

Cartogram Mapping and its Application to Cancer Data Visualisation

Stephanie Kobakian, Jessie Roberts and Dianne Cook

Contents

1	Introduction	1
2	Disease mapping methods	2
2.1	Current best practice map displays for cancer data	2
2.2	Publicly available atlases using choropleth methods	5
2.3	Supporting statistics in public facing atlases	6
2.3.1	Geographic hierarchies	6
2.3.2	Population distribution	6
2.3.3	Statistical uncertainty	6
2.3.4	Demographics	7
2.3.5	Socio-economic indicators	7
2.4	Cartograms as an alternative display	7
2.4.1	Contiguous	9
2.4.2	Non-Contiguous	10
2.4.3	Alternative Displays	10
3	A discussion of mapping methods	11
4	Animation and Interactivity	13
5	Acknowledgements	13
6	References	13

Abstract

1 Introduction

Cancer statistics directly represent and relate to the people living within geographical areas. Geospatial statistics have been presented on maps to communicate information to the general

public for centuries as they utilise familiar geographic shapes. The mapping of diseases summarises spatial variations and can be considered a descriptive statistic of the relationship between a disease and the underlying geography (Elliott et al. 2001). The distribution of the statistic must be visible, it is not enough for areas on maps to be recognisable. It is reasonable to explore views that enhance the communication of the cancer statistics, especially as it is the people that are of interest, not the land they live on. This has spurred innovations over the previous centuries to enhance maps to effectively communicate cancer outcomes, and health outcomes more broadly.

The visualisation methods used to present cancer statistics will depend on the intended message and users of the map. Presenting statistics as visualisations requires transforming individual observations into aggregations of communities as geographical units. Visualising diseases on maps is often the first step in exploratory spatial data analysis and effectively helps in the formulation of hypotheses (Jahan et al. 2018). Disease maps help to present geographic patterns that may have been overlooked in a table, obscuring the geospatially related statistics (Moore and Carpenter 1999). By providing a visual representation of cancer outcomes, geographic patterns of disease are able to be identified and effectively addressed. Exeter (2017) recognises one of the key challenges with mapping spatial patterns of disease is the design of visualisations. This paper addresses the visualisation techniques and their applications to cancer statistics. Highlighting the differences and historic use of these displays.

2 Disease mapping methods

2.1 Current best practice map displays for cancer data

A choropleth map is used to display the characteristics of a spatial relationship of measurements. A choropleth map is a true map of the topology, constructed for visual inspection of spatial patterns on a familiar geographic form. 1 1 shows a choropleth map where each state of the United States of America is coloured by the average annual rate of new cases of lung and bronchus cancer from years 2012 to 2016. Identifying and explaining spatial structures, patterns, and processes involves considering the individuals in communities and organising communities into representable units (Moore and Carpenter 1999). A choropleth is constructed by drawing the geographic or political boundaries, and filling the shapes with colours to represent values of a measured variable (Tufte 1990). Early versions of choropleth maps used symbols or patterns instead of colour. As an alternative storage device to a table, it preserves locations for geographically ordered data, with usage dating back to the 1800s (Berry, Morrill, and Tobler, n.d.). Bell et al. (2006) discuss the use of choropleths to visualise cancer data, and Walter (2001) gives an overview of the development of these maps for displaying disease data.

Utilising the familiar state boundaries can make a map intuitive to read (Brewster and Subramanian 2010), and allow viewers to visually infer the spatial relationships in the data, i.e. how cancer rate differs across the states. The familiarity of the geography is a worthy consideration when presenting results of spatial analysis. Just as geographers are no longer the only creators of maps, Bell et al. (2006) suggests the audiences of spatial health data analysis have extended beyond researchers to the public, policymakers and the media. While the areas are recognisable shapes, they are often politically driven boundaries with individual areas being of non-uniform size, containing different population densities and subject to change over time. The different population and geographical sizes of administrative areas can attract attention to the shades of the unpopulated but large areas (Tufte 1990). Choropleths can inhibit visual inference when presenting human related statistics as

