

Novel spatiotemporal evaluative methodology of COVID-19 pandemic velocity based on differential equations

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Abstract

Introduction: The trajectory of disease outbreaks has been characterized through second order differential equations.

Objective: To develop a universal methodology to predict the velocity of COVID-19 pandemic in the United States, Spain, Belgium, and Austria based on differential equations and ranges of the number infected.

Methodology: Seven comparison ranges were established to analyze discrete values of COVID-19 total cases. Then, right-angled triangles where their base represented the number of days elapsed and their height the maximum number infected that was reached for each range were designed to then find the triangles' areas. Given that there is a change rate between the triangles' areas with respect to time, their velocity was found through a differential equation. Finally, these results were used to compare the propagation speed of the pandemic in these four countries.

Results: The areas obtained for the right-angled triangles for all the countries varied between 2.888 and 1.056.204. The change rate between the triangles areas and the days elapsed for a range change oscillated between 3.079 and 1.264.558, while the variation of the number infected with respect to time presented values between 4.6 and 21549.7.

Conclusion: An acausal generalization was developed based on differential equations that allows to simplify and facilitate the spatiotemporal evaluation of COVID-19 pandemic velocity which is useful for public health

Introduction

Generations of mathematicians have found a link between geometry with different mathematical operations and reasonings (1). Euclid's Elements is a literary work that compiles over 200 years of mathematical knowledge. This work is considered to be the first source of deductive reasoning, theorems, postulates and axioms. Within this book, the Pythagorean postulates and its subsequent followers work is found. These historical characters are considered as the pioneers to acknowledge the necessity of systematic proofs and provide scientific processes to geometric considerations (2). Among this knowledge, the Pythagorean theorem is found, which has been applied in most of mathematics (2-5) and physics fields (6).

The first issues in calculus history were the calculation of areas, volumes, and others (7). Within antique Greek mathematical figures, Archimedes is found, who formulated a mathematical solution called the Method of Exhaustion, which solved the quadrature of the parabola (7). However, this method was quite complex, which is why other mathematicians later refined it. For example, it was demonstrated that areas, under certain curves, can be approximated through the sums of circumscribed and inscribed rectangles, whose difference can be made arbitrarily small (7). Then, infinite series were established. The key point of

this story is when Newton and Leibniz generalized on their own, all that previous knowledge in a single calculus, independent of its geometrical significance (7).

This is how another branch of pure and applied mathematics rises, called as differential equations (8). Its first applications were to isoperimetric problems through optimization exercises, among others (8). A differential equation links derivatives to a function of one or more variables (9) and it can be classified according to its type: ordinary or partial; the former refers to an equation that contains only derivatives of one or more dependent variables with respect to a single independent variable, while the latter the equation involves partial derivatives with respect to one or more independent variables (9).

SARS-CoV-2 is the etiologic agent responsible for coronavirus induced disease 2019 (COVID-19). It has been considered that the initial COVID-19 breakout was originated in Wuhan, China (10), however, the disease spread to nearby cities in China (11,12) and then to the rest of the world. Therefore, the World Health Organization considered COVID-19 as a pandemic on March 11th, 2020 (12). Thus, to quantify the extent of the disease, it is necessary to estimate the propagation velocity of the pandemic among different sets of populations, using for this purpose the reproductive basic number R_0 (13).

Classical compartment models such as the susceptible-infected-recovered (SIR) and susceptible-exposed-infected-resistant (SEIR) models has been used (14,15). The SIR modelling, which assumes no births or deaths during the development of an epidemic, is defined as a nonlinear system of three ordinary differential equations that can be implicitly solved. Furthermore, its infectiousness dynamic depends on $\beta/\gamma=R_0$ (13). Professionals on epidemiology can apply more than 1000 deterministic epidemiological models that can combine in compartment studies the incidence for a certain disease, the time spent in each compartment, the demographic structure, and demographic-epidemiological interactions (16). This augments the possibilities of applying different models to solve public health problems.

The purpose of this work is to develop a predictive methodology based on differential equations that universalizes and simplifies the spatiotemporal prediction of the COVID-19 velocity of propagation in any country.

