Ternary Diagram for Visualizing Epidemic Progression

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Abstract

In this work, we develop a ternary diagram approach for visualizing the progression of a disease outbreak. Based on cumulative epidemic statistics, the fraction of patients classified as active cases (A), recovered (R), and deceased (D) at any given time is plotted on a ternary diagram. The location of the point gives the relative proportions of cases in these three categories. The trajectory of this point over time provides an alternative scale-free indication of the state of the outbreak. This technique offers an alternative to the mainstream epidemic curves that plot the number of cases against time and can reveal trends not easily detected in conventional data displays. Because it relies on relative proportions rather than absolute numbers of patients in different categories, this method is more robust to errors caused by low diagnosis and detection rates. Such insights allow better prioritization of areas where more intensive measures are needed.

Keywords COVID-19 · Epidemic curve · Non-pharmaceutical interventions · Data visualization

Introduction

The COVID-19 pandemic has escalated into a major global health crisis that has infected over a hundred million people and claimed the lives of millions of victims to date. With the limited availability of vaccines and therapeutics, most countries have resorted to implementing non-pharmaceutical interventions (i.e., community quarantines and lockdowns) to stem the spread of the virus. These measures have been largely successful in “flattening the curve,” thus preventing healthcare systems from being inundated by COVID-19 patients (Feng et al. 2020). Epidemic curves that plot the number of cases against time are the most common graphical tools for displaying and analyzing dynamic trends in an outbreak (Mathieu and Sodahlon 2017). In the current pandemic, real-time monitoring of case statistics is being used in many countries to guide lockdown measures and adjustment. Relaxation of non-pharmaceutical interventions can be justified by a

downward trend in cases, while re-imposition of stringent lockdowns can be done if a renewed surge seems imminent.

In the COVID-19 pandemic case, the use of epidemic curves is hampered by limited testing capacity or compliance. The latter factor puts a natural upper limit to the official number of cases and may thus provide a distorted picture of the extent of the outbreak. Such a problem is particularly true in the developing world due to resource constraints on testing capacity (Lee 2020). Alternative approaches have thus been proposed to address this flaw. For example, Delgado et al. (2020) argue that the cumulative mortality rate relative to the general population should also be tracked during the course of the outbreak. Monitoring excess mortality above background levels is also proposed to estimate the accurate scale of the pandemic (e.g., VANDOROS 2020); however, analysis of excess mortality is also confounded by deaths resulting indirectly from COVID-19 or the imposed control measures. For example, patients with life-threatening conditions may be unable to get proper health care due to hospital congestion. An alternative approach to tracking an outbreak’s progress provides much-needed information to guide decisions on pandemic control measures.

In this paper, we propose an alternative approach to displaying epidemic data using a ternary diagram. Such diagrams are commonly used in chemical engineering, chemistry, geology, and material science to provide graphical depictions of three-component mixtures; for example, notable process engineering applications include property integration (El-Halwagi et al. 2004) and biorefinery synthesis (Tay et al.

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2011). The next section describes the logic of this approach. We then apply this display to COVID-19 data of Spain, Italy, the USA, and the Philippines. We discuss insights that can be drawn from the alternative display and then give conclusions and prospects for future work.

Visualization approach

Our proposed visualization method is based on a ternary diagram. At any given time, the cumulative infected population can be regarded as a mixture of active cases (A), recovered patients (R), and deceased victims (D). The fractions of A, R, and D in the total infected population can be plotted in a ternary diagram, as shown in Fig. 1. The vertices A, R, and D correspond to states of the system where all patients are under treatment, recovered, or deceased, respectively. The edges of the ternary diagram indicate states of the system where all patients fall into just two of the categories. For instance, the edge between vertices R and D corresponds to a population where all patients have either recovered or died. The interior of the ternary diagram signifies states where patients fall under all three categories. The proportion of patients in the interior is determined based on this location, as illustrated in Point 2 in Fig. 1. For this example, 20% of the cases have recovered, as shown in the green line, while 10% died, as shown in the red line. The rest are active cases undergoing treatment, as shown in the orange line.

Figure 1 further illustrates the stylized trajectory of a generic outbreak. Each point in the ternary diagram represents the case distribution at a particular time (however, the time dimension is not explicitly represented in the ternary diagram). All outbreaks begin at vertex A (Point 1), corresponding to an early state before any of the patients recover or die. Furthermore, all outbreaks terminate along the edge between

vertices R and D, a state at which all patients have either recovered or died, and none are left under treatment. The exact location along this edge gives the cumulative case fatality rate of about 3% as indicated by Point 5. The trajectory of the outbreak between the logical initial and final states can be plotted based on case statistics; examples are Points 2, 3, and 4. Note that this approach is naturally scale-free since the progress is tracked based on ratios of patients in the three groups, rather than absolute headcount.

