” is “1:11:115”. This energy ratio has demonstrated the relative degrees of damage on internal organs resulted from glucose levels based on SD-VGT model.

(3) From FD analysis results, there are two different sets of energy ratios. First energy calculation uses the PPG wave through fast Fourier transfer operation (FFT). Second energy calculation uses the (strain*stress) wave, i.e. (PPG * PPG change * stress of carbs) through a fast Fourier transfer operation (FFT). The first PPG calculation shows their energy ratio of “normal : pre-T2D : T2D” is “2145(100%) : 12782 (596%) : 42180 (1966%)”. The second (Strain*Stress) calculation shows their energy ratio of “normal : pre-T2D : T2D” is “3.77 million (100%) : 129.2 million (3427%) : 22438 million (595172%)”. This second energy ratio is far

too large in comparison with the first energy ratio due to this variable (strain multiplying stress) provides a double amplification effect. Therefore, from now on, the author decides to use the original PPG wave as the variable to conduct his follow-on frequency-domain energy calculation, not the variable of "strain*stress". For this particular study, the FD energy ratio from using PPG variable for "normal : pre-T2D : T2D" is "1 : 6 : 20". This energy ratio has demonstrated the relative degrees of damage to internal organs resulting from glucose levels based on the FD-FFT model.

(4) The comparison of these 2 sets of energy ratios for "normal ; pre-T2D : T2D" are SD-VGT case = 1:11:115; FD-FFT case = 1 : 6 : 20. These two sets of calculated numerical values are somewhat different, but the pattern of comparison and the relative energy levels among these 3 glucose cases are very similar, i.e. T2D is worse than pre-T2D and pre-T2D is worse than normal. Although this statement matches with the common medical knowledge; however, these MPM research results can indeed provide a "quantitative" feeling to reconfirm this common medical knowledge. In summary, the average PPG ratio for "normal ; pre-T2D : T2D" is "95 mg/dL (1.0) : 136 mg/dL (1.43) : 317 mg/dL (3.34)", but the ratio of their associated energies are TD's 1:2:11; SD's 1:11:115; and FD's 1:6:20. This curve of PPG associated energy moves from normal case to T2D case with an exponential growth rate in comparison with the PPG's pseudo-linear growth rate.

This article has explained the relationship among 3 standard PPG cases shown in the GlycemicEdge chart. The quantitative energy findings via TD-PPG square, SD-VGT, and FD-FFT methods have revealed that severely high energy impact and internal organ damages happen in the severe T2D case with the average PPG at 317 msg/dL (20 times higher energy from FD to 115 times higher energy from SD damages).

The SD-VGT energy tool adopted from engineering and the wave theory with 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 these complex biophysical behaviors of glucose requires a deeper knowledge of physics, engineering, and mathematics, more than depending on biology and chemistry alone. It should be noted that the time-domain analysis results can only offer some limited reference 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 work and also published nearly 700 medical research papers. The author has never forgotten his advice to him that he should always focus on and enhance his basic 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.

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.

For reading more of the author's published VGT or FD analysis results on medical applications, please locate them through three published special editions from the following three specific journals:

(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

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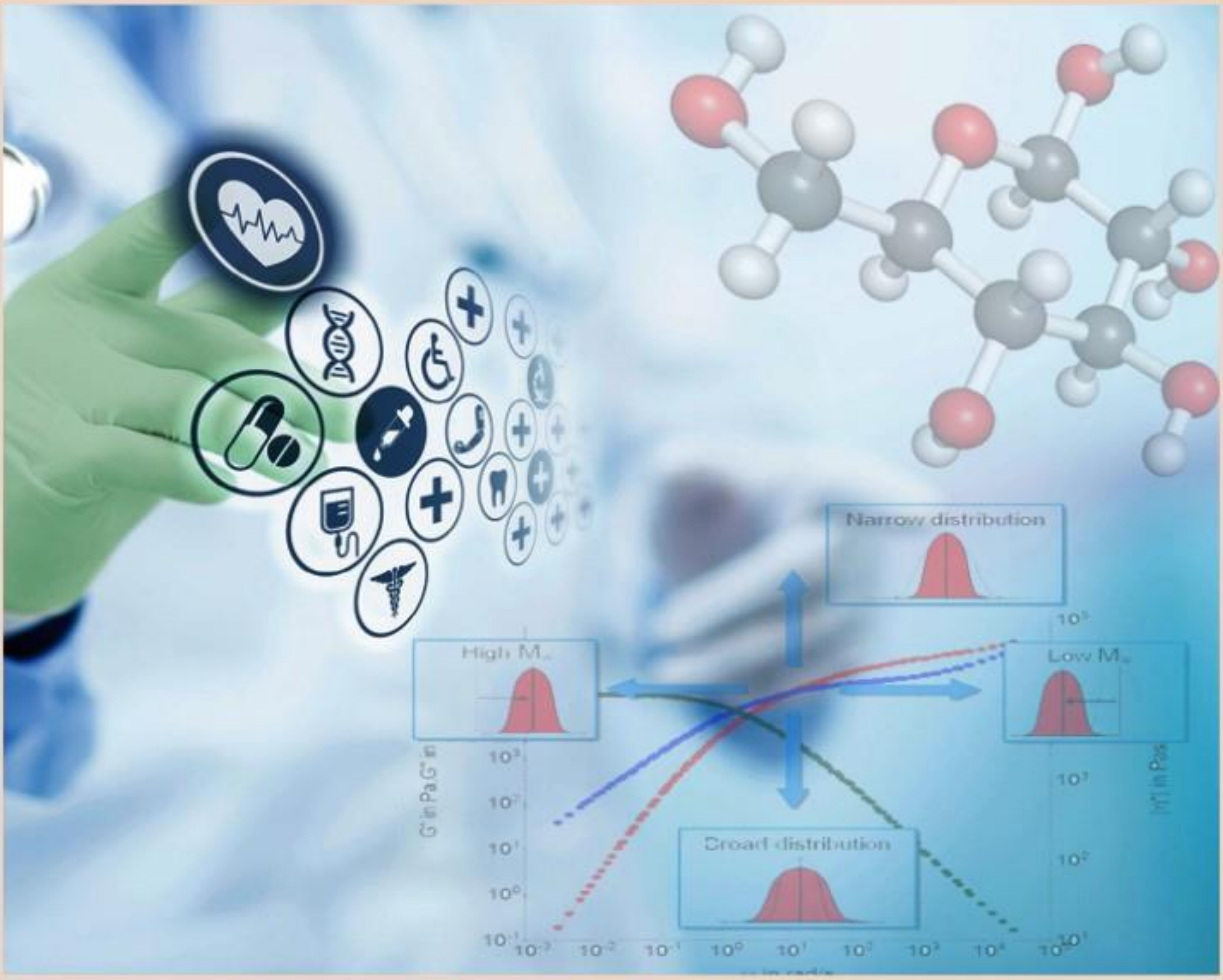
Gerald C. Hsu



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