Methodology

Ranges of the number infected: 7 ranges of values were defined to analyze the progression of the number infected with COVID-19; the extremes of these ranges are:

Value	Range
0 - 200	1
201 - 10.000	2
10.001 - 30.000	3
30.001 - 60.000	4
60.001 - 110.000	5
110.001 - 170.000	6
>170.000	7

Spatiotemporal area of the pandemic's triangle (SAPT): this triangle is generated from the height, represented by the variable y (it is also the value of the maximal number infected for a single range), and its base, represented by the variable x , that represents the number of days elapsed from the beginning of the pandemic until the maximal y value was presented (see figure 1). It is evaluated through the following expression:

$$A = \frac{xy}{2} \text{ Equation 1}$$

Change of the number infected in ranges with respect to time (dy/dt):

$$\frac{dy}{dt} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{y_2 - y_1}{\Delta x} \text{ Equation 2}$$

Where y_2 is the value of the number infected in the first day in which the dynamic is clustered in a range and y_1 is the same but for the previous range; while x_2 value is the first day in which the dynamic is found in a range measured from the beginning of the pandemic in each country and x_1 is the same value but for the previous range. Δx is the difference in days, $x_2 - x_1$.

Implicit derivation: considering that the triangles' areas vary according to the number infected (variable y) and time (variable x), the variation of the area is expressed through the following differential equation:

$$\frac{dA}{dt} = \frac{1}{2} \left(x \frac{dy}{dt} + \frac{dx}{dt} y \right) \text{ Equation 3}$$

Population

Within the countries that headed the worldwide list with the highest and lowest number of cases daily reported for COVID-19 until May 8, 2020, data from the United States, Spain, Belgium, and Austria were

chosen for the study. All datasets were retrieved from the WHO website (17).

Procedure

The total number of COVID-19 cases daily reported in the United States, Spain, Belgium, and Austria were retrieved from the WHO datasets to then assign their corresponding range according to the definitions. For example, for a value of 213 individuals infected, range 2 was associated since this range includes this value. This procedure was repeated with the complete daily sequence of ranges. Then, it was observed in the dynamic when a range change was presented, and the counting of days elapsed was done until the cutoff date set for this study in each country.

Next, each range change was represented through a right-angle triangle (SATP) where the base (x) represents the number of days elapsed from a range change while height (y) represents the maximal value of the number infected that determined the range change. According to the quantity of ranges that one country manages to occupy from the dynamic of the number of cases, in a same plot, right-angle triangles were sketched. Once these triangles were obtained, their area was evaluated through Equation 1.

Hereafter, the instantaneous velocity of the pandemic propagation for a country was evaluated when the number of total COVID-19 cases changed between ranges. For that, the difference or variation in days elapsed to transit between one range to another was calculated (see Equation 2). When this variation was found in days, the next step was to evaluate the velocity of the range in that time with Equation 2.

Then, SATP were calculated through Equation 3 when the triangles were on their initial state and after a range change occurred since variations of its base (time elapsed) and height (maximal value for the number infected in a range). Variations of triangles' bases and heights were assessed through equation 2. Finally, the areas values and their change ratio were compared among the countries evaluated.

Results

The total number of cases by COVID-19 until May 8, 2020, for the United States of America was 1,215,571, in Spain it was 221,447, in Belgium it was 51,420 and in Austria it was 15,673.

The variation of the time in days to go from one range to another ranged between 3 and 46. The values of the speed of the range (dy/dt) were between 4.6 and 21549.7. For all countries, these values will show the speed with which the change in the number of infected occurs for the moment in which the change in range occurs, but only for that point, in such a way that when comparing these values among the analyzed countries, it is observed that this measure allows establishing differences in how fast or not the change in the range occurred, showing the differences in the dynamics of the number of infected between countries. Thus, the countries with a dynamic that has shown an increase in the number of infected, such as Spain and the United States, obtained the highest values, while the other 2 countries with the least tendency to increase their number of infected obtained the lowest values for the passage

from range 2 to 3, and thereafter, the other range changes, which are the changes of greatest interest, since in a pandemic rank 1 will be easily overcome (see table 1).