The progression of an epidemic with undetected cases can also be illustrated in Fig. 2. The presence of undetected cases can only be estimated indirectly, as they are, by definition, not directly observed. For example, the true extent of COVID-19 is generally thought to be greater than official figures based on estimates based on surplus death statistics (Russell et al. 2020). Two ternary plots are presented here; one follows the trajectory for the estimated actual number of cases, and the other follows the recorded cases. Each point represents a specific time in the epidemic. This is compared to the conventional epidemic curve, where the number of active cases is plotted against time. Three points are used as reference for the comparison of the two diagrams: one point is on the time where the number of active cases starts to rise, another is when the number of active cases peaks, and the last one is when the epidemic ends. In this case, it can be seen that the ternary diagram based on recorded cases follows a path that approximates the true (but unknown) path of the outbreak. By comparison, when conventional epidemic curves are used, there are large differences between the trajectory based on recorded cases and the real one. This shows the robustness of the representation even with the constraint on testing capacity or compliance to testing protocols. In addition, a time dimension can be added perpendicular to the plane of the ternary diagram, so that the progress of the outbreak occurs through the interior of the resulting prism. The ternary diagram can be seen as a 2-dimensional projection of such a display.

Fig. 1 Illustration of the visualization approach with five sample points

Fig. 2 Ternary diagram representation of epidemic progression with undetected cases

Illustrative example: progression of COVID-19 in selected countries

To illustrate the use of the ternary display, the progression of COVID-19 in selected countries is analyzed. The data for active cases, recoveries, and deaths as of December 22, 2020 were obtained from the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (2020). The daily proportions of cases under treatment, recovered, and deceased are plotted in the ternary diagram as A, R, and D, respectively. The countries we consider are Spain, Italy, the USA, and the Philippines.

Figure 3 shows the trajectory of different countries affected by the pandemic. Spain and Italy are selected for comparison with the curves generated by Saez et al. (2020). Each point in the ternary diagram represents the distribution of cases in a particular day. The USA has the highest number of confirmed cases worldwide and is thus included here. The Philippines is also considered a representative developing country that is not as well-endowed for the pandemic response as the other nations that are analyzed. All countries start at vertex A of the ternary diagram, representing the initial growth in the number of cases while treatment protocols and deaths are not yet present. The general initial trend sees each country's path initially arcing inward from vertex A, and then settling into a near-horizontal rightward trajectory. The latest status of each

country's COVID-19 response is indicated by the triangular point in the ternary diagram. The distances between successive points represent the rate at which the pandemic progresses in a country. For instance, two successive points in Spain's trajectory show increased recovery rates from 20 to 35% during the early course of the pandemic. The ternary diagram also indicates countries, such as the USA, where the rate of new cases is more than the rate of reports of recovered patients. As shown in the ternary diagram, the steady and progressive trajectory for the Philippines is due to combined programs of time-based recoveries, continuous lockdown, and steady infection rates. These trends indicate the need for continuous and stringent measures to control the spread of the disease.

The dynamics of the disease outbreak is also visible in the ternary diagram. The distances between successive points represent the rate at which the pandemic progresses in a country. Fig. 4 shows the trajectory of cases for Italy. Here, it can be seen that in the first six months since the start of the pandemic, there was steady progress towards managing the pandemic, with 80% of the confirmed cases having recovered by late summer. However, the next three months saw a resurgence in the number of cases; thus, the trajectory reverses direction. This reversal might be a delayed effect of the easing of the lockdowns during the summer. This part of the trajectory reflects the progression of the second wave of the pandemic.

Fig. 3 Progression of selected countries to address the COVID-19 pandemic problem

The ternary diagram indicates an improving epidemic progression if the trajectory is moving forward while a worsening epidemic progression if the trajectory is moving backwards. Finally, the trajectory was corrected in autumn, and is once again in the desirable rightward direction. The case of Italy illustrates how the ternary diagram allows the analyst to visualize the pandemic trend and draw useful insights for supporting the development or modification of public health policies. The ternary diagram indicates an improving epidemic progression if the trajectory is moving forward while a worsening epidemic progression if the trajectory is moving backwards.

Representation of the epidemic with a ternary diagram reveals important insights that conventional epidemic curves do not show. First, the progression of the epidemic in a ternary diagram is shown in two dimensions; changes in the relative numbers of active cases, recovered patients, and deceased victims are represented by the direction of

the movement of the points signifying a country's daily state. Comparison of the progress of interventions of different countries can also be made easily. Since this technique can also be applied on the scale of cities or regions within a country, prioritization in providing additional measures from shared resources can be done rapidly. Third, the dynamics are indicated by the spread of successive points along a given trajectory. The ternary diagram provides a single indicative display that tells whether a particular city, region or country is beating the pandemic. Lastly, it shows the effect of the second wave as indicated by the reversal in the direction of the trajectory.

Conclusions

We have developed a novel ternary diagram approach for displaying epidemic statistics. The advantage of this technique

Fig. 4 COVID-19 progression in Italy and selected points for analysis

compared to conventional epidemic curves is that it relies on relative proportions of active cases, recovered patients, and diseased victims, rather than absolute numbers, making it more robust to potential data errors resulting from underestimating the real number of cases. Experience with COVID-19 has shown that underestimation of the extent of an outbreak is likely in the case of a highly contagious and novel pathogen. We demonstrate this technique using the COVID-19 data of Spain, Italy, the USA, and the Philippines. The illustrative example shows how the use of this technique, along with conventional epidemic curves, can reveal insights that would not otherwise be evident. This technique relies on the process integration principle that visualization is essential for effective decision support, and it may be extended in the future to account for additional factors or dimensions using display techniques developed for other process integration problems (Shelley and El-Halwagi 2000). The method is generally applicable to all disease outbreaks and can be used at smaller geographic scales than country-level analysis. It can be used to give insights for prioritizing facilities, financial aid, and other measures to manage an outbreak.

Declarations

Conflict of interest The authors declare no competing interests.

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