

# HOW TO COUNT ILLNESS?

Basic epidemiological concepts for  
understanding the COVID-19 epidemic



**January 2021**  
**Second edition**

The Association of Schools of Public Health in the European  
Region  
(ASPHER)

# TABLE OF CONTENTS

<b>1 Numbers, proportions, ratios and rates</b>	C. Signorelli, J.M. Martin-Moreno, B. Frascella	04
<b>2 Crude and adjusted epidemiological measures</b>	C. Signorelli, J.M. Martin-Moreno, B. Frascella	07
<b>3 Point and period prevalence of a disease</b>	C. Signorelli, J.M. Martin-Moreno, B. Frascella	08
<b>4 Incidence of a disease, cumulative incidence and attack rate</b>	C. Signorelli, J.M. Martin-Moreno, B. Frascella	09
<b>5 Case fatality rate and infection fatality rate</b>	J. Pinto Da Costa	10
<b>6 Recovery rate</b>	C. Signorelli, B. Frascella	12
<b>7 Mortality rate, cumulative death rate and excess mortality</b>	J.M. Martin-Moreno, A. Wong	13
<b>8 Standardized Mortality Ratio</b>	J.M. Martin-Moreno, A. Wong	16
<b>9 Sensitivity and Specificity</b>	A. Wong	18
<b>10 Positive predictive value, negative predictive value and overall efficacy of a screening program</b>	T. Weitzel, M. Bertin	21
<b>11 Random error, bias, sample, iceberg phenomenon</b>	T. Weitzel	24
<b>12 <math>R_0</math>, <math>R_t</math> and the epidemic curve</b>	C. Signorelli, M. Bertin, T. Weitzel, B.Frascella	26
<b>13 Epidemiological surveillance</b>	M. Sheek-Hussein	30
<b>14 Epidemiological trend</b>	M. Sheek-Hussein	34
<b>15 Herd Immunity</b>	J. Pinto Da Costa	37

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## FOREWORD

*There are over a hundred definitions of epidemiology. The one I use is “the study of disease in populations”. It’s simple and easy to remember.... Epidemiologists will probably question if it’s right...*

*There has never been a greater interest in epidemiology than right now in the COVID-19 pandemic. There are have-a-go epidemiologists from all walks of life – people who use numbers for a living – mathematicians, statisticians, geographers, philosophers computer programmers, even accountants and quantity surveyors can be found showing their insights on the twitter sphere. There is some brilliant stuff out there, and new ways of presenting data hopefully giving us all new knowledge to keep people safe and stop the spread of this terrible virus. Our major newspapers have built up extensive repositories of data often shared for free, sometimes ahead of academic institutions and national governments. And in the common parlance, who would have imagined three months ago we would all be talking “epidemiology”, “ $R_0$ ”, “ $R_t$ ”, “prevalence”, “incidence”, “predictive value” and many more terms. But we must also encourage our politicians and public to get beyond a superficial understanding of the terms they are using and recognise some of the pitfalls, misconceptions and potential errors inherent in what we do.*

*It is necessary for us all to understand what we mean by these terms. Colleagues in the Association of Schools of Public Health in the European Region (ASPHER) – the oldest Association of Public Health – represent the great teaching engines of public health in Europe and beyond. This rapidly constructed compendium will hopefully help journalists, business consultants, other stakeholders and also members of the general public to develop their knowledge and expand the power of citizen science. We are all citizens of the world now, and we must all play our part in controlling and preventing the further spread of this pandemic.*

*We are now into the second edition of our introduction to epidemiology. The first edition has been widely used in many countries and translated into ten languages. I commend this new glossary to epidemiology to you all.*

*John Middleton  
President ASPHER*

# 1. Numbers, proportions, ratios and rates

## Standard definitions:

**ABSOLUTE NUMBERS:** Quantification of a phenomenon not dependent on other figures (i.e. mere counting).

**RELATIVE NUMBERS:** Values which are dependent on other figures or numbers.

**PROPORTIONS:** A type of fraction in which the numerator is included in the denominator. A proportion's values range from 0 to 1, and it can be expressed in decimals or percentage (0% to 100%).

**RATIOS:** A fraction in which the numerator is not included in the denominator.

**RATE:** A measure of the frequency of occurrence of a phenomenon in a defined population, in a given period. The components of a rate are the numerator (i.e. number of cases), the denominator (reflecting the defined population – explicit or implicit place, region, or country – and the specified time-frame in which the events occurred), and usually a multiplier (as 100, 1 000, 100 000 etc.).

$$\text{Rate} = \frac{\text{Number of events in specified period}}{\text{Person – time (Time each person was observed, totaled for all persons)}} \times 10^n$$

## Development of the concepts and examples:

The **absolute number** of cases satisfies general administrative needs such as number of hospitalization or number of deaths. To have a clearer idea of a health phenomenon, the number of cases should be divided by the reference population. The example in Table 1 refers to notified COVID-19 cases in five countries.

**Table 1.** COVID-19 cases as of November 23<sup>rd</sup> 2020

Country	Absolute number of cases	Total population	N. of cases per 100,000 population
U.S.A.	11,972,556	328,200,000	3,648
Italy	1,408,868	60,400,000	2,332
United Kingdom	1,512,049	66,600,000	2,270
Iceland	5,277	360,000	1,466
Andorra	6,256	77,000	8,125

(Source: <https://www.who.int/> Retrieved on 23 November 2020)

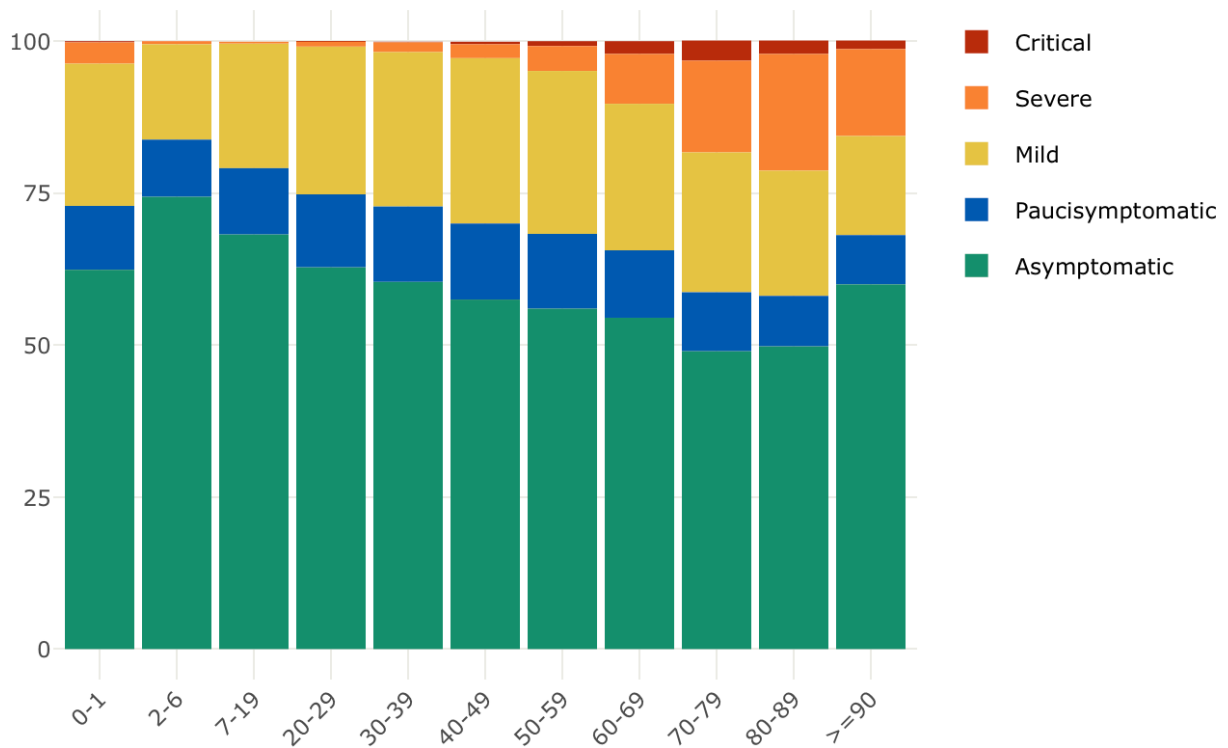


An example of a **ratio** is the male to female ratio of mortality for COVID-19. In Italy this was 3:2 according to data available on May 21th, but the distribution is now more even. (Epicentro, Istituto Superiore di Sanità)

The **proportion** of asymptomatic cases of SARS-CoV-2 infection is the number of asymptomatic individuals with a positive test result, divided by the total number of individuals with a positive test: the numerator is included in the denominator. Figure 1 shows the proportion of Italian cases which were asymptomatic, critical, severe, mild, paucisymptomatic, and not further specified.

**Figure 1.** Clinical presentation of COVID-19 cases in Italy

**Proportion (%) of COVID-19 cases of COVID-19 notified in Italy by current clinical status and age group (data available for 505120 cases)**



(Source: Italian National Institute of Health (ISS); update 12 November 2020. Available at [epicentro.iss.it](http://epicentro.iss.it))

The **rate** introduces the variable “time”. Table 2 shows the comparison of the cumulative mortality rate of six countries, which is the proportion of a population that dies over a specified time, i.e. from the start of the epidemic to November 2020.

**Table 2.** Cumulative COVID-19 crude mortality rate of selected countries (as of 23rd November 2020)

Country	Confirmed COVID-19 Deaths	Population (million)	COVID-19 Mortality Rate (deaths per million)
Belgium	15,618	11.42	1,368
France	48,384	66.99	722
Italy	49,823	60.43	824
Spain	42,619	46.72	912
Sweden	6,406	10.18	629
UK	54,751	66.49	823

(Source: <https://www.who.int/> Retrieved on 23 November 2020)

## 2. Crude and adjusted epidemiological measures

### Standard definition

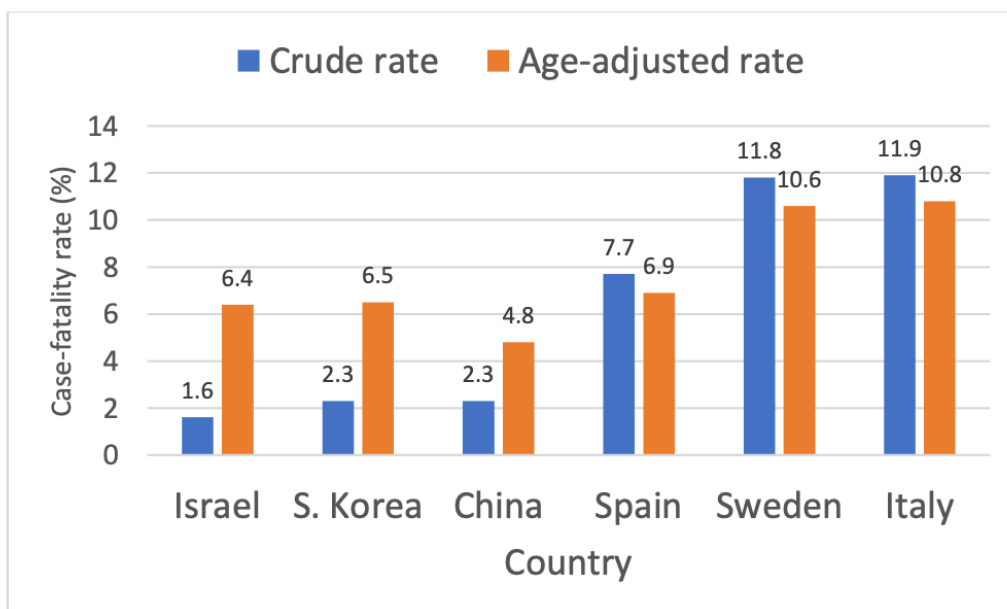
**CRUDE:** A crude measure consists of the "raw" data (i.e. cases divided by population), not adjusted for any factor that may interfere with the final interpretation.

**ADJUSTED:** The adjusted measure is standardized to take into account factors that might condition the results, and therefore distort our direct interpretation of it. We may need to adjust for age, gender, race, or any other key confounding factor.

### Development of the concepts and examples:

The **crude** mortality rate (explained later) is the proportion of the number of all deaths during the year to the average population in that year. It's easy to understand that the older the population, the higher the mortality rate will be. Instead, the **age-adjusted** measures (mortality rate in the example) takes into account the differences in population age distribution. In the example in Figure 2, the difference between Israel and Spain in crude case fatality rates for COVID-19 is reduced after adjusting for age, as the population is older in Spain than in Israel.

