Wave Reflection and Transmission in Multiply Stented Blood Vessels

[1]Karan Kamboj, [2]Vikramjeet Singh, and [3]Vinod Kumar

[1] Department of Mathematics, I.K. Gujral Punjab Technical University, Campus Kapurthala, Jalandhar, Punjab-144623, India
[2]Department of Mathematics, I.K. Gujral Punjab Technical University, Campus Amritsar, Punjab-143105, India
[3]Department of Mathematics, Guru Kashi University, Talwandi Sabo, Bathinda, Punjab-151302, India

Article Info
Page Number: 2715-2728
Publication Issue:
Vol. 71 No. 4 (2022)

Article History
Article Received: 25 March 2022
Revised: 30 April 2022
Accepted: 15 June 2022
Publication: 19 August 2022

Abstract
The introduction of a rigid stent into an elastic artery results in the formation of wave reflection sites at the entry and exit of the stent. It has been demonstrated that the stiffness of the stent, as well as its length and position within the diseased channel, all have an effect on a stent's clinical performance. The net haemodynamic effects of these reflections are highly dependent on the stent's length and position inside the diseased channel. Closed circulatory systems display a delicate equilibrium between the effects of vascular elasticity and viscous fluids in order to facilitate the smoothing of the pulse and prevent "resonance during the cardiac cycle. The placement of stents in the artery tree disrupts this equilibrium by making the arterial tree more rigid and by adding a periodic structure that is capable of" complex interactions with the fluid. Wave reflection in blood vessels has been thoroughly described in the literature; however, it has always been connected to a significant difference in geometry, such as vessel branching. This is because wave reflection is only observed when there is a significant difference between the two geometries. The characteristics of the wave's dispersion are investigated in this paper, and the stent construction has an effect on those characteristics. The model incorporates this structure because overlapping stents are utilized in a number of the vascular stinting procedures.
Keywords - Wave reflections, vessel, vascular.

Introduction

The study of biomedical acoustics, which is an established subfield of acoustics research, focuses on investigating the ways in which acoustic and ultrasonic waves interact with biological systems such soft tissue, bone, and organs. The diagnoses of medical conditions and a wide variety of technological applications both make use of a number of well-established notions and thoughts. Research into the transmission of acoustic waves via biological materials such as vascular tissue is one area of study. Analyzing acoustic waveguides and solving biomechanical issues that include pulsed flow both rely heavily on mathematical modelling as essential research tools. Heart disease, often known as "cardiovascular disease (CVD), is the leading cause of mortality in people in the Western world. A disease process known as atherosclerosis is responsible for the development of cardiovascular disease (CVD) by narrowing and/or obstructing blood arteries. Analytical models and numerical simulations of pulsating blood flow in an artery without a stent can be found, for instance, in". Ischemia, or a deficiency in the delivery of oxygen to tissues, can develop in the area that is supplied by a damaged artery as a result of a reduction in both the velocity and volume of blood flow. [1]

Restoring sufficient flow and protecting against ischaemia can be accomplished with treatment options like intraluminal stenting. The outcome of stenting is impacted by the anatomical location of the arteries that are affected by the disease. "For example, coronary stents have a high success rate in increasing channel patency, preventing further cardiac ischaemia, and eliminating the need for surgical bypass". In peripheral vascular disease, however, stenting of bigger limb arteries has not been as effective, and a great deal of effort and financial investment has been put into determining why this is the case. It is not known what caused the differences in the outcomes of the stenting procedure; nonetheless, it is highly likely that the reasons are complex. The arterial walls are elastic and sensitive to pulse waves, which originate in the left ventricle of the heart and change in frequency and regularity depending on the level of physical activity and the state of the patient's health. It is likely that constriction of arteries changes the propagation of pulse waves across the arterial network, which in turn changes the flow dynamics. This might result in occlusion restenosis due to changes in the artery wall, such as decreased flow velocity or higher wall shear stresses. These changes could lead to occlusion. Even though wave reflection "in blood arteries is a well-known phenomena, it has always been linked to significant geometrical changes in the arterial tree, such as vascular branching". This is because wave reflection in blood vessels has always been related with these modifications.[2]

This study's objective is to determine whether or not waves can be reflected in an artery that has been stented owing to the strength of the stents. Wave propagation in cylinders that are filled with fluid has been researched to great lengths in the published research. "The study of the dynamics of fluid-filled cylinders serves as the foundation for the analysis of any pipe system; hence, this research may be applied to a broad variety of different contexts. Numerous studies were conducted in order to ascertain the resonance frequencies and wave propagation in such systems, both with and without the fluid". The results of these studies were compared and contrasted. Few studies have focused on the propagation of waves in blood arteries, particularly when the systems display a repeated pattern in their shape. This is despite the fact that several computer models for haemodynamics have been developed. A new study investigates several types of stents based on their natural frequencies; however, the analysis is restricted to the metallic construction; this restriction is one of the limitations of the study. The vast majority of stents now on the market are designed according to a pattern that is unique to a particular brand. This pattern creates the system's unit cell by iterating a simple cell around the device's perimeter. The construction of the implanted stent is made up of a multitude of unit cells, which are repeated along the longitudinal axis of the channel. Because of these characteristics, it appears that a stented artery may "be modelled as a fluid-filled periodically reinforced cylinder. This cylinder is distinguished by a unit cell that is composed of the arterial wall, the structure of the stent, and the blood".