The areas evaluated for each of the ranges with equation 1 ranged from 48,899 to 280,953 for the United States of America, between 4,369 and 1,056,204 for Spain, between 4,673 and 229,418 for Belgium and between 2,888 and 101,820 for Austria. While the derivative of SAPT varied between 3,079 and 123,157 for all countries (See table 1). In this way, the derivative of SAPT temporarily differentiates space as it changes in each of the countries.

Table 1. Range (R), values of the base (x) and the height (y) of the right triangles; the variation from one range to another in days(Δx); instantaneous range speed (dy/dt); the temporal space area and the rate of change of the pandemic area in the United States of America, Spain, Belgium and Austria with respect to time(dA/dt).

R	Estados Unidos de América						España					
	X	y	Δx	dy/dt	Área	dA/dt	X	y	Δx	dy/dt	Área	dA/dt
1	1	1					1	1				
2	47	213	46	4,6	4.899	5.007,3	35	257	34	7,5	4.369	4.500,8
3	60	10442	13	786,8	67.873	91.478,4	47	11178	12	910,1	67.068	88.455,0
4	64	31573	4	5282,8	63.146	232.194,0	54	33089	7	3130,1	115.812	200.325,4
5	67	68334	3	12253,7	102.501	512.998,8	58	64059	4	7742,5	128.118	352.650,5
6	71	122653	4	13579,8	245.306	727.387,1	64	110238	6	7696,5	330714	577.002,0
7	74	187302	3	21549,7	280.953	1.078.290,7	76	176034	12	5483,0	1056204	1.264.558,0
R	Bélgica						Austria					
	X	y	Δx	dy/dt	Área	dA/dt	X	y	Δx	dy/dt	Área	dA/dt
1	1	1					1	2				
2	36	267	35	7,6	4.672,5	4.809,3	17	361	16	22,438	2.888	3.078,7
3	56	10836	20	528,5	108.360,	123.156,6	37	10182	20	491,050	101.820	110.904,4
4	71	30589	15	1316,9	229.417,5	276.166,3						
5												
6												
7												

From these results, it is possible to observe how the SAPT changes in each of these countries, as they increase the days before the day in which the change in rank occurred, showing the differences between countries, with the number of days elapsed. from the beginning of the epidemic until the change of rank occurs. For example, the comparison between the areas of the four countries in range 3 shows that the area of the pandemic in Belgium is 1.3 and 1.8 times greater than in the United States of America and Spain, respectively; while for SAPT in Austria, the ratio is 1.5 compared to SAPT in the United States and Belgium. One explanation for this is that Belgium took 11 days more than Spain to go to rank 3. In this way it can be seen that the heights of the triangles of all countries to go to rank 3 are practically the same, what changes are the days elapsed to move from one rank to another; so the difference between areas will show us how fast or slow the number of people infected with COVID-19 will occur in one country compared to the others. In other words, it is possible from the SAPT analysis to observe how the pandemic spreads as it changes its range, which allows us to differentiate between the dynamics of the epidemic for any country, anytime, anywhere.

The ratio of change between the number of cases of COVID-19 and the time it takes to move from one range to another, allows evaluating the speed of infection as it spreads in different countries. For example, the comparison between Austria and Belgium shows that the spread of infection has a higher

speed in Austria because it only lasted 17 days at level 2, while Belgium was 36 days. But then, Belgium changes its level which is reflected in its speed, reaching Austria in rank 3. In this way, the derivative of the area of each right triangle (dA/dt), also allows evaluating the speed of change of the infection energy range, completely differentiating the dynamics of pandemic and COVID-19 infection, between countries.

In light of these results, it can be seen that the methodology has the ability to mathematically differentiate the pandemic dynamics between countries, finding a unique way to calculate the speed of the epidemic from the areas and differential equations.