**Figure 2.** Crude and age-adjusted COVID-19 case-fatality rates for six countries



(Source: Green MS et al., The confounded crude case-fatality rates for COVID-19 hide more than they reveal - a comparison of age-specific and age-adjusted rates between six countries. Preprint <https://doi.org/10.1101/2020.05.09.20096503>)

### 3. Point and period prevalence of a disease

#### Standard definition

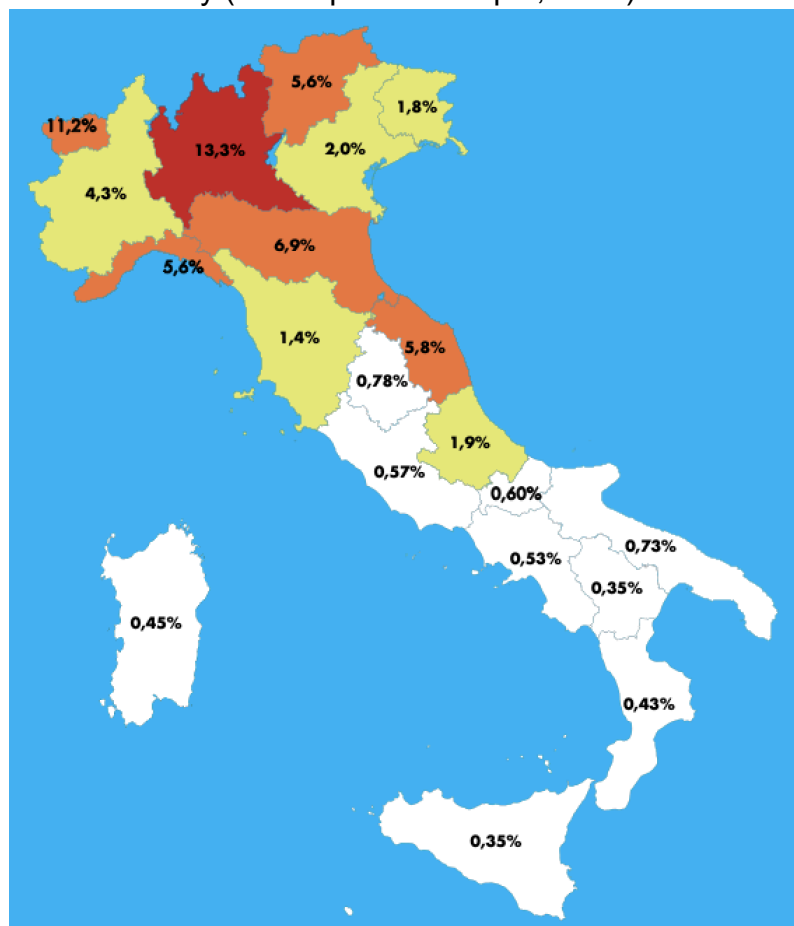
**PREVALENCE OF A DISEASE:** A measure of disease occurrence: the total number of individuals who have a disease at a particular time, divided by the population at risk of having the disease at that time. It gives a snapshot of the population at a certain point in time (**point prevalence**).

**PERIOD PREVALENCE OF A DISEASE:** The proportion of individuals with a disease during a defined period of time. To calculate a period prevalence, the most appropriate denominator for the period must be found. Prevalence differs from incidence in that prevalence includes all cases, both new and preexisting, in the population at the specified time, whereas incidence is limited to new cases only.

#### Development of the concepts and examples:

Normally it makes more sense to calculate the point prevalence (at a certain time) such as the number of people affected by a disease (i.e. 5% of the EU population is affected by diabetes). In the case of an epidemic of a new disease such as COVID-19 it might make more sense to calculate the period prevalence (how many people have become infected since the beginning of the epidemic to date). Note that for non-communicable diseases the prevalence is more stable than for infectious disease where the recovery can be quick. Figure 3 shows the estimated period prevalence of COVID-19 in Italian regions, which is the prevalence of the disease estimated in the period starting from the beginning of the epidemic to date.

**Figure 3.** The estimated period prevalence of COVID-19 in Italy (Data update 7th April, 2020)



(Source: Signorelli C et al., COVID-19 in Italy: impact of containment measures and prevalence estimates of infection in the general population, Acta Biomed 2020)

## 4. Incidence of a disease, cumulative incidence and attack rate

### Standard definition

**INCIDENCE OF A DISEASE:** The number of new cases of a disease occurring during a given period in a specified population. It could be measured in terms of **incidence proportion** (when the people in the numerator, those who develop disease, are all included in the denominator, i.e.: the entire population) or in terms of **incidence rate or person-time incidence** (when time is directly incorporated into the denominator, see above for the definition of *rate*).

Synonyms of incidence proportion are two very important terms in outbreaks research:

**CUMULATIVE INCIDENCE:** The proportion of the population at risk for a disease and that develops the disease during a specified interval of time.

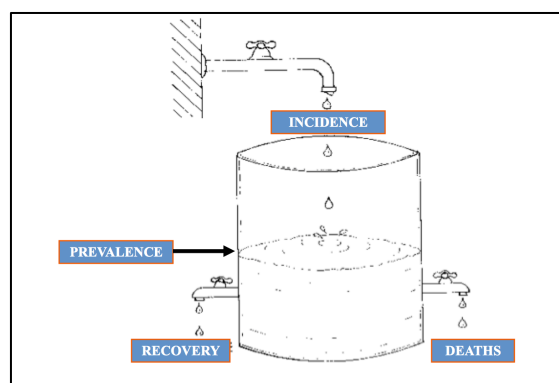
**ATTACK RATE:** The proportion of a group that experiences the outcome under study over a given period, generally very short (e.g., the incubation period during an outbreak).

### Development of the concepts and examples:

Normally, incidence is calculated per year per 1 000 or 100 000 population depending on the frequency of the disease. In the case of an epidemic of a new disease such as COVID-19 it makes more sense, at least initially, to present data considering the cumulative incidence.

The underlying concepts representing incidence and prevalence are interrelated. Prevalence measures how much of a disease or a condition is spread in a population at a given time, and is a function of the incidence (the rate of occurrence of new cases) and the average duration of the condition (the length of the process or disease). Thus, incidence conveys information about the risk of contracting the disease, whereas prevalence indicates how widespread the disease is (Figure 4).

**Figure 4.** Relationship between incidence and prevalence



(Source: Signorelli C, Elementi di metodologia epidemiologica, Società Editrice Universo, 7<sup>th</sup> edition)

## 5. Case fatality rate and infection fatality rate

### Standard definitions

**CASE FATALITY RATE (CFR):** The proportion of people that die of a disease, among all people affected by that disease i.e. cases. The numerator is the number of cause-specific deaths and the denominator is the number of diagnosed cases (incident cases) of that condition. It measures the severity of the condition. These are some examples of CFR for renowned diseases:

- *Rabies*: 100%
- *Pancreatic cancer*: 90%
- *Meningococcal disease*: 10%
- *Influenza*: 0.1%

**CRUDE CFR:** The CFR without adjustment. The formula is:

$$CFR(\%) = \frac{\text{Number of disease-specific deaths among the incident cases}}{\text{Number of incident cases during a specified period of time}} \times 100$$

**ADJUSTED CFR:** The CFR is adjusted to take into account confounding factors that might alter the results, e.g., age, under-reporting or delay from hospitalization to death. Statistical techniques are used to adjust the rates among the populations to be compared.

**ESTIMATED CFR:** When the total number of cases is not completely known, it can be estimated for example from the number of deaths. If there is a high number of undiagnosed cases, the CFR would be overestimated. According to the latest estimates, the crude CFR of COVID-19 varies between 1.6% and 11% (Green MS et al., 2020) while the estimated CFR varies between 0.5% and 1.1% (Russel TW, et al. 2020).

**INFECTION FATALITY RATE (IFR):** The proportion people that die from an infection, among all the people with that infection. The numerator is the number of infection-specific deaths and the denominator is the number of infections. It measures the severity of the condition. The formula is:

$$IFR(\%) = \frac{\text{Number of infection-specific deaths among the incident infections}}{\text{Number of incident infections}} \times 100$$

It is not used very much during a pandemic, during which we only account for the diagnosed cases. It will be more useful when wide serological studies will be performed.

### Development of the concepts and examples:

The CFR and IFR are not true rates, but in fact proportions, i.e. the numerator is restricted to deaths among the cases included in the denominator.

Considering the data from WHO on 24<sup>th</sup> of November 2020, since the beginning of the epidemic, there were 58,900,547 cases worldwide and 1,393,305 deaths.

So, the CFR would be calculated as follows:

$$CFR = \frac{1,393,305}{58,900,547} \times 100 = 2.4\%$$

CFR is a poor indicator of mortality risk in an ongoing pandemic, since the denominator refers only to a part of the cases (those who have been diagnosed and notified) and depends on the case definition used, the testing criteria and the capacity of testing across countries, making data hard to compare.

Because nucleic acid testing is limited and currently available primarily to people with significant indications of and risk factors for COVID-19, and because a large number of infections with SARS-CoV-2 result in mild or even asymptomatic disease, the IFR is likely to be significantly lower than the CFR.

## 6. Recovery rate

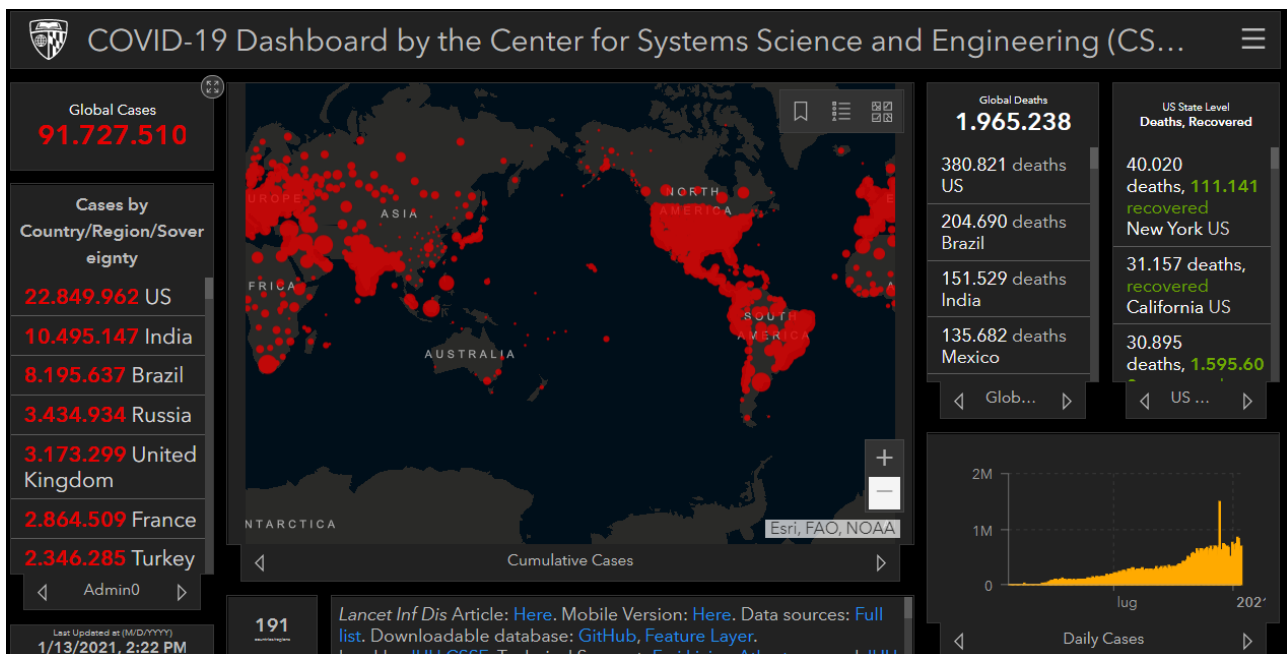
### Standard definition

**RECOVERY RATE:** The rate of transition from the state of being infected to the state of absence of disease.

### Development of the concepts and examples:

Recovery rate is one of the most frequently disseminated pieces of data during the COVID-19 epidemic compared to the number of those newly infected. In the first phase of the epidemic, the number of patients recovered was less than the new cases (recovery rate less than incidence rate), after the peak epidemic was reached, the patients who recovered exceeded new cases.