Because stents are normally considerably "smaller than the primary wavelength of arterial blood pulses" it is believed that there will be no significant reflection of pulse waves from the stents. As was mentioned before, even little shifts in the pulsatility of the local flow can have significant effects on a person's physiological state. Another essential fact to keep in mind is that interactions between the stent and the pulse wave can change the features of the blood pulse even when the stented region is not present. In conclusion, shorter pulse wavelengths have been linked to some cardiac problems (such as atrial fibrillation). In these circumstances, greater frequencies arise, particularly when inconsistencies in the pulse waveform occur, which results in higher harmonics. As a consequence, the internal structure of the stent may potentially be relevant during reflection or transmission of the sound. The purpose of this study is to investigate whether or not there is a potential for enhanced reflection frequency bands as a consequence of the insertion of a single stent and the interaction of two following stents, while also taking into account the periodicity of the building of the stent. Bloch waves in periodic structures are extremely important for this Endeavour. In the fields of "solid-state physics, photonics, and acoustics, Bloch waves are frequently the subject of investigation in periodic multi-scale media. In the most recent decade, the idea of met materials has been introduced and investigated in relation to applications in problems involving wave propagation". According to and the book, there is a formal link between the wave dispersion characteristics of infinite periodic media and the transmission challenges identified for multi-scale structured interfaces. This relationship was established in both of these sources. As a consequence of this, the presence of a stent in the vascular tree results in the formation of a met material that is able to produce "non-natural" occurrences, which are typical of materials of this type. The purpose of this research was to develop an analytical model for pulse flow via a stent that was used to reinforce a blood artery. The model takes into consideration the fluid–solid interaction within the context of a transmission problem. It is common knowledge that the wave will reflect off of the edge of the stent in this situation. On the other hand, no research has been done to study the connection that exists between the microstructure of the periodic stent and the attributes of reflection and transmission that it possesses. Because of the enormous wavelength of the pulses, it is anticipated that the stent periodic structure will have very little impact on the processes that occur in the low-frequency world. "The significance of frequency ranges that are established by the periodic structure of the stent is another topic that is discussed in this work. In addition, the interaction that occurs between two stents that are physically separated by a certain distance is investigated for the very first time. Researchers have discovered that the reflection and transmission coefficients of a system of stents are greatly dependent on the distance between the stents. In order to analyze the reflection coefficients, analytical methods are utilized, and the result is the discovery of transmission resonances".[3]

The development of a straightforward model that is able to take into account the influences of the stent microstructure in pulse reflection analysis is an essential part of the investigation that we are conducting. It is preferable to have a model that has a minimal spatial dimensionality, is linear, and has a small number of free parameters. Because of these characteristics, a number of essential features of blood flow, including viscosity and local fluid–elastic or rigid body interactions, intricate blood flow patterns, and challenges related to turbulent flow, are not addressed. On the other hand, the suggested model may give suggestions for simulations that are more sophisticated, on a larger scale, and require a significant amount of computer resources. These simulations may focus on crucial parameter values or essential nodes in the artery tree. The following is an outline of the paper's structure: First, the linear one-dimensional arterial pulse model with variable wave propagation speed is created. This model is used to study arterial pulses. This model incorporates many types of pulse wave speed fluctuation inside of each characteristic cell that makes up the stent (2). Provides an analytical solution for a time harmonic volumetric flow pulse in a stented zone. After that, the properties of reflection and transmission of a basic stented area are investigated in relation to pulse frequency and other stent parameters such as microstructure (fourth). In the fifth step of the process, a parametric analysis is carried out with regard to the length of the stented sections and their separation length. In the end, the findings are applied to a real-world scenario that involves a comparison of two processes for placing stents in terms of reflection properties. These procedures are: placing a single long stent as opposed to placing two smaller ones with a slight gap between them. "Wave reflection and transmission in multiple stented blood arteries, research published in 2017 by Papathanasiou TK, Movchan AB, and Bigoni D. Proc. R. Soc. A 473, 20170015. (doi:10.1098/rspa.2017.0015)"

Objective

1. Study on wave reflection.
2. Study on "transmission in multiply stented blood vessels".

Research methodology

Governing equations

Waves that are able to travel throughout the system may be analyzed and their dynamic characteristics determined with the help of the Bloch–Floquet technique. Finding the link between frequency and wavenumber, also known as the Bloch–Floquet parameter, may be accomplished with the use of this approach. The true solutions to the dispersion relation are what are known as dispersion curves, thus the name of the relation itself. Both the group velocity, which is represented by the slope of the curve, and the phase velocity are displayed on the dispersion curves for each frequency (secant slope). They also illustrate the frequency ranges within which waves are able to physically travel within the system (these frequency ranges are referred to as "pass bands") and the frequency ranges within which waves are unable to propagate (these frequency ranges are referred to as "no pass bands") (called stop-bands). The Bloch–Floquet analysis reduces the complexity of the issue by zeroing in on a single unit cell, which in this context refers to the arterial wall, the stent construction, and the blood. In the equations that follow, the letters "a," "s," and "f," respectively, denote the artery, the stent, and the fluid (blood), respectively. [4] The tiny displacement hypothesis was utilized in this investigation. In order to compute the dispersion relation, the artery is assumed to be a solid cylinder that is hollow on the inside and formed of a linearly elastic and isotropic ally homogeneous material. Because of this, the equations describing its motion are

$$\mu_a \nabla^2 \boldsymbol{u}_a + (\lambda_a + \mu_a)\nabla(\nabla \cdot \boldsymbol{u}_a) = \rho_a \frac{\partial^2 \boldsymbol{u}_a}{\partial t^2},$$