Discussion

This is the first investigation that develops an universal methodology that spatiotemporally predicted the change velocity of COVID-19 pandemic between different countries and it is applicable to any country. This methodology was designed in the context of differential equations, whose solution allows to quantify the velocity changes of the pandemic in real time, which is useful to be applied in public health. The simultaneous evaluation of the areas in each range of the number infected in different countries allows to simplify and obviate a highly nonlinear and discontinuous process. As in quantum mechanics, that is an acasual theory, it is possible to conduct evaluations of phenomena, this methodology would be useful to asses different interventions in public health such as quarantines and similar.

The ranges established for this methodology arose from an analogy between the number infected with COVID-19 and the quantity of electrons that are distributed in different discrete energy levels (18). Furthermore, electrons can transition from one discrete energy level to another, through a process that is called quantum leap (19). This process is considered to be unpredictable considering the high randomness in quantum physics and that both theoretically and experimentally possible to predict (19). From this perspective, it was observed that the changes of the number infected with COVID-19 when a transition is made from a range to another, is that this phenomenon is as well predictable from the velocity of the spatiotemporal areas, evaluated at the end of each range, differentiating like this the dynamic of the pandemic from one country to another. Considering these results, this work rises the level of epidemiology and public health as a discipline to a fundamental science, simplifying and universalizing the dynamics of the pandemic.

It is worth noting that ancient geometry looked for the mechanical equilibrium of things, reason why it was not possible to represent movement from a geometrical reasoning (20). Thereby, Euclidean geometry is static, while differential calculus allows geometry and phenomena dynamic. For instance, if a right-angled triangle whose sides are 8 cm and 6 cm respectively, in a given moment, but then, it is required to calculate the speed with which the area expands as the first side decreases 1 cm/s and the second side increases 2 cm/s (21). This kind of thinking allows to observe how the area varies with a proportion of 5 cm²/s. The study uses universality of static Greek geometry to calculate the areas of right-angled triangle and at the same time, it applied the dynamic in the point where a transition is made from one range to

another. This union allowed to develop predictions and making objective and reproducible comparisons for the pandemic

The acausal context from which this methodology was developed, simplifies the mathematical reasoning in the SIR and SEIR models as well as with the more than 1000 deterministic epidemiological models and their cause-effect relationships (16) by a simple and direct differential equation applicable for any pandemic and / or epidemic. Additionally, a new deductive and systematic mathematical reasoning is demonstrated, with which the propagation speed of the pandemic is established in real time applicable to any country, independent of the estimation of R_0 . In addition to this, the methods used to achieve the best estimate of R_0 in different periods of time (22) and the different cities of the same country (23) are simplified.

The measure of $\frac{dy}{dt}$ in the change in the range of infected for each of the dynamics of the countries studied constitutes a speed of the number of infected for the point in which the change in range occurs, which will allow establishing Quantitative comparisons between the dynamics of the countries, in such a way that it is possible to differentiate how quickly or not the range changes, thus allowing the establishment of an objective and reproducible quantitative measure that would replace the use of R_0 , simplifying and generating a reliable measure. of the evolution of the epidemic or in this case, pandemic. This $\frac{dy}{dt}$ measure could also be calculated before the change in range or between ranges occurs, allowing to differentiate the dynamics of the number of infected between countries.

In the framework of theoretical physics and contemporary mathematics such as statistical mechanics, chaos, dynamic systems and quantum mechanics, the design of predictive methodologies from an acausal perspective (24-30), simplify the problems found in the different scenarios of Medicine. Unlike all the risk factors and the qualitative factors linked to the study of epidemics that usually make it difficult to obtain predictions. Furthermore, the analysis focused on some quantitative variables allows their interpretation to be more accurate and the impact of public health decisions can be evaluated. From this line of research other methodologies have been designed to make annual predictions of the number of infected with epidemics such as dengue and malaria in Colombia (24-27). Also, for the area of cardiology (28), in Infectiology (29) and in Immunology (30).