**Figure 5** Johns Hopkins University dashboard of the world's situation of COVID-19 cases



(Source: COVID-19 Dashboard by the Center for Systems Science and Engineering at Johns Hopkins University, accessed on 13 January 2021)

On the right side of the dashboard (Figure 5) the cumulative number of deaths and of recovered cases can be found.

There is a delay in the confirmation of recovered cases that is due to two factors. First, countries have different criteria to define a case as recovered; for example, in Italy a case can be considered recovered only after there is evidence of two negative swab tests done 48-hours apart. Second, infected individuals can remain contagious and shed the virus for a relatively long time even after they have recovered from the COVID-19 clinical illness.



## 7. Mortality rate, cumulative death rate, excess mortality

### Standard definition

**MORTALITY RATE:** is a measure of the number of deaths (in general, or due to a specific cause) in a particular population, in relation to the size of that population, per unit of time.

The numerator is the number of persons dying during the given time period; the denominator is usually expressed as the size of the population among which the deaths occurred (usually estimated as the midyear population).

$$\frac{\text{Number of deaths during a given period}}{\text{Number of persons at risk of dying during the period}} \times 10^n$$

We may speak about **crude death rates** (total number of deaths during a given time interval divided by mid-interval population per 1,000 or 100,000), or **cause-specific death rate** (number of deaths assigned to a specific cause during a given time interval).

**CUMULATIVE DEATH RATE:** The proportion of a group that dies over a specified time interval. It is the incidence proportion of death.

**EXCESS MORTALITY:** Mortality that is above what would be expected based on the non-crisis mortality rate in the population of interest (i.e. in “normal conditions”). Excess mortality is thus mortality that is attributable to the crisis conditions.

$$\text{Excess Mortality} = \text{Observed Mortality in Crisis} - \text{Expected Mortality in Non-crisis}$$

### Development of the concepts and examples:

The mortality rate of a country is the number of deaths divided by the population, usually expressed in deaths per million inhabitants. During the COVID-19 epidemic the definition *death toll* was used, especially in the US to indicate the number of people who die because of an event such as a war or an accident.

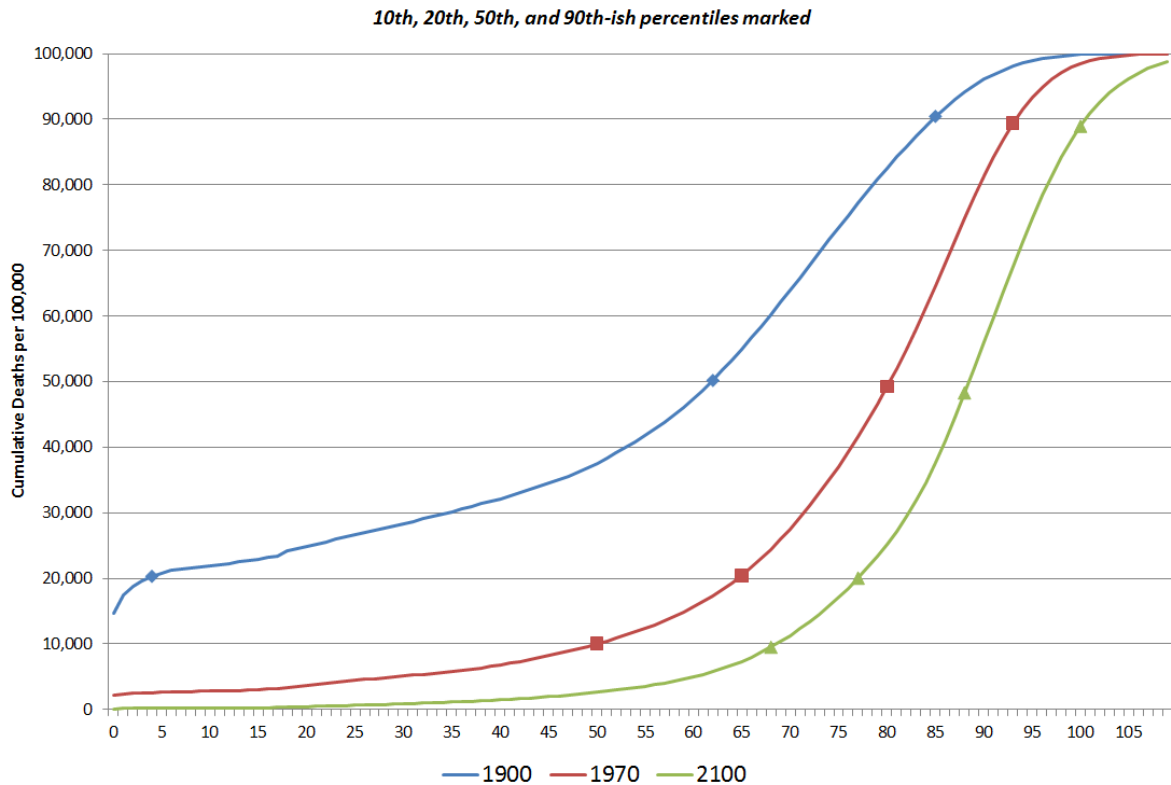
Cumulative death rate refers to the proportion of individuals alive at the start of a specific period of time that dies over that period.

An example of cumulative mortality rate can be found on page 5 (Part 1: Absolute numbers, proportions and rates), where Table 2 shows the comparison among the cumulative mortality rate of some countries.

The concept of cumulative death rate is illustrated by the graph in Figure 6, which shows 3 groups of people: born in 1900, 1970, and 2100 (projected data). At the beginning of life, deaths per 100,000 were low for all three groups. As time goes by, people die and the cumulative deaths increase. At around 100-105 years old, the cumulative death rates are approaching 100% for all three groups. When we compare the curves of the 1900 cohort and the 1970 cohort, we can see that cumulative death rate was higher for the 1900 cohort

than the 1970 cohort at all ages, meaning that throughout a life time, people born in 1970 survived better than those born back in 1900.

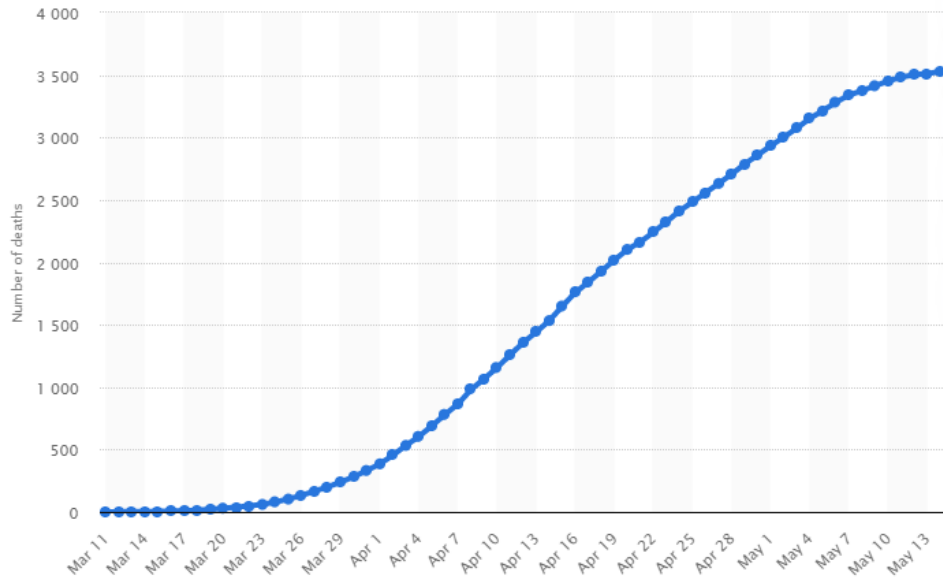
**Figure 6.** Male cumulative mortality curves, by cohort, actual and projected.



(Source: Meep. Mortality Monday: How young is “So young to die”?; Retrieved from: <https://stump.marypat.org/article/676/mortality-monday-how-young-is-so-young-to-die>)

Cumulative death rate is not widely used in the reporting of COVID-19 burden but cumulative number of COVID-19 deaths is often used as a descriptive measure. Figure 7 presents an example from Sweden while in Figure 8 the estimated excess of deaths in NY City are illustrated.

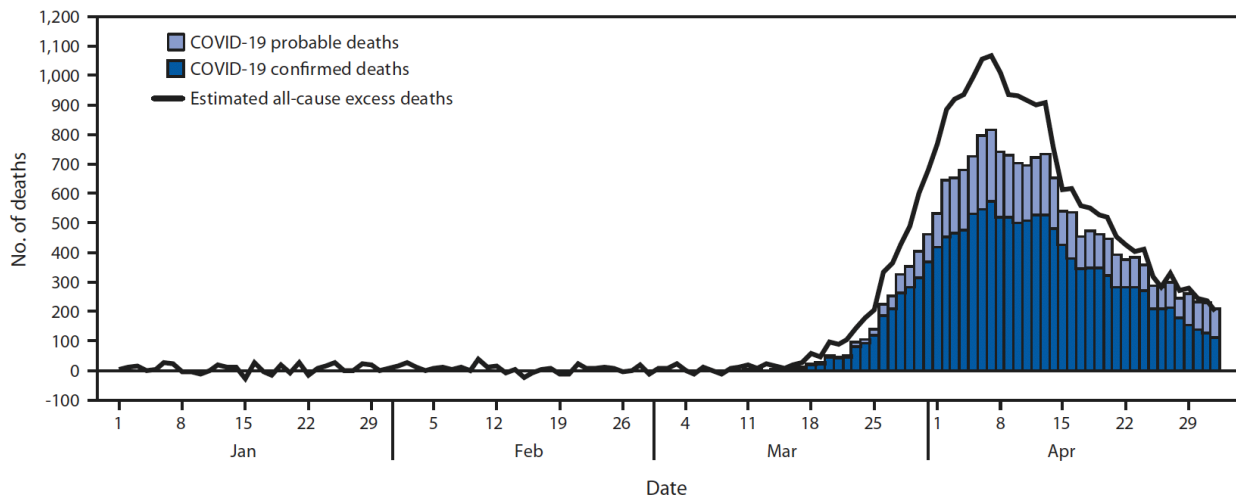
**Figure 7.** Cumulative number of COVID-19 deaths in Sweden (as of mid-May 2020)



(Source: Statista. Cumulative number of coronavirus (COVID-19 deaths in Sweden since March 11, 2020; Retrieved from: <https://www.statista.com/statistics/1105753/cumulative-coronavirus-deaths-in-sweden/>)

**Figure 8.** Total estimated excess deaths in NY City (as of 2nd-May 2020)

FIGURE. Number of laboratory-confirmed\* and probable† COVID-19–associated deaths and total estimated excess deaths<sup>§</sup> — New York City, March 11–May 2, 2020



\* Death in a person with a positive laboratory test for SARS-CoV-2 RNA.

† Death in a person without a positive test for SARS-CoV-2 RNA but for whom COVID-19, SARS-CoV-2, or a related term was listed as an immediate, underlying, or contributing cause of death on the death certificate.

§ Total excess all-cause deaths were calculated as observed deaths minus expected deaths as determined by a seasonal regression model using mortality data from the period January 1, 2015–May 2, 2020.

(Source: MMWR, 15 May 2020)

The accuracy of excess mortality projected based on modeling depends largely on the assumptions of the projection method. Since COVID-19 is an ongoing outbreak and the data are evolving continuously, assumptions that are true today may not be true after a certain period when new data emerge.

## 8. Standardized Mortality Ratio

### Standard definition

**STANDARDIZED MORTALITY RATIO (SMR):** The ratio of the number of deaths observed in the population over a given period, to the number that would be expected over the same period if the study population had the same age-specific rates as the standard population. If the ratio is greater than one, it is interpreted as excess mortality in the study population. If less than one, the study population is interpreted as having lower than expected mortality. The ratio can be directly expressed as the result of that quotient, or expressed by a factor of 100 (in other words, multiplied by 100).

### Development of the concepts and examples:

During the COVID-19 epidemic, the SMR was often used (with its confidence intervals) to evaluate the potential excess mortality of the populations affected by the epidemic considering the age distribution of the population, because older populations naturally have a tendency to have higher observed total mortality.

The most frequently used standardization is age standardization because age is an important risk factor for health outcomes. It can be misleading if we compare the mortality of two countries with very different age structure. For many diseases, mortality tends to be higher in an older population. Table 3 compares mortality adjusted by age profile in three countries.