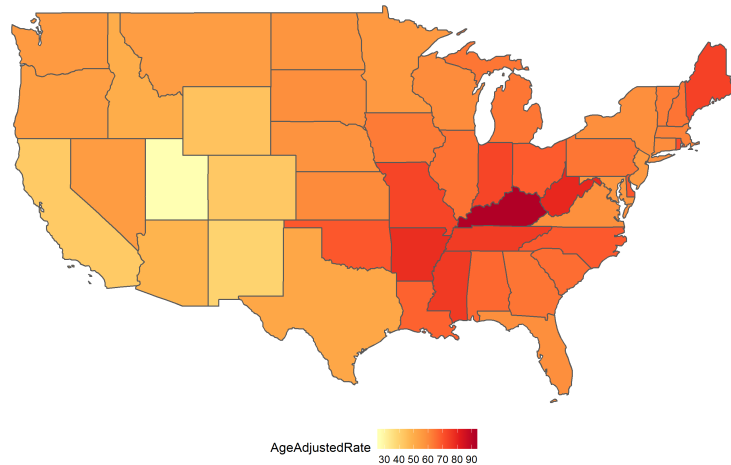


Figure 1: A choropleth map of the United States of America. Each state has been coloured according to the average age-adjusted rate of incidence for lung and bronchus for females and males in the United States 2012-2016. The state of Utah has an unusually low rate of lung and bronchus incidence. The state of Kentucky is high, the surrounding states also have high rates. There is a pattern of average higher rates toward the East Coast and lower rates toward the West Coast.

the display may draw attention from the ‘potentially more important results in the more populous communities’ (Exeter 2017).

Choropleth maps can be useful devices for communicating information to public on a familiar map base. A cancer atlas is a choropleth map, or collection of maps, representing cancer incidence and mortality for a country, or group of countries. In epidemiology, choropleths are often used as a tool to study the spatial distribution of cancer incidence and mortality. The data collection methods of cancer mortality rates across regions, and the administrative control within regions lends itself to choropleth visualisation. d’Onofrio et al. (2016) provides the definition of a cancer atlas, beginning with Haviland’s maps in 1875, they attribute UK cancer atlases to Howe (1963), and early work in US cancer atlases can be attributed to Burbank (1971). The increasing development and use of disease maps can be attributed to the availability of geographic information system software (Exeter 2017). The choropleth maps presented levels via hatchings or dots on a black and white scale. These atlases were key to developing hypotheses regarding areas with unusually high rates, geographic correlations, work related exposures, and high risk diets (d’Onofrio et al. 2016).

Almost 100 years of cancer mapping in the United States and the United Kingdom has seen increased effectiveness in the presentation cancer statistics. Mortality rates are now often presented as relative rates of risk across the population, and age adjusted to correct for the higher prevalence of cancers in older populations. Howe (1989) describes Stock’s development of the standardised mortality ratios through the 1930s. Table 1 presents summarises the measures presented in published cancer atlases, and provides a definition of each measure.