Declarations

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Competing interests:

The authors declare no competing interests

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Figures

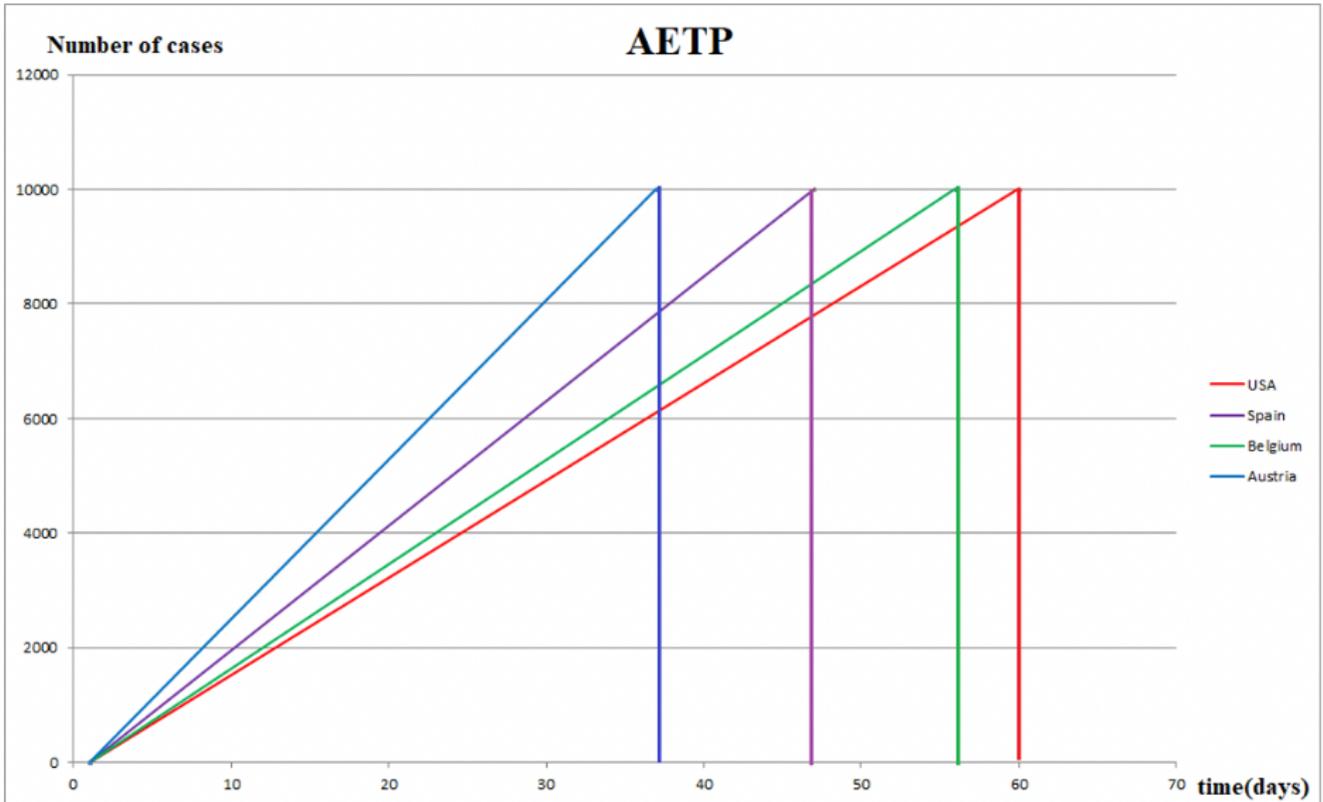


Figure 1. Right triangle of the COVID-19 pandemic for the United States of America. Where the side $\overline{AB} = 60$ (days), the side $\overline{BD} = 1.0442$ (maximum number of total infected by COVID-19 of rank 3); the side $\overline{AC} = 64$ (days); the side $\overline{CE} = 31573$ (maximum number of total infected by COVID-19 of rank 4). The area of the right triangle $ABD = 67,873$ and the right triangle $ACE = 63,146$.

Figure 1

SAPT for the change in range between 2 and 3 for the dynamics of the COVID-19 pandemic for the United States of America, Spain, Belgium and Austria.