**Table 3.** Mortality and age structure in England, Belgium and France

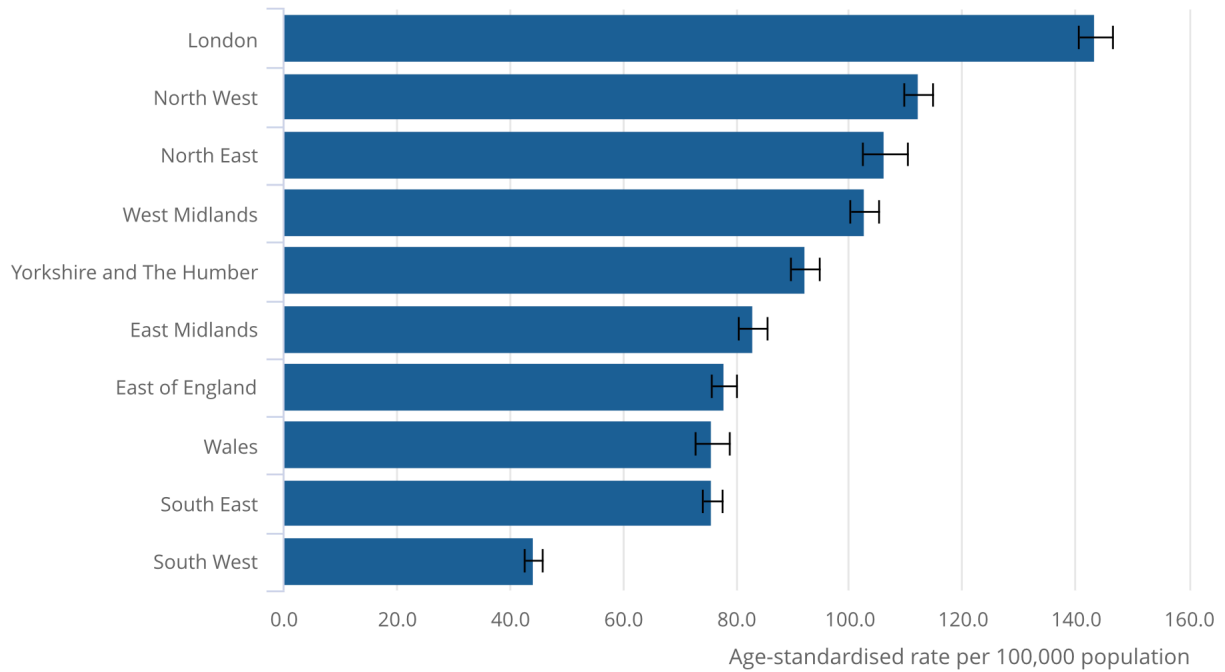
	ENGLAND				BELGIUM				FRANCE		
	Deaths	Population (000)	Deaths per million pop		Deaths	Population (000)	Deaths per million pop		Deaths	Population (000)	Deaths per million pop
80+	533	2439	219	75+	534	1042	512	1444	6231	232	
60-79	261	9394	28	65-74	119	1190	100	320	7315	44	
40-59	271	14161	19	45-64	45	3102	15	151	16991	9	
20-39	66	14304	5	18-44	5	3642	1	16	19325	1	
0-19	1	6290	0	0-17	1	2615	0	0	15411	0	

(Source: Neil Monnery. Adjusting Covid-19 expectations to the age profile of deaths; Retrieved from: <https://blogs.lse.ac.uk/businessreview/2020/04/09/adjusting-covid-19-expectations-to-the-age-profile-of-deaths/>)

After age-standardisation, the SMR can then be compared directly and age can no longer explain the apparent difference, instead, other demographic factors, such as gender and socioeconomic status, or health system differences might play a role in the difference in SMR.

Figure 9 is an example, comparing the COVID-19 SMRs in different regions in the UK.

**Figure 9.** Age-standardised mortality rates for deaths involving the coronavirus (COVID-19), per 100 000 population, England and Wales, by country and region (1 March-31 July 2020)



(Source: Office for National Statistics. Deaths involving COVID-19 by local area and socioeconomic deprivation: deaths occurring between 1 March and 17 April 2020; Retrieved from: <https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths/bulletins/deathsinvolvingcovid19bylocalareasanddeprivation/deathsoccurringbetween1marchand31july2020>)

## 9. Sensitivity and Specificity

### Standard definition

**SENSITIVITY OF A TEST:** The probability that a diseased person (case) in the population tested will be identified as having the disease by the test. Sensitivity is thus the probability of correctly diagnosing a case, or the probability that any given case will be identified by the test (synonym: true-positive rate).

**SPECIFICITY OF A TEST:** The probability that a person without the disease (non-case) will be correctly identified as not having the disease by the test. It is thus the probability of correctly identifying a non-diseased person with a test (synonym: true-negative rate).

The relationships are shown in Table 4.

**Table 4.** Contingency table (2 entrance table) used to calculate sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV)  
(see section 10 for explanation of PPV and NPV)

		True status (gold standard)		Total
		Diseased	Not diseased	
Screening test results	Positive	a	b	a+b
	Negative	c	d	c+d
Total		a+c	b+d	a+b+c+d

- a. Diseased individuals detected by the test (true positives)
- b. Non-diseased individuals who tested positive (false positives)
- c. Diseased individuals not detectable by the test (false negatives)
- d. Non-diseased individuals who tested negative (true negatives)

$$\text{Sensitivity} = \frac{a}{a + c}$$

$$\text{Specificity} = \frac{d}{b + d}$$

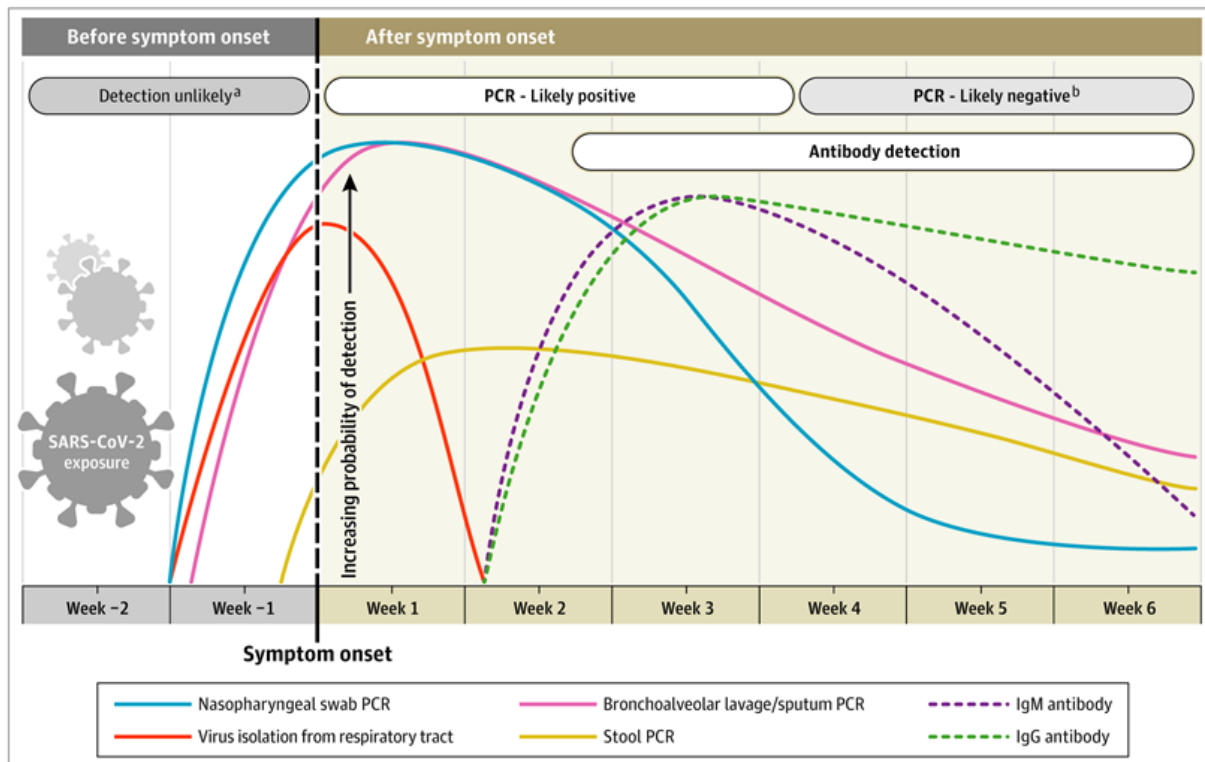
### Development of the concepts and examples:

No test is perfect and there is often a trade-off between test performance and time or cost of the test. It is important to know when to use what type of test. Various screening and testing methods are employed in COVID-19 and how a specific test is used hinges on its sensitivity and specificity. Mass screening aims at testing a large population and individuals with a positive result will receive another test for confirmation; therefore, it is important to use a highly sensitive test to minimize the probability of missing any case and it is less of a concern even if you have some false positive. For confirmatory purpose, you would prefer a highly specific test to exclude the non-diseased.

COVID-19 can be tested by detecting the viral RNA in the nasopharynx or by detecting the antibodies against the virus in blood.

Viral RNA detection is highly specific and is therefore used in many countries to confirm a case in COVID-19. However, the timing of the test and how the sample is collected may affect the sensitivity. It is best to test an individual around the onset of symptoms as the concentration of virus is thought to be highest around this time point in the course of disease. Nasopharyngeal swab is recommended because the virus concentration is the highest in this area in most patients, whereas other swabs or saliva may give lower sensitivity. That means if a person is tested too early (before symptom onset) or if the sample is not collected in the best way, the likelihood of false negative increase and you are more likely to miss a case. When exposed to COVID-19, IgM is the earliest antibody produced, which is followed by a large amount of IgG. Therefore, it takes 3 to 7 days for an individual infected by SARS-CoV-2 to produce detectable levels of IgM and most patients have detectable IgG by 14 days following onset of symptoms (see Figure 10). This means, such tests have low sensitivity in the early phase of infection. Due to the time lag, the antibody test is not used for identifying cases for isolation and treatment but it can be useful in mass screening when one is interested in finding out the regional or nation-wide disease burden, including the asymptomatic cases. It is worth noting that the antibodies remain in the body for a period of time and thus can be used to check for previous infection.

**Figure 10.** Trend analysis of SARS-CoV-2 RNA, antigen and antibodies



(Source: Sethuraman N, Jeremiah SS, Ryo A. Interpreting Diagnostic Tests for SARS-CoV-2. JAMA.2020;323(22):2249–2251. doi:10.1001/jama.2020.8259)

Sensitivity and specificity of antibody tests can vary greatly depending on the manufacturers. Table 5 shows the sensitivity and specificity of some commercially available SARS-CoV-2 antibody tests.

**Table 5.** Sensitivity and specificity of some commercial tests

<b>COMMERCIAL TEST</b>	<b>SENSITIVITY</b>	<b>SPECIFICITY</b>
<b>ARTON LABORATORIES</b>	42.2%	97.9%
<b>ACRO BIOTECH</b>	83.3%	100%
<b>AUTOBIO DIAGNOSTIC</b>	93.3%	100%
<b>DYNAMIKER</b>	90.0%	100%
<b>CTK BIOTECH</b>	90.0%	100%

(Source: Ricco M et al., 2020)



## 10. Positive predictive value, negative predictive value and overall efficacy of a screening programme

### Standard definition

**SCREENING:** The presumptive identification of unrecognized disease or defect by the application of tests, examinations or other procedures which can be rapidly applied. Screening tests sort out apparently well persons who probably have a disease from those who probably do not. A screening test is not intended to be diagnostic. Persons with positive or suspicious findings must be referred to their physicians for diagnosis and necessary treatment. The characteristics of a screening test must include accuracy, estimates of yield, precision, reproducibility, sensitivity and specificity, and validity.

**ACCURACY:** The ability of a diagnostic test to correctly classify the presence or absence of the disorder. The diagnostic accuracy of a test is usually expressed by its sensitivity and specificity.

**PREDICTIVE VALUE OF A SCREENING TEST:** The probability of the disease given the results of the test. Predictive values of a test are determined by the sensitivity and specificity of the test and by the prevalence of the condition for which the test is used.

**POSITIVE PREDICTIVE VALUE (PPV):** The probability that a person with a positive test result is a true positive (e.g., does have the disease).