"Where a and a represent the Lamé parameters, a represents the density (mass per unit volume), ua represents the displacement vector, t represents the time, and the coordinate system is denoted by = (/x,/y,/z). The symbol T is used to signify the vector differential operator. Using a mathematical model, the blood is modelled as an acoustic medium".

motion equation.

$$K_f \nabla^2 p_f = \rho_f \frac{\partial^2 p_f}{\partial t^2},$$

"This approximation provides accurate results within the realm of eigenfrequency analysis, as was demonstrated in the aforementioned body of research, where pf and Kf stand for the fluid's pressure and bulk modulus, respectively, and f stands for the fluid's density. The coupling at the fluid–solid contact is estimated utilizing the following stress relationship since the fluid is modelled as an acoustic medium". [5]

$$\boldsymbol{\sigma}_a \boldsymbol{n} = -p_f \boldsymbol{n},$$

The stress tensor in the artery wall is denoted by the symbol a, and the unit outward normal vector is denoted by n. The free nature of the arterial wall's outer boundary can be described by the connection

$$\boldsymbol{\sigma}_a \boldsymbol{n} = \boldsymbol{0}.$$

In the research that has been published, for instance, comparable methods have been created for describing the interaction that occurs "between an elastic medium and other sources during the time-harmonic regime." In addition to the streamlined time-harmonic computations, a comprehensive transient study of the fluid-structure interaction was carried out when a viscous Newtonian fluid was present, as was mentioned in paragraph 5. During the calculations of the transients, "the pertinent wave regimes found in the linear-zed time-harmonic model are given further focus and consideration. In the linear zed time-harmonic simulations, the stent is modelled as a curved wire that has a circular cross section and is constructed of a linear elastic isotropic homogeneous material. It is believed that the stents are in their proper locations and are making contact with the artery wall. In the sake of keeping things as straightforward as possible, the stent-artery wall connection was assumed to be bilateral in this investigation. This indicates that the stents were connected to the inner artery wall. As a direct consequence of this, it is assumed that the continuity of displacements and tractions exists at the interface. There are no additional limitations added to the model so that the user can experiment with a wide variety of vessel deformations. In point of fact, arteries are able to move along with the body and may even stretch and twist as necessary".

Definition of the three-dimensional geometries

As can be seen in figure 2a, the "unit cell for the stinted artery is composed of a hollow cylinder, which represents the vascular wall; two zigzag-shaped coils, which represent the stent pattern; and a cylindrical fluid domain, which represents the blood and is enclosed by the hollow cylinder. A three-dimensional solid is used to depict the artery wall. This solid has a length of 10 millimeters, a lumen diameter of 7.3 millimeters, and a thickness of 0.7 millimeters". As a consequence of this, the outer diameter 2Rb measures 8.7 millimeters, and the average radius measures 4 millimeters; these figures are comparable to those found in the scientific literature (see, for instance,). "The zigzag-shaped coils may be identified by their total of eight crowns and sixteen segments. These coils are defined as beams with a constant circular cross section (0.1 mm diameter). The distance between the opposing crowns is one-third of the unit cell length (3.333 mm), as illustrated in figure 2a; nevertheless, the distance between the centroids of the two coils is one-half of the unit cell length (5 mm) (on the left and right sides, respectively)". [6]

Data analysis

"The transmission problem for two successive stented regions"

This part of the article is going to explore the problem of pulse transmission in a blood channel that has two stented sections that come one after the other. A sample example of reflection and transmission is shown in figure 1.

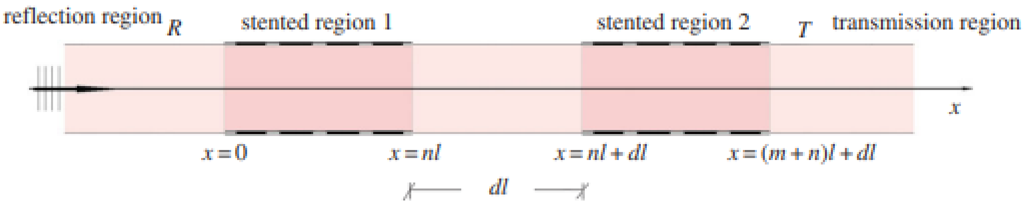

Figure 1. "Reflection–transmission phenomenon for two successive stented regions (Online version in color"

The process of pulse transmission across a series of stented zones as a physical phenomenon. An input pulse that is travelling from the negative to positive x-axis strikes the first stented zone where it is partly reflected at the point where x equals 0. When x equals nl, a portion of the pulse that has already passed through the stented region is partially reflected for a second time (the "right-hand end of the first stent). The pulse travels through the space between the two stents until it reaches the second stented area, where it is partially transmitted and partially reflected at the" point x = nl + d. The pulse then continues to travel through the space between the two stents. The wave that was reflected then makes its way back to the initial stented zone, where it is reflected one again and then transmitted once more. Last but not least, as soon as the wave leaves the second zone at the coordinates x = (n+m)l+d, it experiences a second reflection and then moves into the transmission region. "The whole configuration, which is made up of several different interfaces that only partially reflect light, ought to provide a reflection coefficient diagram that is richerthan the one produced by a single stent. That is, bigger reflection bands are expected to occur at lower frequencies, which may have an effect on the lower harmonics of the arterial pulse spectrum. In this article we will assume that the volumetric flow rate in the reflection, stented, intermediate, and transmission zones is of the kind described in the following".