**NEGATIVE PREDICTIVE VALUE (NPV):** The probability that a person with a negative test result is a true negative (e.g., does not have the disease).

Taking into account Table 5 (in the previous section), the PPV and NPV formulas are the following:

$$PPV = \frac{a}{a + b}$$

$$NPV = \frac{d}{c + d}$$

**PRECISION:** Relative lack of random error.

**REPRODUCIBILITY:** A test that gives results that are identical or closely similar each time it is conducted.

**VALIDITY:** Relative absence of bias or systematic error.

**ADHERENCE:** Usually expressed as the proportion of people who undergo the screening test on all target population; A measure of participation in a screening program

### Development of the concepts and examples:

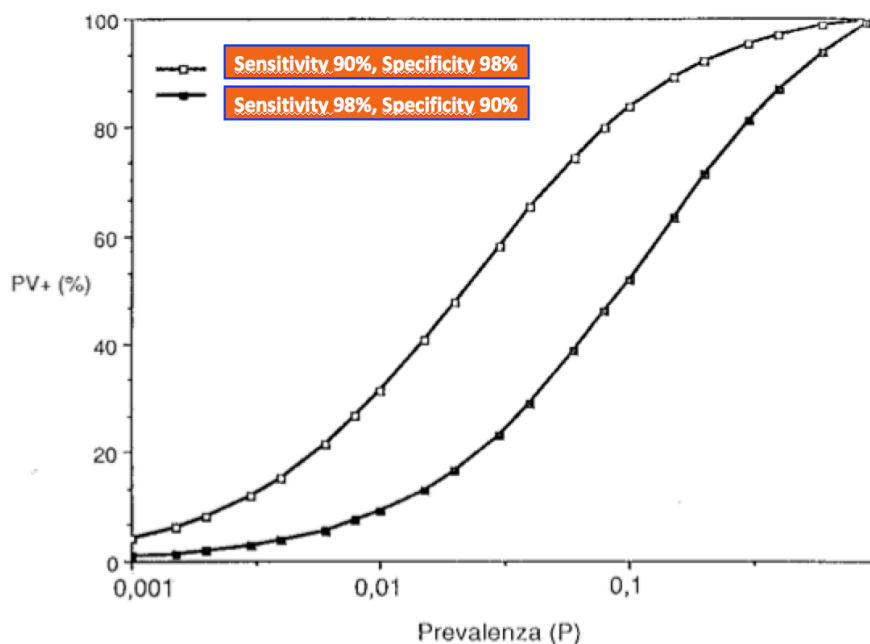
A significant proportion of COVID-19 cases result from the transmission of the virus from asymptomatic or pre-symptomatic cases. **Screening** is a widely employed strategy that consists of testing large populations to find these unrecognized infections. Their aim is to identify as many cases as possible and estimate the spread in the population; a high participation rate in the screenings is therefore essential.

A screening test must meet high quality standards to be efficient: it must be able to correctly detect the presence of the virus, accurately identify cases and be precise to ensure minimal error. Additionally, the test must be reproducible, meaning that it gives consistent results each time it is used.

However, a test almost never correctly diagnoses everyone tested. Sometimes they return a *false positive*, a test result that wrongly identifies a person as being infected or a *false negative*, a test result that fails to identify a person who is infected. To ascertain the likelihood of a positive to be truly diseased or a negative to be truly non-infected, the **predictive values** of these tests are calculated. The predictive values are determined by the specificity and sensitivity of the test (see section 9) but are mainly influenced by the prevalence of the disease in the population considered (see Figure 11). The higher is the prevalence, the higher is the

Many viral tests and antibody tests for COVID-19 are currently being developed. However, they vary in quality and predictive value, which influences the efficiency of screening programmes and can be variable in different populations.

**Figure 11.** Relationship between positive predictive value and prevalence ( $\log_{10}$  scale) of a disease in a population screened

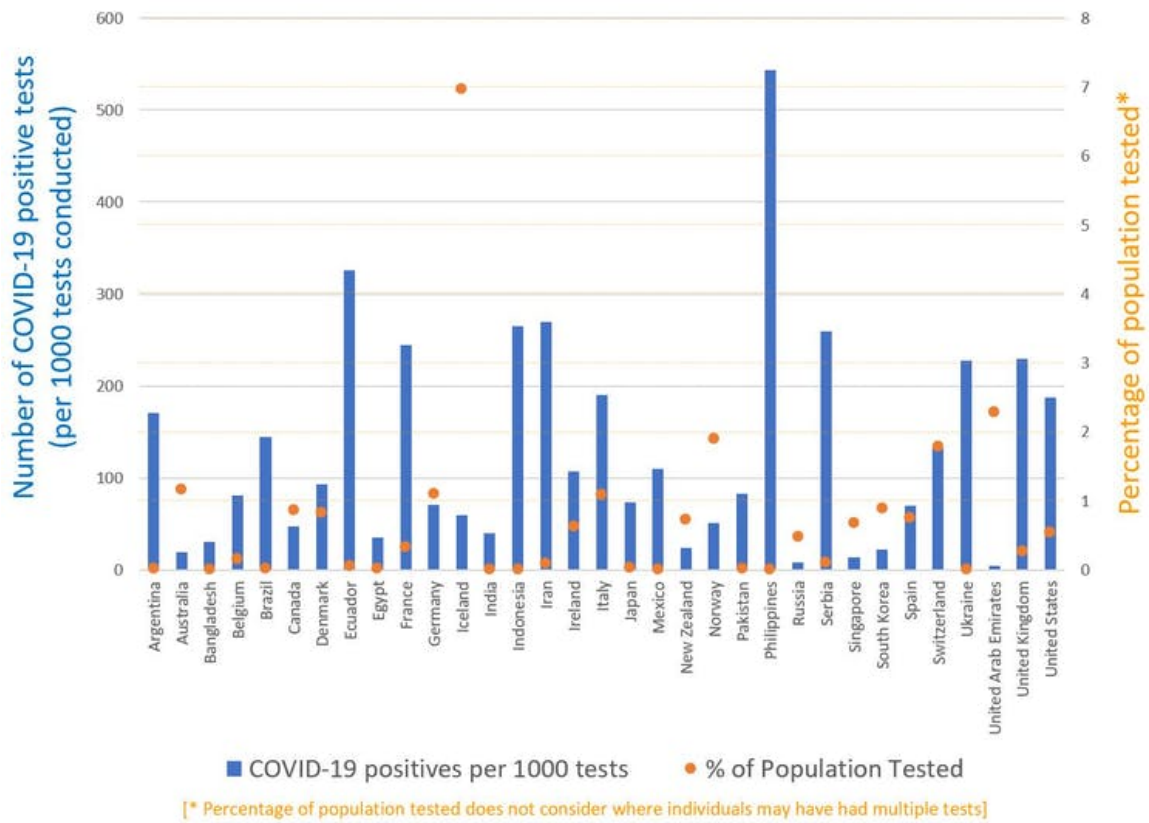


(Source: Signorelli C, Elementi di metodologia epidemiologia, Società Editrice Universo, 2011)

When interpreting data on case numbers, it is important to compare these results to the total number of tests conducted and to the proportion of the population that has been

tested. As has been observed for COVID-19, screening can vary hugely, both between countries and over time (see Figure 12).

**Figure 12.** Relationship between number of positive tests and percentage of population tested (Update April 6<sup>th</sup>, 2020)



(Source: Osborn M. Available at <https://theconversation.com/the-bar-necessities-5-ways-to-understand-coronavirus-graphs-135537>)

## 11. Random error, bias, sample, iceberg phenomenon

### Standard definition

**RANDOM ERROR:** Error occurs because of random variations in observation or measurement. Increasing the sample size of a study can reduce random error, but cannot reduce bias.

**BIAS:** Systematic deviation of results from the truth. An error in the conception and design of a study (or in the **collection, analysis**, interpretation, reporting, publication, or review of data) leading to results or conclusions that are systematically different from truth.

**SELECTION BIAS:** A bias caused by the modality in which the sample was selected. E.g., when the study sample is not representative of the population because some characteristics are over- or under-represented in the study population.

**INFORMATION BIAS:** A bias caused by misclassification of the status of subjects included in the study (e.g., symptoms, risk factors).

**SAMPLE:** A subset of the population that is included in the study.

**ICEBERG PHENOMENON:** That portion of disease which remains unrecorded or undetected despite physicians' diagnostic endeavors and community disease surveillance procedures is referred to as the "submerged portion of the iceberg." Detected or diagnosed disease is the "tip of the iceberg." The submerged portion comprises disease not medically attended, medically attended but not accurately diagnosed, and diagnosed but not reported.

### Development of the concepts and examples:

When epidemiological studies about COVID-19 are conducted, researchers chose a group of individuals that they want to study in order to answer their research question, the **population**. From this target population, a number of individuals is selected to participate in the study. This is called a **sample**. This sample should be representative of the population so that the findings allow researchers to draw conclusions about various aspects of COVID-19 in the target population.

The data collection process of a study can be flawed by random error and bias.

**Random errors** can occur because of unknown and unexpected changes in observation and measurement. Having a larger sample could minimize the effect of such errors on the study results.

**Bias** is a systematic error which results in misleading study results. It can occur in a number of ways:

1. **Selection bias** refers to issues with the way the sample for a study is selected, making it non-representative for the target population. The wide differences in studies of COVID-19 deaths across countries can be attributed to selection bias because each country has a different way of recording their deaths.

Selection bias is clearly present when using reported cases for the denominator of rates for COVID-19. If only those with more severe symptoms are tested this will affect the denominator of the incidence rates and case-fatality rates. It will thus depend on

the testing strategy of each country. If more mild cases are identified, this is likely to reduce the incidence and case-fatality rates.

Selection bias may also affect the numerator if only deaths occurring in hospital are reported.

**2. Information bias** arises from the misclassification of symptoms or risk factors of study participants. This is often the result of incomplete medical records, testing errors or the misinterpretation of records. This is a pitfall for COVID-19 studies because exposed/infected individuals could be classified as non-exposed/non-infected and vice versa.

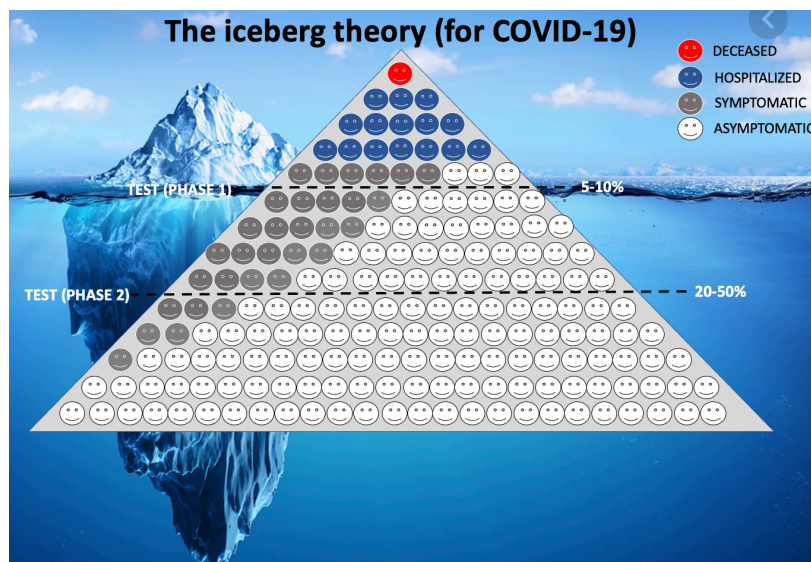
Information bias can be present in the numerator of the COVID-19 incidence and case-fatality rates, due to the way in which the cause of death is coded. This could be particularly problematic in elderly people with multiple co-morbidities, leading to difficulties in assigning the true cause of death.

Information bias may also occur in the denominator of incidence and case-fatality rates. The inclusion and exclusion of COVID-19 cases will depend on the sensitivity and specificity of the diagnostic procedures.

**3. Lag time bias** occurs since there is a lag time between the reporting of the case and the death, which can occur up to weeks later. In country reports, cases and deaths are usually reported at the same time, so the cases in the denominator are usually an overestimate of the true denominator, which should be the number of cases reported sometime earlier. This will have a more dramatic effect when the number of cases is rising rapidly.