$$Q_R = q_R(\xi)e^{i\omega\eta}, \quad -\infty < \xi < 0,$$

$$Q_1 = y_1(\xi)e^{i\omega\eta}, \quad 0 < \xi < n,$$

$$Q = v(\xi)e^{i\omega\eta}, \quad n < \xi < n + d,$$

$$Q_2 = y_2(\xi)e^{i\omega\eta}, \quad n + d < \xi < n + m + d$$

$$Q_T = q_T(\xi)e^{i\omega\eta}, \quad n < \xi < \infty,$$

And

The flow rate waves observed in the reflection and transmission zones are the same as those observed when only a single stent is present in the system. It falls somewhere in the middle of the spectrum.

$$v(\xi) = D_3 e^{-i\omega\xi} + D_4 e^{i\omega\xi}.$$

"The stented sections make use of the same approximation that is used for a single stent while doing so. Constants" D1 and D2 are associated with the first stented region, whereas constants D5 and D6 are associated with the second stented region. In the analysis of the two stented parts, there will be a total of eight constants to take into consideration. In order to solve the transmission issue and calculate the reflection coefficient R and the transmission coefficient T, there are a total of eight matching requirements that must be satisfied. [7] "These conditions are satisfied at the interfaces x = 0 and x = nl, x = (n + d)l, and x = (n + m + d)l by the continuity of the volumetric flow rate and the continuity of c2q/x, both of which appear in divergent form in the equation. The following is a list of the eight interface criteria for variables that are not dimensional":

$$\frac{dq_R}{d\xi} = Y_1(\xi) \quad \text{and} \quad q_R(\xi) = -\frac{1}{\omega^2}\frac{dY_1}{d\xi}, \text{at}\, \xi = 0,$$

$$\frac{dv}{d\xi} = Y_1(\xi) \quad \text{and} \quad v(\xi) = -\frac{1}{\omega^2}\frac{dY_1}{d\xi}, \text{at}\, \xi = n$$

$$\frac{dv}{d\xi} = Y_2(\xi) \quad \text{and} \quad v(\xi) = -\frac{1}{\omega^2}\frac{dY_2}{d\xi}, \text{at}\, \xi = n + d$$

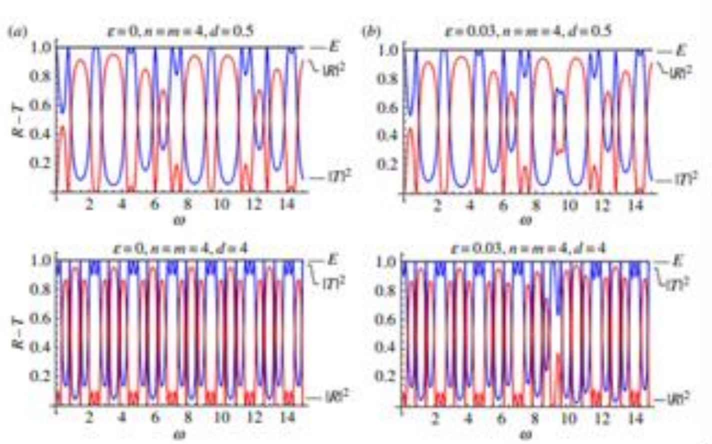

Figure 2 "Reflection–transmission diagrams for two stents with n = m = 4, and different values of d, ε. In all cases, it is f = cos2 (πξ), C = 3".

And

$$\frac{dq_T}{d\xi} = Y_2(\xi) \quad \text{and} \quad q_T(\xi) = -\frac{1}{\omega^2}\frac{dY_2}{d\xi}, \text{ at } \xi = m + n + d.$$

A linear system with the form Au = b is created by "using these equations. This linear system is used for the computation of Di, where I = 1, 2,..., 6, R and T". Appendix A contains the system's detailed description in its simplest form.

"Transmittance of the two-stent system"

An examination of the transmission and reflection properties of a two-stent system will be carried out using parametric analysis. In the following study, we will look at the scenario in which f(x) = cos2() is true. The responsiveness of the two-stent system may be controlled through a variety of different settings. "In addition to the stent compliance moduli C and, there is also the number of periodic cells in the first stent, which is denoted by n N, the number of periodic cells in the second stent, which is denoted by m N, and the distance between the two stented" sections, which is denoted by d. Diagrams of wave reflection and transmission are depicted in Figures 10 and 11, respectively, for mean nondimensional wave speeds of C = 3 and C = 1.5. Under each of these conditions, n = m = 4 is the number of periodic cells that may be found in each stent. In the example shown in column a, microstructure effects are not taken into consideration, hence the value for this cell is 0. The relative R–T graphs for = 0.03 are displayed in column b of the table. The variable that changes from row to row is denoted by the letter d and refers to the distance that separates each stent. The first and second rows of Figures 10 and 11 correspond, respectively, to the alternatives with d equal to 0.5 and 4. The results of having two stents implanted in a blood artery one after the other with a gap of d in between them are illustrated in Figure 10. Altering the distance between the stents has a significant impact even at low frequencies, in contrast to increasing the distance between the stents, which has only a marginal effect and increases reflection at high frequencies. "There exist bands of maximal reflection with values significantly higher than |R| = 0.9 inside the non-dimensional frequency range 0 1. These bands fall within the range 0 1. As the distance between the two stents increases, the first peak of the reflection coefficient declines, while the succeeding high reflection zone shifts to lower frequencies. The existence of diversity in the properties of the stent has an influence on the response, particularly at extremely high non-dimensional frequencies". [8]