The “iceberg phenomenon” is a metaphor that can be used to explain that a health phenomenon is not always observed and reported. This is quite evidently true for COVID-19 where only a small proportion of cases is known (the tip of the iceberg) (see Figure 13). The submerged part below water represents all cases that remain undetected or unrecorded. This comprises asymptomatic or mild cases, but also cases which are not medically attended or properly diagnosed. This number can be 10 to 25 times higher than the reported cases of COVID-19, highly dependent upon the number of tests performed.

**Figure 13.** Visualization of the iceberg phenomenon



(Source: Signorelli C, 2020)

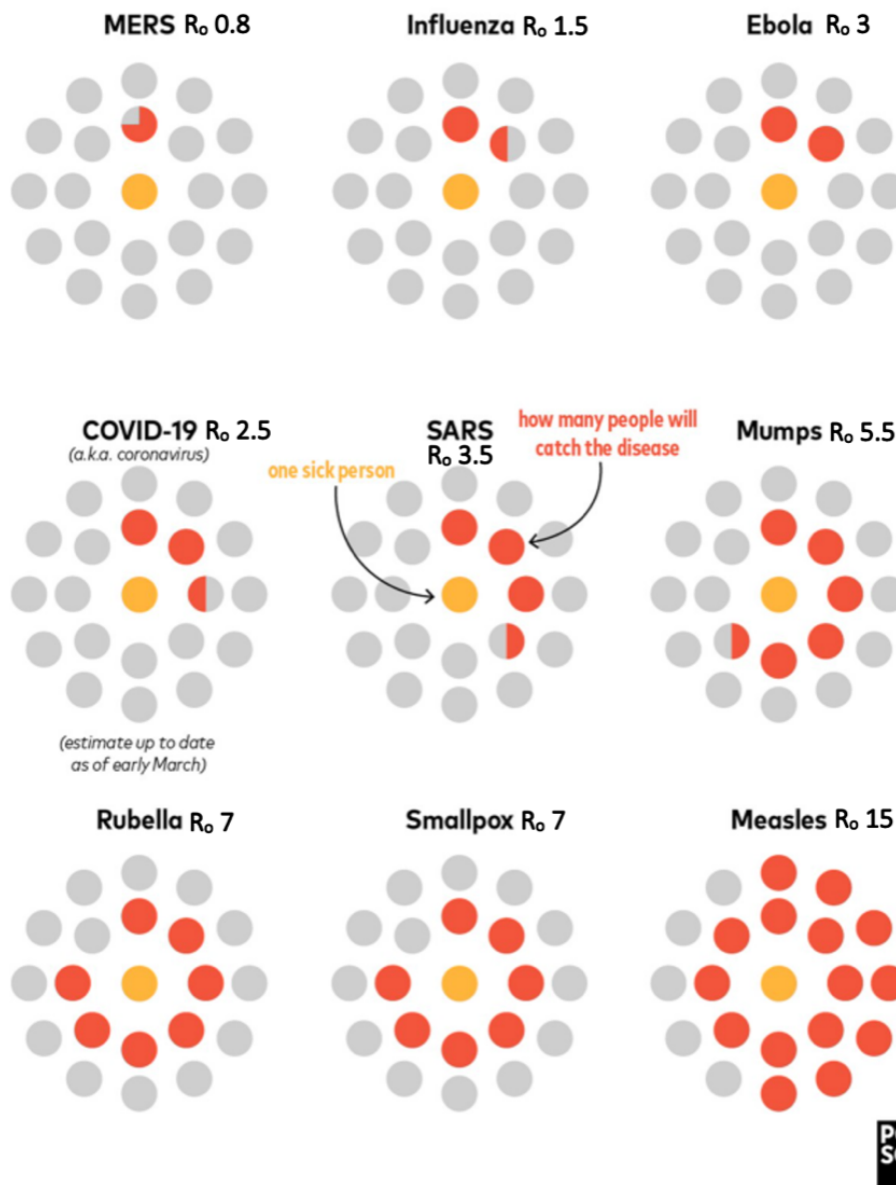


## 12. $R_0$ , $R_t$ and the epidemic curve

### Standard definition

**BASIC REPRODUCTION NUMBER ( $R_0$ ):** A measure of the number of infections produced, on average, by an infected individual in the early stages of an epidemic (when, virtually, all contacts are susceptible).

**Figure 14.** Values of  $R_0$  of selected infectious diseases



Coronavirus is on par with SARS in terms of infectiousness. Infographic by Sara Chodosh

(Source: Francis MR, Just how contagious is COVID-19? This chart puts it in perspective. Available at <https://www.popsci.com/story/health/how-diseases-spread/>)

**EFFECTIVE REPRODUCTION NUMBER ( $R_t$ ):** The value of the  $R_0$  index can be changed as a result of the introduction of preventive measures (i.e. physical distancing, use of masks, etc.) or following a reduction in the number of susceptible people due to post-infection acquired immunity or to vaccinations. This reproduction number is defined as  $R_t$ , that is the actual transmission rate of the virus at a given time  $t$ . This appropriately denotes the effective reproduction number during an evolving epidemic such as COVID-19.

**EPIDEMIC CURVE:** A graphic plotting of the distribution of cases by time of onset, in a linear or logarithmic scale. When presented in a logarithmic scale, the vertical axis is graduated by orders of magnitude (1, 10, 100, 1,000), and this is the preferred method to plot an epidemic that is growing exponentially, so that large numbers do not skew the entire graph.

Development of the concepts and examples:

An **epidemic curve** of an outbreak is a statistical graph that visualizes the number of cases and their temporal progression. It commonly shows the number of new cases on the vertical axis and the corresponding date on the horizontal axis. Figure 15 presents an example of the global epidemic curve of COVID-19.

**Figure 15.** Total cases of COVID-19 worldwide in linear (left) and logarithmic (right) scales (as of November, 13 2020)



(Source: Retrieved from <https://www.worldometers.info/coronavirus/worldwide-graphs/>)

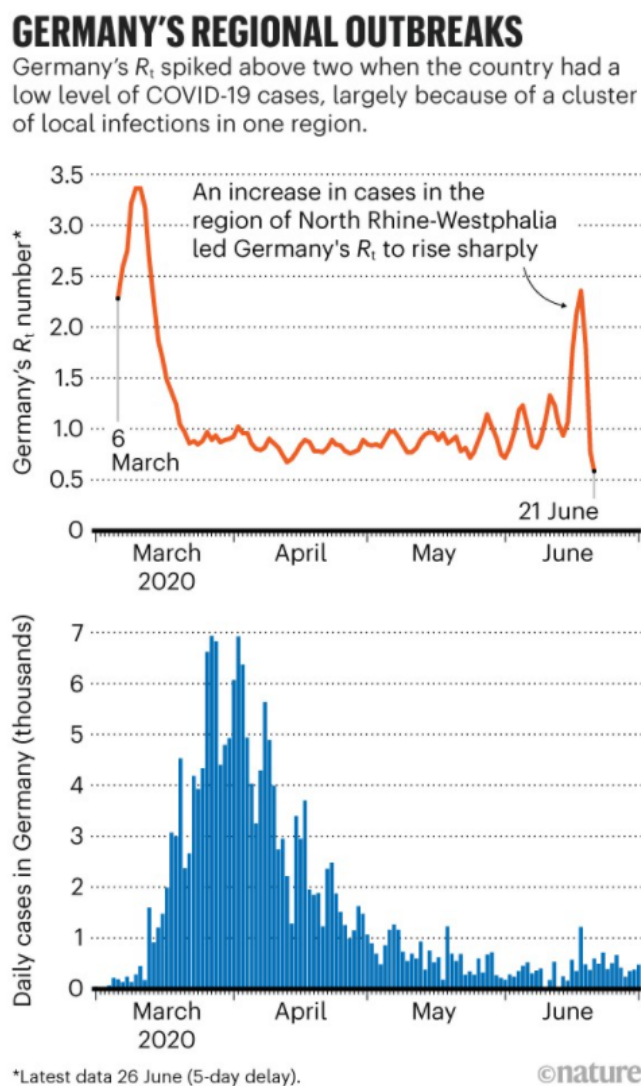
The progression of the epidemic curve of COVID-19 depends on the **basic reproduction number  $R_0$**  (pronounced *R nought*), which measures the potential for the virus to spread in the population.  $R_0$  can be defined as the average number of new cases generated by an infectious case in a totally susceptible population. As the virus that causes COVID-19, SARS-CoV-2, is a novel virus, the world population has not been exposed before, effectively making everybody susceptible.

Generally speaking,  $R_0$  depends on the number of days people are infectious, the number of susceptible people they interact with and the chance of transmission during such an interaction.

An epidemic only develops if  $R_0$  is greater than 1. This means that every infected person on average infects more than one new person. Modelling studies currently estimate the  $R_0$  of COVID-19 at between 2 and 3, but this is subject to change.

A crucial point for the calculation of  $R_0$  and  $R_t$  is to have reliable information on the total number of infected people in the various geographical areas and on the date of infection or onset of symptoms, data not easy to obtain in the case of the COVID-19 epidemic. Therefore, in this context,  $R_0$  and  $R_t$  were estimated only at a later time and the usefulness of using the  $R_t$  index to predict the evolution of the epidemic – as it was proposed to do in phase 2 of the epidemic – does not appear supported by sufficient scientific evidence, also due to the frequent changes in external conditions (reopening of some business activities, resumption of social contacts). Figure 16 represents the estimate of effective reproduction number ( $R_t$ ) in Germany over time.

**Figure 16.** Trend of reproduction number  $R_t$  compared with the incidence of cases in Germany

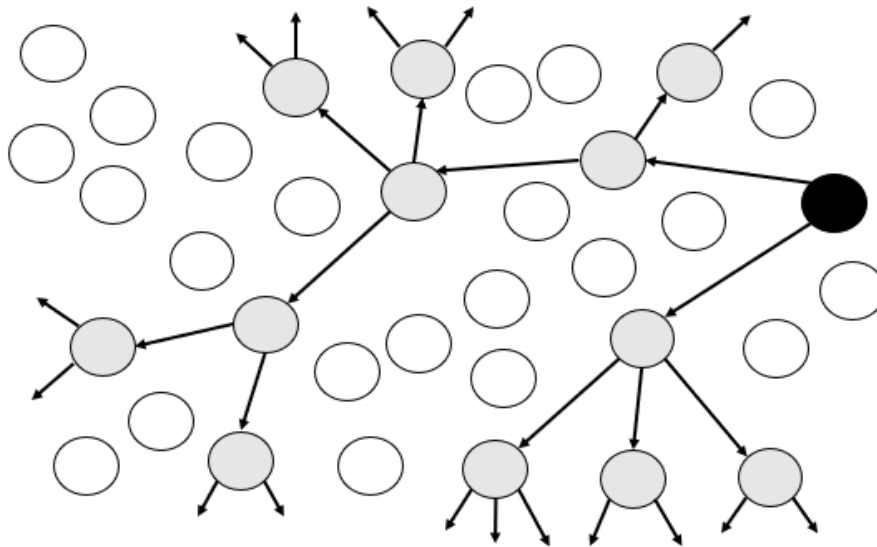


Source: Robert Koch Institute/Johns Hopkins



(Source: Adam D, A guide to R — the pandemic’s misunderstood metric. Nature 583, 346-348 (2020))

**Figure 17.** Schematic spread of COVID-19 in a group



(Source: ASPHER original work)

The black dot at the right border (Figure 17) represents the person who introduced the virus to the group. They infect two other persons, the grey dots, who then in turn infect 5 other persons, and so on.

The goal of the current mitigation strategies (see Section 14), such as social distancing, is to push  $R_0$  below 1. This would mean that one infected person on average infects less than one other person, leading to the epidemic petering out.

Since COVID-19 may confer some immunity, the potential for the virus to spread changes as the epidemic develops. More people become immune after their infection and the susceptible population decreases. This is measured by the **effective reproduction number**, denoted as  $R_t$ .

However, one needs to be mindful that various contextual factors, such as behavior or living conditions, can influence the spread. This results in varying  $R_t$  depending on the setting.

## 13. Epidemiological surveillance

### Standard definition

**CASE DEFINITION:** Establishing unified standard criteria for categorizing for person, place, time, and clinical features (CDC 2020).

#### **CRITERIA FOR CASE DEFINITION:**

- I. **SUSPECT CASE:** Unspecified initial sign and symptom
- II. **PROBABLE CASE:** Description of clinical criteria and epidemiological link
- III. **CONFIRMED CASE:** Laboratory confirmation

**CASE FINDING:** First identify the primary source, the person that public health authorities suspect as the index case. After that the goal is to identify and trace as many cases as possible in order to establish the magnitude of the outbreak.