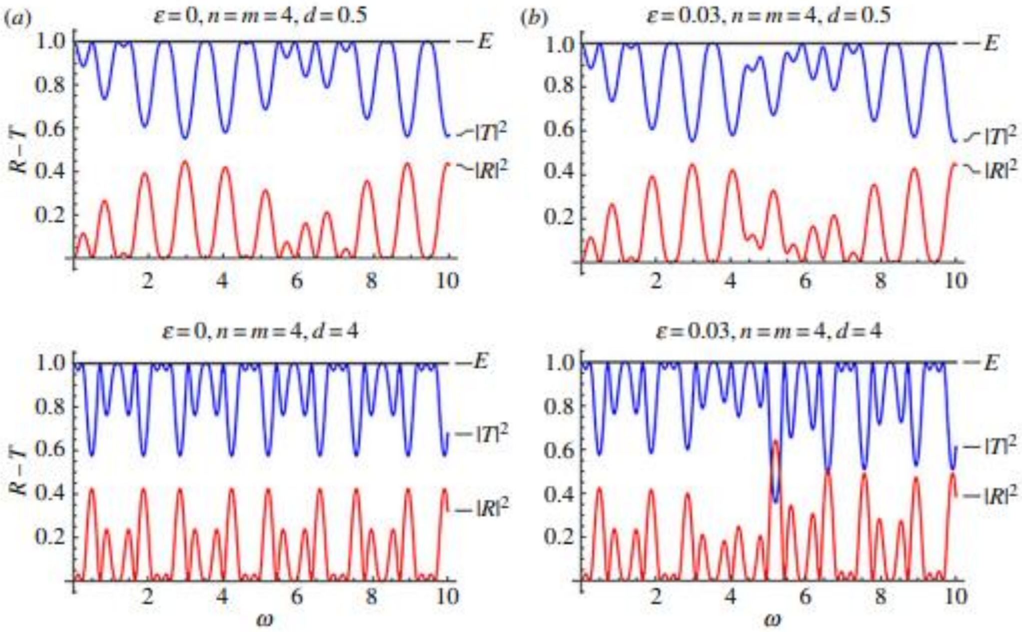

Figure 3."Reflection–transmission diagrams for two stents with n = m = 4, and different values of d, ε. In all cases, it is f = cos2 (πξ),C = 1.5".

"Influence of the stent compliance on the transmittance of the two-stent system"

In the case when C is equal to 1.5, which describes geometry with two stents, the impact of the stent's microscopic structure is more readily visible. When opposed to C = 3, the stents in this scenario are more compliant, "and the effect of increased becomes far more significant. When d = 4, a larger reflection zone" emerges around the number 5. The following conducts an analysis of the limit situation C = (1) 1 of an exceptionally compliant stent, in which the effect of the periodic structure plays a crucial role. The conclusion of this matter is illustrated in figure 12. The following values of d are taken into consideration: 0.5, 1, 4, and 8. It never deviates from the value of 0.03 In conclusion,"the number of periodic cells in the stents is shown to be n = m = 4 in figure 12a, but in figure 12b, it is shown to be n = m = 8 In any given situation, 'bumps' in the reflection–transmission coefficient curves will manifest themselves close to the non-dimensional frequency 3. The severity of these spikes increases in proportion to the growing number of periodic cells. As the distance d between the two stents increases, the number of low-amplitude spikes that form also increases". [9] During this phase, the major spikes are shrunken down to a more manageable size. Further research will be done to explore the significance of the distance d that separates the two stents. In order to accomplish this goal, we will suppose that the stents do not include any periodic structures, and the corresponding value will be 0. The contour graphs of the reflection coefficient as a function of the non-dimensional frequency and the distance between the stents d are shown in figures 13 and 14, respectively. Stent shown in Figure 13 has a C value of 3, which indicates that it is rather "stiff." Figure 14 displays outcomes that are analogous to these with a stent with a compliance parameter of 1.5. In each circumstance, four different stent length combination options are researched and evaluated. The following is a list of the combinations that are possible: I n = m = 4, (ii) n = 4 and m = 8, (iii) n = 8 and m = 4, and (IV) n = m = 8. Under all and all conditions, research is conducted into the domain of relatively low non-dimensional frequencies. Figure 13, which corresponds to C = 3, demonstrates the existence of a very narrow band that is distinguished by high transmission at extremely low frequencies, i.e. 0.05, and that takes place regardless of the value of d. "This band is shown to exist. When the value of d is increased, this results in the formation of high reflection zones that have intermediately narrow improved transmission bands for the configuration in which n = m = 4. This occurs when the frequency is substantially higher. When the frequency remains the same, an increase in d results in a narrowing of the high reflection zones. Remember that the [10] is an important factor to consider".

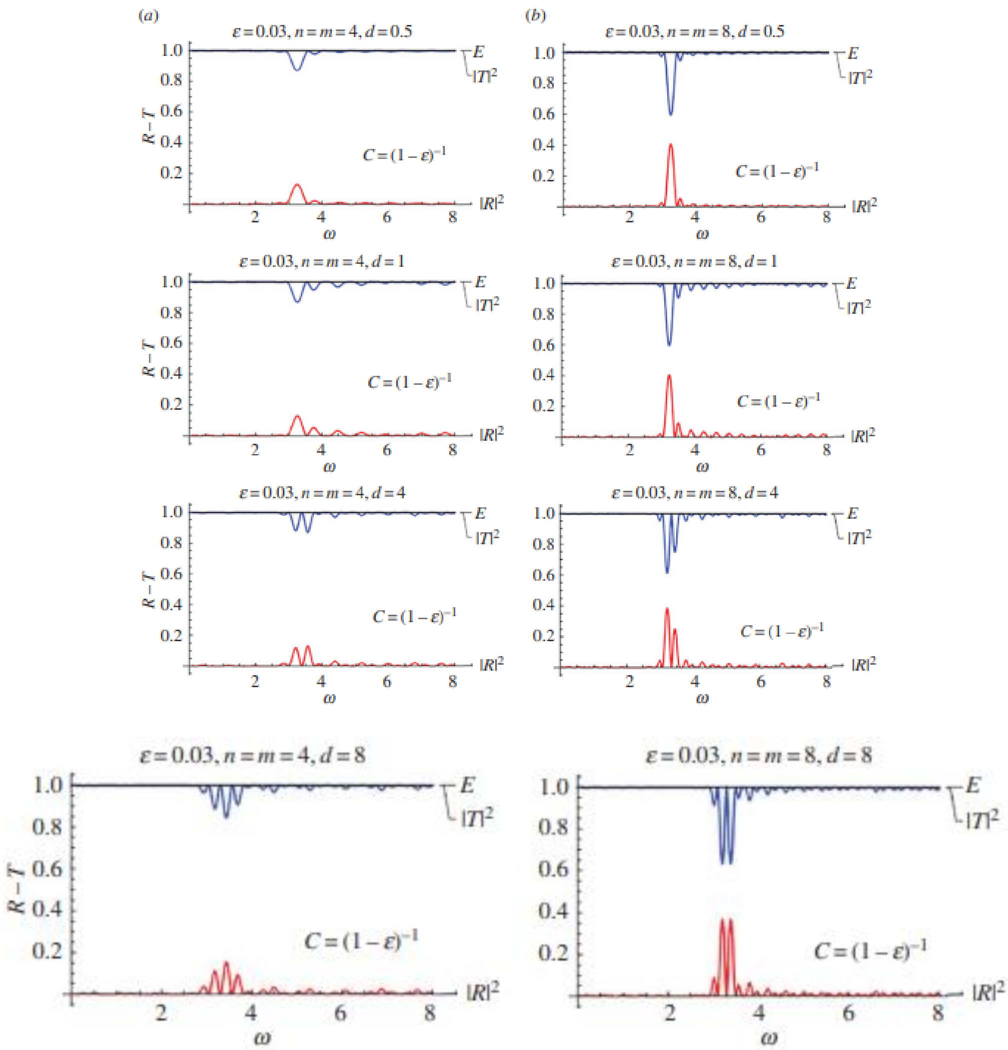

Figure 4 "Reflection–transmission diagrams for two stents with n = m = 4, and different values of d. It is f = cos2 (πξ), C = (1 − ε) −1 and ε = 0.03".

"It is possible to see that the diagrams for n = 4 and m = 8 (figure 13b) and n = 8 and m = 4 (figure 5) are identical to one another. This suggests that the reflection and transmission properties of a two-stent system with different stents are not impacted by the order in which the stents are inserted into the system, at least not within this frequency range. This finding may prove useful in situations when stents of varying sizes need to be put into a certain location. As the number of periodic cells increases (for n = m = 8), a narrower transmission band with higher performance appears at around the value of = 1.2 for all possible values of d. High reflection branches converge in this zone from lower frequency zones as well as higher frequency zones".[11]