**CONTACT TRACING:** “Contacts” are subjects that have come into contact with an infected person during the incubation period or the symptomatic stage of the disease, thus having the potential of being infected. An important part of the process of epidemiological surveillance consists in tracing the contacts of infected people, collecting information on their present infection status and following up with them to record the onset of any symptoms. Subsequently, they might be quarantined by health authorities. During the COVID-19 pandemic the use of digital contact tracing has been implemented by some countries; despite its efficiency, this method may raise important privacy issues which have to be balanced with the public health imperative.

**INCUBATION PERIOD:** The incubation period is essentially the time between exposures to the causative agent until the onset of symptoms for each disease agent. For example, the incubation period for COVID-19 is thought to extend to 14 days, with a median time of 4-5 days from exposure to symptoms onset

**ISOLATION:** separates sick (or infected) people with a contagious disease from people who are apparently healthy. It can be applied at the individual, group, or community level.

**QUARANTINE:** separates and restricts the movement of apparently healthy people who were exposed to a contagious disease to see if they become sick. It can be applied at the individual, group, or community level.

**QUARANTINE OF GROUPS:** Refers to quarantine of people who have been exposed to the same source of illness (e.g., at public gatherings, airline, school, workplace).

**WORKING QUARANTINE:** Refers to people who are at occupational risk of infection, such as healthcare workers, who may be restricted to their homes or designated facilities during off duty hours.

**COMMUNITY-WIDE QUARANTINE:** Refers to closing of community borders or the establishment of a real or virtual barrier around a geographic area (*cordon sanitaire*). (Cetron and Landwirth. Public health, ethics, and quarantine, 2005)

## Development of the concepts and examples:

### **CASE DEFINITION:**

**Laboratory Criteria** Laboratory evidence using a method approved or authorized by the U.S. Food and Drug Administration (FDA) or designated authority:

- Confirmatory laboratory evidence:
  - Detection of severe acute respiratory syndrome coronavirus 2 ribonucleic acid (SARS-CoV-2 RNA) in a clinical specimen using a molecular amplification detection test
- Presumptive laboratory evidence:
  - Detection of specific antigen in a clinical specimen
  - Detection of specific antibody in serum, plasma, or whole blood indicative of a new or recent infection (Serologic methods for diagnosis are currently being defined):

### **Epidemiologic Linkage**

One or more of the following exposures in the 14 days before onset of symptoms:

Close contact\*\* with a confirmed or probable case of COVID-19 disease; OR

- Close contact\*\* with a person with:
  - clinically compatible illness AND
  - linkage to a confirmed case of COVID-19 disease.
- Travel to or residence in an area with sustained, ongoing community transmission of SARS-CoV-2.
- Member of a risk cohort as defined by public health authorities during an outbreak.

**Figure 18.** Historic depiction of a quarantine area

\*\*Close contact is defined as being within 6-feet for at least a period of 10 minutes to 30 minutes or more depending upon the exposure. In healthcare settings, this may be defined as exposures of greater than a few minutes or more. Data are insufficient to precisely define the duration of exposure that constitutes prolonged exposure and thus a close contact. (CDC -2020)

The World Health Organization released an interim guidance to perform an accurate **contact tracing**. They state that contact tracing can only be effective if countries have adequate capacity



(Source: Malta: view of the quarantine area. Etching by M-A. Benoist, c. 1770, after J. Goupy, c. 1725.)

to test suspect cases in a timely manner. Otherwise, testing and contact tracing strategies can focus on specific high-risk settings with vulnerable individuals, such as hospitals and care homes.

The terms **quarantine** and **isolation** are strictly related to the plague and date back to the year 1377. The chief physician of Ragusa, Jacob of Padua, established a place outside the city walls for the treatment of sick (or suspected to be infected) citizens for 40 days to land travelers. Furthermore, in 1423 Venice set up one of the first known 'Lazzaretto' (quarantine station) on an island near the city, and the Venetian system became a model for other European countries. (Source: Cosmacini G. et al., 2001; Sehdev P.S. et al., 2002). That being said, quarantine doesn't necessarily last for 40 days: its duration depends on the maximum incubation period of a disease. For example, the incubation period of measles lasts 9 to 15 days, for MERS-CoV the incubation period lasts 5 to 7 days; finally, influenza has an incubation period that lasts from a few hours to a couple of days.

An estimation of the maximum duration of the incubation period as precise as possible is necessary to plan public health interventions, including active surveillance, infection control and modeling of the epidemic.

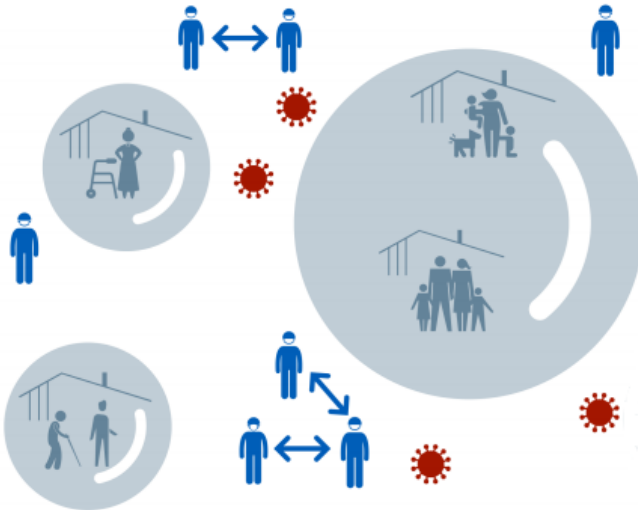
According to a study by Johns Hopkins Bloomberg School of Public Health, published on Annals of Internal Medicine, COVID-19 has a median incubation period estimated between 2 to 14 days. 97.5% of people develop symptoms within 11.5 days from exposure, hence the recommended quarantine period of 14 days is a reasonable amount of time.

**Figure 19.** Example of quarantine life in 2020 during COVID-19 pandemic



Quarantine measures have not been used for a long time, but it's included in the International Health Regulations (adopted by WHO) and it's been employed for COVID-19 due to its relatively long incubation period, in particular for contacts of confirmed cases and areas with high concentration of cases.

**Figure 20** - Social “bubbles”



(Source: Robert Koch Institut infographic)

**"BUBBLE"** - Technical definition, used during the COVID-19 pandemic, referring to a group of people that only meet among themselves, making it more difficult for an infectious agent to spread, granting that everyone in the "bubble" is apparently healthy. Members of a bubble have to follow strict rules to minimize outside contacts as much as possible. In doing so, if a subject is found to be positive to an infectious agent, contacts are easier to identify. It is a strategy to allow particular groups of people to interact in a protected environment, also proposed by the European Commission to reduce social contacts of family members.

It was used by professional sport teams to permit the continuation of competitions; in the context of schools, the constitution of "class bubbles" was used to reduce contacts and contain the spread of SARS-CoV-2 infection.



## 14. Epidemiological trend

### Standard definition

**EPIDEMIOLOGICAL TREND:** is the branch of epidemiology that deals with causes and distribution of diseases in the general population over time, to assess if there have been significant changes in disease patterns throughout the world. It applies statistics to explain present disease patterns but also to help predict how they may change in the future.

**EPIDEMIC:** The occurrence in a community or region of cases of an illness clearly in excess of normal expectancy.

**OUTBREAK:** An epidemic limited to a localized increase in the incidence of a disease, e.g., in a village or town.

**PANDEMIC:** An epidemic occurring worldwide or over a very wide area, crossing international borders, and usually affecting a large number of people.

**SPORADIC:** An infectious disease occurring irregularly, from time to time, and generally infrequently.

**ENDEMICITY:** The constant presence of a disease or infectious agent within a given geographic area or population group.

**SECOND WAVE, THIRD WAVE:** During an epidemic or pandemic, after their initial peak of cases, infectious diseases often have the tendency to re-emerge in a different segment of the population and spread again, giving rise to a second wave (and sometimes third wave) of disease (Figure 22).

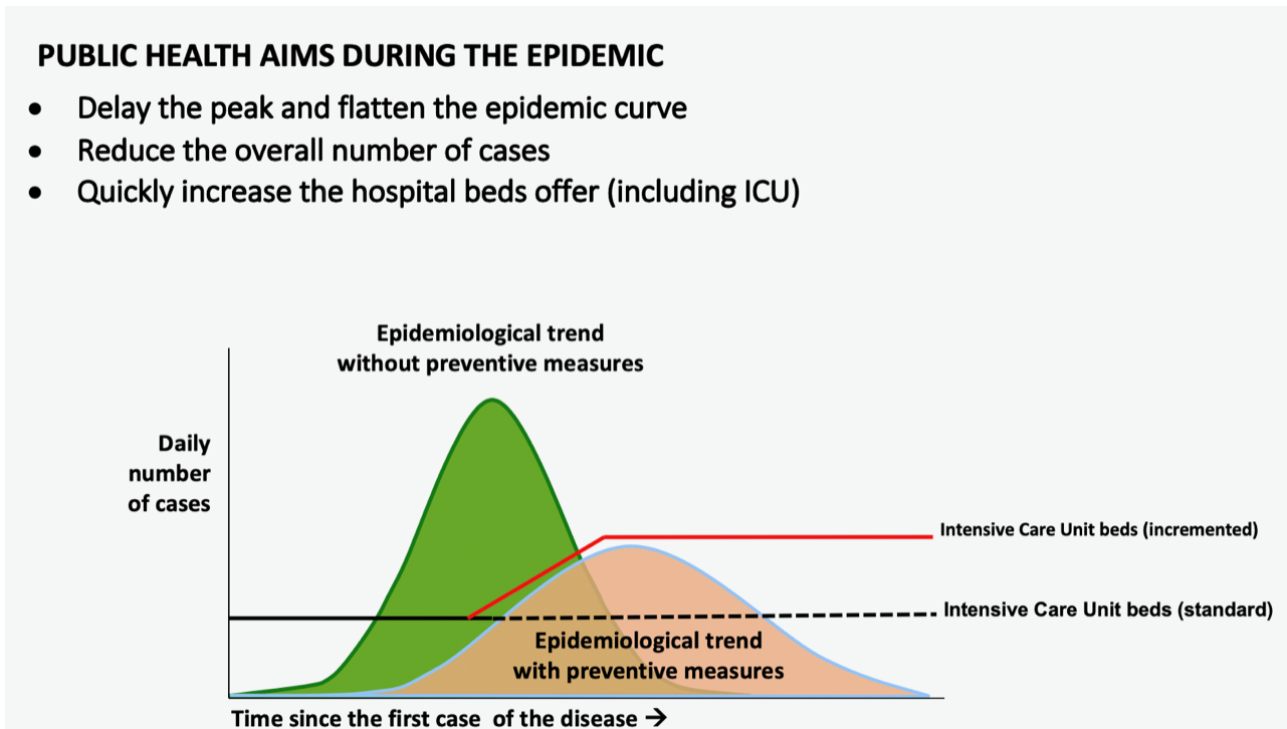
### Development of the concepts and examples:

COVID-19 is considered to have started as an outbreak limited to the province of Wuhan, China. Then the number of reported cases started increasing rapidly, marking an epidemic. It was declared by the WHO Public Health Emergency of International Concern (PHEIC) on January 30<sup>th</sup> 2020. On March 11<sup>th</sup> 2020, the WHO declared the COVID-19 a pandemic, spread over several countries and continents.

**Flattening the curve:** The commonly used phrase “Flattening the Curve” is a public health strategy to reduce the number of new COVID-19 infections to a level within the capacity limits of a healthcare system. This is particularly important for intensive care unit (ICU) beds that patients with severe illness from the virus need (red line in Figure 21). The faster the epidemic curve rises, the quicker a healthcare system can be overloaded and reach its capacity limits (the part of the green curve above the red line in Figure 21). To avoid this, a flatter epidemic curve is needed. This can be achieved by interventions, such as containment and mitigation measures (social distancing, use of masks, personal hygiene behavior, lockdown, etc.), that slow the spread of the virus (brown curve). The same number of people may still become sick but the number of cases spreads over a longer

time period. This reduces the number of people requiring care at the same time and allows hospitals to treat everyone. In Figure 21 the standard way to illustrate this phenomenon graphically is integrated with a possible increase of hospital beds in order to satisfy the demand, as happened in many countries during the first phase of COVID-19 epidemic.