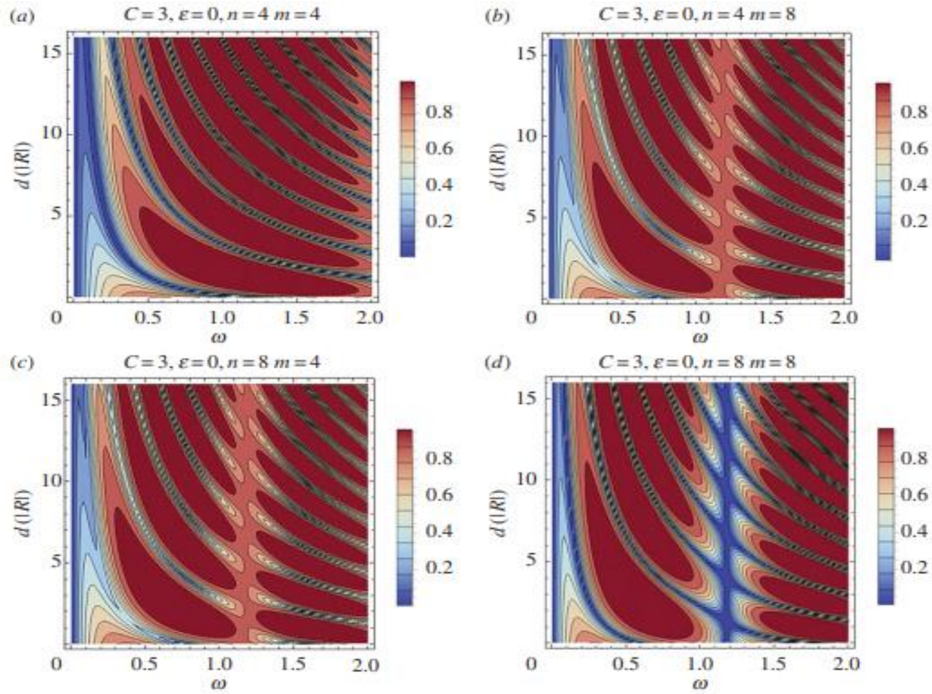

Figure 5."Contour plot ofthereflection coefficient forthe case oftwosuccessive stents as a function ofthe frequency andthe non-dimensional distance between them dthe stent hasC = 3 and no periodic structure (ε = 0)".

The example of a more compliant stent with C = 1.5, which may be seen in figure 14, has similar tendencies. The more compliant stent exhibits a better transmission band at a frequency of 1.2 in each and every one of the instances that were examined. There are two additional strong reflection zones at the coordinates 0.6 and 1.8 "in the case where n = m = 8. These narrow high reflection bands have a tendency to form at lower frequencies as the length of the stents increases and/or the compliance level increases. For a value of C equal to 1.5, the reflection and transmission properties of a two-stent system with" independent stents are not affected by the order in which the stents are placed. Last but not least, it is important to discuss the connection that exists between the two stents, which have a close distance between one another, "and the Fabry–Pérot-type reflector configurations. Recent research in has investigated a phenomenon that is qualitatively comparable to water wave propagation over uneven patches of undulating seabed profiles that have a gap between them".

RESULT

"The effect of the periodic structure of the stent on the pulse reflection and transmission coefficients, in addition to the interaction between two successively placed stents, has been investigated. It has been demonstrated that the periodic structure found inside a stent may cause considerable reflection effects when the frequency is increased. In more severe cases, this may have an effect on higher harmonics of irregular pulses".

The instance of two consecutively implanted stents is especially crucial since strong reflection zones occur at very low frequencies. The amount of space that exists between the stents has a significant bearing on the frequency range and reflectivity.[12]

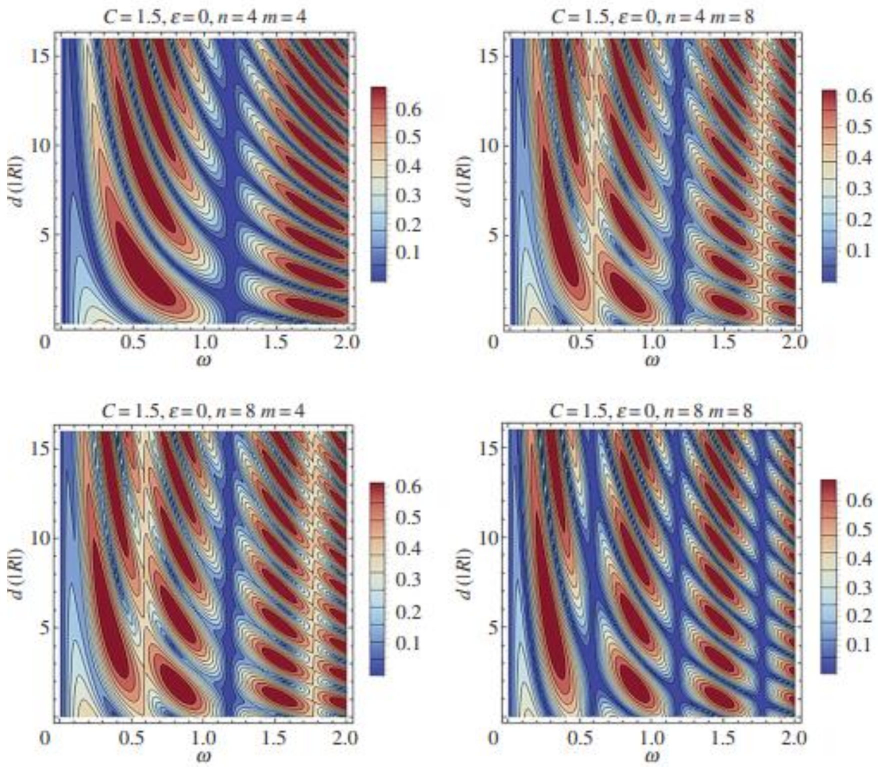

Figure 6 "shows a contour plot of the reflection coefficient for the case of two sequential stents. This coefficient is plotted as a function of the frequency and the non-dimensional distance between the stents. C of the stent is equal to 1.5, and it does not have a periodic structure (= 0)". [13]