**Figure 21.** The public health strategy during the COVID-19 pandemic: “flattening the Curve”



(Source: Signorelli C, et al., 2020)

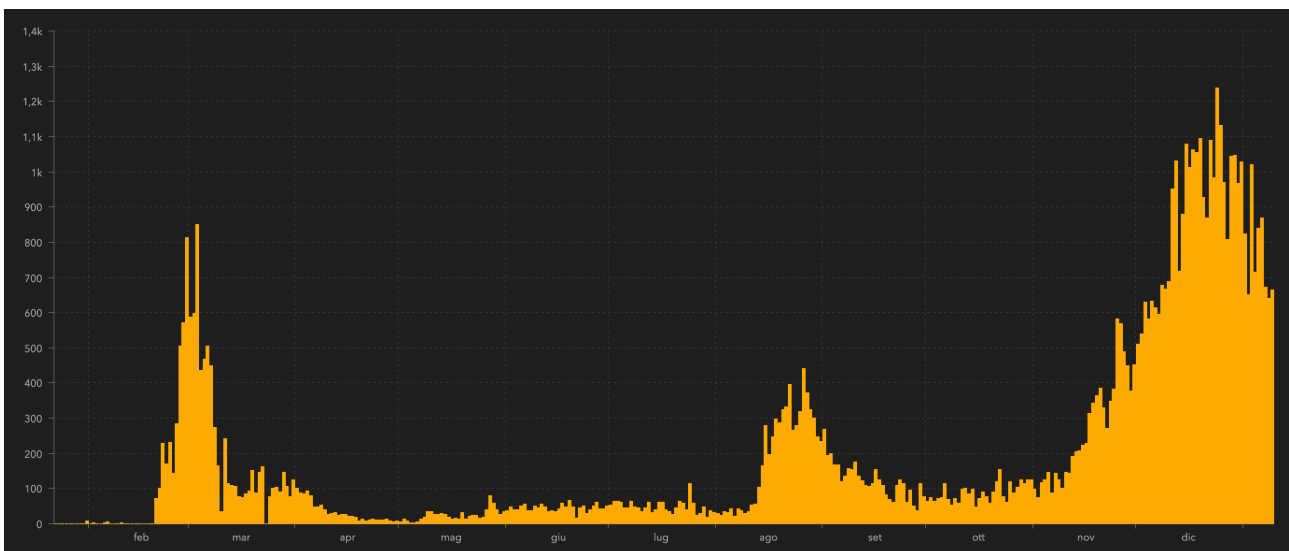
**Containment measures:** applied to prevent (or to delay) the spread of the infection when the overall number of cases is limited. They include case-finding, detection of imported infections and “first generation” transmissions, isolation, contact tracing, treatments and quarantine to prevent the spread of the epidemic and the creation of small “closed” areas (defined sometimes “red zones”).

**Mitigation measures:** a collective term recommended by WHO for actions in affected countries in phase 5 and 6 of pandemic alert; they are applied to reduce the transmission and thus the impact of a pandemic and introduced when there is sustained community transmission despite the containment measures. Complete and partial lockdowns and curfews have been implemented as mitigation measures during the COVID-19 pandemic. The aim is to reduce the overall number of people affected, ensure the maintenance of healthcare delivery, maximizing care for those with the disease and protecting at risk groups.

**Second and Third wave during COVID-19 pandemic:** After reaching a peak in early spring 2020 in many countries, there has been a reduction of incidence of COVID-19 cases,

since many countries implemented mitigation and containment measures. Unfortunately, starting from July-August 2020, a considerable further increase in COVID-19 infections has emerged across Europe, representing an increasing threat to healthcare services and public health. Notification rates have been increasing both in younger and older age groups. The number of cases has shown a marked escalation in recent weeks, and although the two waves are not comparable because the number of tests conducted increased significantly, evidence points to an increase in rates of viral transmission. The impact in terms of pressure on healthcare services and mortality has become increasingly severe. The current epidemiological situation in most countries, defined as “second wave” of the pandemic (and sometimes a third wave) is a serious concern as it poses an increasing risk of transmission, requiring immediate, targeted public health action.

**Figure 22.** Daily cases of COVID-19 in South Korea: first, second and third wave



(Source: COVID-19 Dashboard by the Center for Systems Science and Engineering at Johns Hopkins University, accessed on 13 January 2021)



## 15. Herd immunity

### Standard definition

**HERD IMMUNITY:** Resistance of a population to invasion and spread of an infectious agent, also called community immunity. It's based on the agent-specific immunity of a high proportion of the population reducing the likelihood that an infected person will come in contact with a susceptible one. This refers to the concept that a population that has already been widely infected will develop herd immunity to the virus, and this will eventually eliminate or significantly reduce community transmission and protect the most vulnerable, who must, in the meantime, be shielded. The proportion of the population required to be immune varies according to the agent, its transmission characteristics, the distribution of immune and susceptible individuals, and other (e.g., environmental) factors.

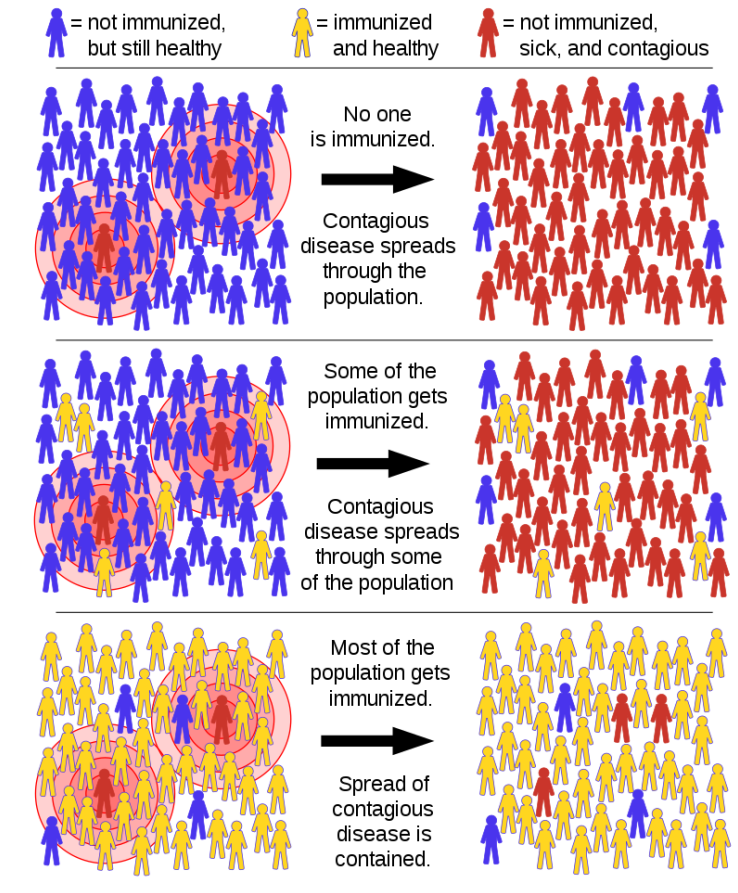
### Development of the concepts and examples:

**Herd immunity** can be achieved with the infection of a relevant part of a population or through vaccination campaigns. See Figure 23 for three different infectious disease spread scenarios based on the immunity proportion of the population. In November 2020 the COVID19 ASPHER Task Force released the statement "Getting through the pandemic in Europe in the winter of 2020/21" commenting on the misuse of COVID-19 herd immunity. They emphasized the need to use successful timely virus suppression strategies, through community adoption of non-pharmaceutical interventions, ensuing vaccination strategies when available and any other scientific developments alongside the many that have been rapidly developed so far. In COVID-19, the form of acquired population immunity from actual infections is different to the acquired herd immunity that follows systematic delivery of a comprehensive population vaccination programme, and it would probably result in recurring outbreaks and epidemics that place an unacceptable and longer strain on economies and healthcare systems. Carrying on a herd-immunity based agenda would increase the COVID-19-related inequalities, since poorer communities are less protected and might have predisposing health conditions from earlier ages. In addition, there is increasing proof of long COVID and post-COVID syndromes, that are debilitating and can create social dependence.

It's crucial to specify that policies based on herd immunity are not evidence based, as literature reporting COVID-19 seroprevalence studies highlighted subsequent surge in cases also where herd immunity was supposed to be achieved (Boadle 2020; Signorelli et al. 2020). In addition, evidence remains inconclusive on whether personal immunity to the virus degrades with time.

The natural herd immunity argument is not currently supported by scientific evidence, its achievement is still far away and might hit especially vulnerable groups, thus creating moral and ethical problems. They concluded that it is dangerous, and unfounded in the science, to advocate use of herd immunity as a means to pandemic control at this time.

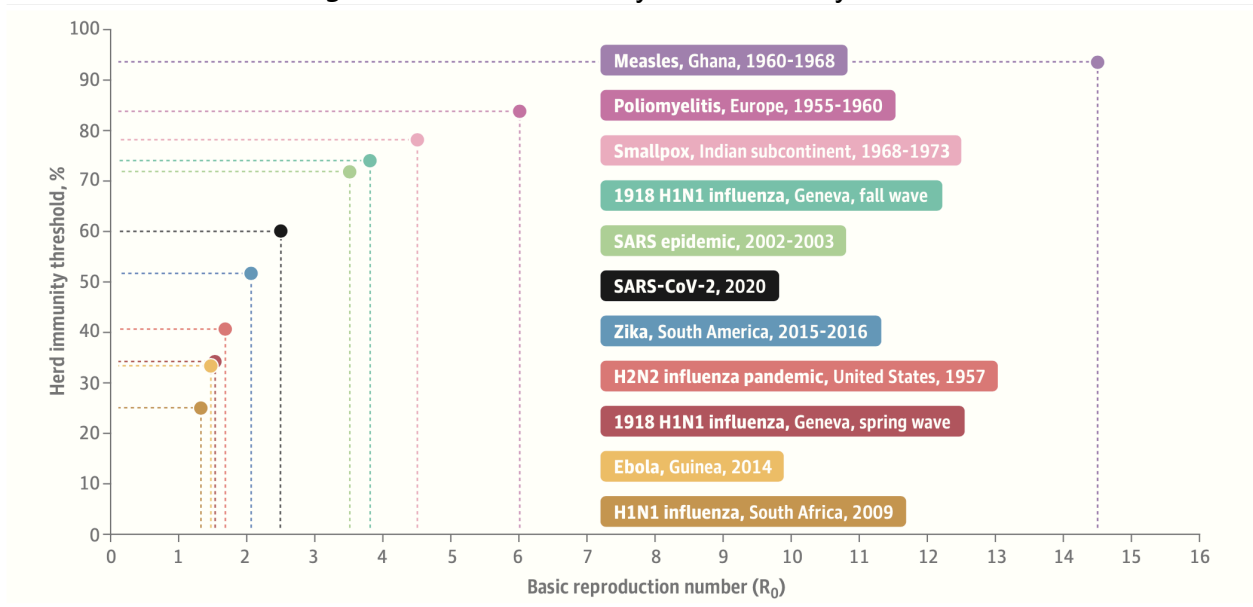
**Figure 23.** Three different scenarios – with different community immunity proportions – as an example of herd immunity.



(Source: Tkarcher - Own work, CC BY-SA 4.0, <https://commons.wikimedia.org/w/index.php?curid=56760604>)

**Herd immunity threshold** The proportion of the population necessary to the achievement of the herd immunity, and interruption of the endemic transmission of the pathogen. It varies according to the mode of transmission and the contagiousness of the infective agent. Recently, an article published by Saad B. Omer on the Journal of the American Medical Association, compared the herd immunity thresholds of 11 infectious diseases, and results are depicted in figure 24. They reported that most studies have estimated that, assuming no population immunity and that all individuals are equally susceptible and equally infectious, the herd immunity threshold for SARS-CoV-2 would be expected to range between 50% and 67%, in the absence of any interventions. The also reason that a critical factor in sustaining herd immunity is the durability of immune memory. For seasonal coronaviruses, the immunity has been shown to be short lived, and for such diseases outbreaks are likely to reappear if no vaccine is distributed. Notably, a herd immunity-based approach has been proposed to fight COVID-19, but Omer et al. highlighted how this would results in substantial mortality, since most of the population would not have immunity to the pathogen. On the other hand, the distribution of an effective vaccination would be a valuable mean of reaching herd immunity.

**Figure 24.** Herd immunity thresholds by disease



The locations included are the locations in which the threshold was measured.

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