CONCLUSION

The dynamic response of multi-scale stented vascular systems, which is often disregarded, has been added to our understanding as a result of this work. Surgeons have observed that vascular blockages and aneurysms typically arise around vascular junctions, which is consistent with the fact that branching blood arteries are known to reflect waves in the field of medical acoustics. [14] According to a simplified but theoretically sophisticated model that is based on Bloch–Floquet waves, a stented blood channel displays numerous kinds of dynamic deformations. "It has been demonstrated that axisymmetric and non-axisymmetric deformations, both of which are connected with so-called stop-bands, and consequently have a detrimental effect on the flow of fluid through stented channels. Trapped modes are given special attention for clusters of stents that are separated by a limited distance, and asymptotic approximations are constructed in order to perform predictive analysis of the waveforms that are associated with these clusters. It has been demonstrated that the Bloch–Floquet wave theory is a viable basis for time-harmonic modelling of waves in stented blood vessels". The methodology presented here makes it possible to do both qualitative and quantitative analyses of the wave reflections a stent produces. It is possible to draw the conclusion that the utilization of two successive stents may be beneficial at low frequencies provided that the gap in between them is appropriately chosen. However, prior study and careful planning are required for this method, as shifting to frequencies that are only slightly higher may have the opposite of the desired impact. In further studies, the existing model may be utilized to carry out an in-depth analysis of the transmittance features that are present in particular frequency bands. The end result, regardless of the conditions, is always a pressure differential that is positive in the direction that the flow is going. This pressure differential, when superimposed on the underlying pressure distribution within the vessel, has the overall effect of facilitating rather than impeding the flow of whatever is being carried by the vessel.[15]

REFERENCES

[1] Duraiswamy N, Schoephoerster RT, Moreno MR, Moore Jr JE. 2007 Stented artery flow patterns and their effects on the artery wall. Annu. Rev. Fluid Mech. 39, 357–382. (doi:10.1146/ annurev.fluid.39.050905.110300)

[2] Alderson H, Zamir M. 2004 Effects of stent stiffness on local hemodynamics with particular reference to wave reflections. J. Biomech. 37, 339–348. (doi:10.1016/S0021-9290(03)00289-6)

[3] Sherwin SJ, Formaggia L, Peiró J, Franke V. 2003 Computational modelling of 1D blood flow with variable mechanical properties and its application to the simulation of wave propagation in the human arterial system. Int. J. Numer. Meth. Fluids 43, 673–700. (doi:10.1002/fld.543)

[4] Migliavacca F, Petrini L, Montanari V, Quagliana I, Auricchio F, Dubini G. 2005 A predictive study of the mechanical behaviour of coronary stents by computer modelling. Med. Eng. Phys. 27, 13–18. (doi:10.1016/j.medengphy.2004.08.012)

[5] Moravej M, Mantovani D. 2011 Biodegradable metals for cardiovascular stent application: interests and new opportunities. Int. J. Mol. Sci. 12, 4250–4270. (doi:10.3390/ijms12074250)

[6] Colombo A, Stankovic G, Moses JW. 2002 Selection of coronary stents. J. Am. Coll. Cardiol. 40, 1021–1033. (doi:10.1016/S0735-1097(02)02123-X)

[7] Van de Vosse FN, Stergiopulos N. 2011 Pulse wave propagation in the arterial tree. Annu. Rev. Fluid Mech. 43, 467–499. (doi:10.1146/annurev-fluid-122109-160730)

[8] Gosling RG, Dunbar G, King DH, Newman DL, Side CD, Woodcock JP, Fitzgerald DE, Keates JS, MacMillan D. 1971 The quantitative analysis of occlusive peripheral arterial disease by a non-intrusive ultrasonic technique. Angiology 22, 52–55. (doi:10.1177/000331977102200109)

[9] Stergiopulos N, Spiridon M, Pythoud F, Meister JJ. 1996 On the wave transmission and reflection properties of stenoses. J. Biomech. 29, 31–38. (doi:10.1016/0021-9290(95)00023-2)

[10] Stergiopulos N, YoungDF, Rogge TR. 1992 Computer simulation of arterial flow with applications to arterial and aortic stenoses. J. Biomech. 25, 1477–1488. (doi:10.1016/ 0021-9290(92)90060-

[11] Katritsis DG, Camm AJ, Gersh BJ. 2016 Clinical cardiology: current practice guidelines. Oxford, UK: Oxford University Press.

[12] Carta G, Brun M. 2015 Bloch-Floquet waves in flexural systems with continuous and discrete elements. Mech. Mat. 87, 11–26. (doi:10.1016/j.mechmat.2015.03.004)

[13] Brun M, Giaccu GF, Movchan AB, Movchan NV. 2012 Asymptotics of eigenfrequencies in the dynamic response of elongated multi-structures. Proc. R. Soc. A 468, 378–394. (doi:10.1098/rspa.2011.0415)

[14] Cabuz AI, Felback D, Cassagne D. 2007 Homogenization of negative-index composite metamaterials: a two-step approach. Phys. Rev. Lett. 98, 037403. (doi:10.1103/PhysRevLett. 98.037403)

[15] Willis JR. 2011 Effective constitutive relations for waves in composites and metamaterials. Proc. R. Soc. A 467, 1865–1879. (doi:10.1098/rspa.2010.0620)