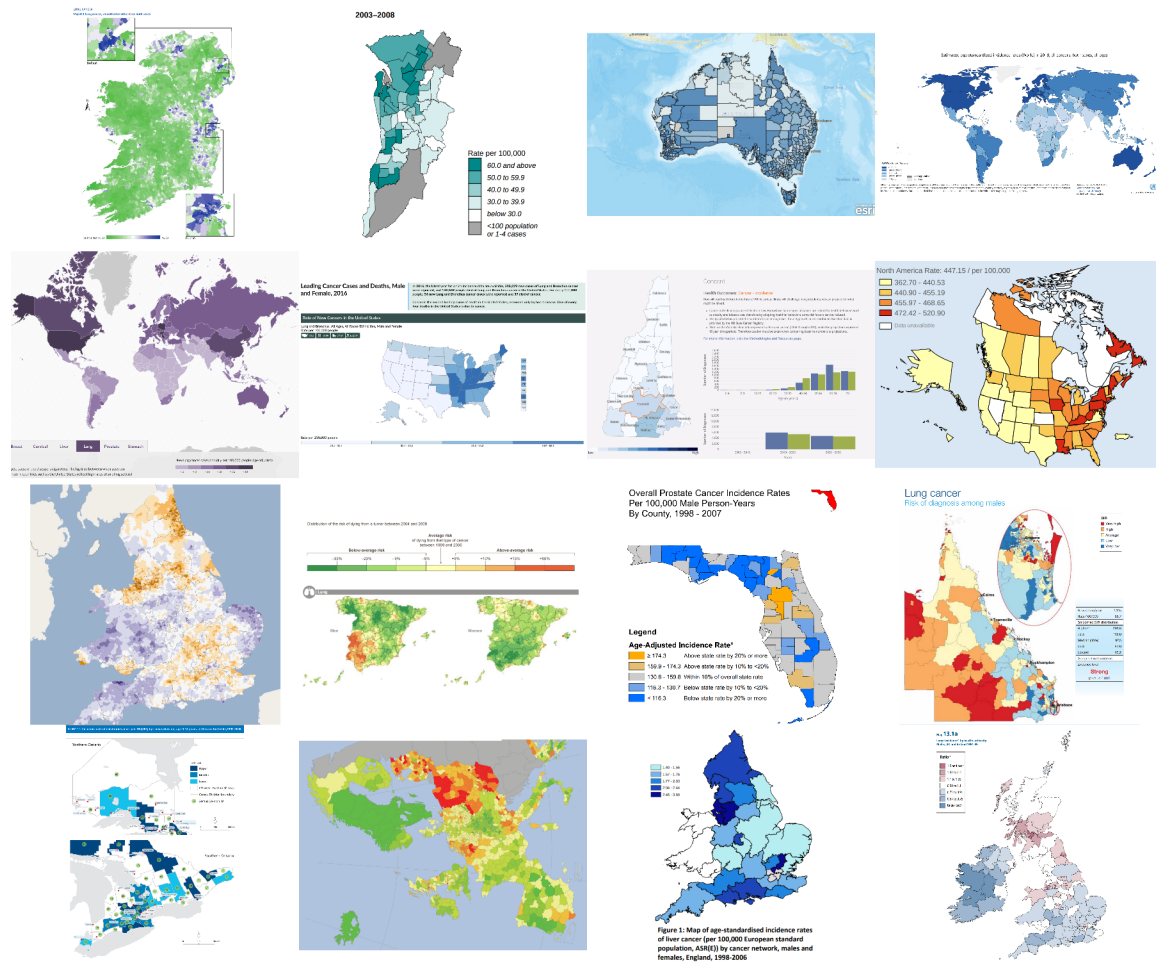
Table 1: Measures used to report cancer statistics

Measure	Details
1. IR (Incidence Ratio)	$(IR)_i = \frac{(Incidence\ Rate)_i}{Average\ Incidence\ Rate},$

Measure	Details
	Cancer incidence rate in region i over the average cancer incidence rate for the total region
2. SIR (Standardised Incidence Ratio)	IR standardised by age structure in each region i
3. RER (Relative Excess Risk)	$RER = \frac{(Cancer\ related\ mortality)_i}{Average\ cancer\ related\ mortality}$ Represents the estimate of cancer related mortality within five years of diagnosis Also referred to as ‘excess hazard ratio’
4. Age Adjusted Relative Risk	RR standardised by age structure in each region i
5. Rate per 100,000	Cancer incidence per 100,000 population
6. Age Adjusted Rate per 100,000	#5 standardised by age structure or region
7. New cancer cases per 100,000	Specific methods could not be found
8. Count	Crude cancer counts
9. Below or above Expected	Alternative expression of the SIR

The atlas of Cancer in Queensland (Cramb, L Mengersen, and Baade 2011) focussed on highlighting the difference in experience for those living in rural and disadvantaged areas. They used Standardised Incidence Ratios modelled via Bayesian methods, and explored the information presented in a range of selected atlases. These atlases provided Incidence, Survival and Mortality rates to the public on Areal or Isopleth map bases.

The presentation of these rates considered not only the map base, but also appropriate choices of colour blind friendly colour schemes, and categories of the values to highlight significantly different areas.



2.2 Publicly available atlases using choropleth methods

Cancer maps are effective communication tools for a general public or non-expert audience. They are commonly used in the public domain to communicate results of sophisticated statistical analyses. The heavy use of choropleth maps within the research literature is also reflected in the types of maps that are found in the public domain. A grey literature review of cancer atlases available in the public domain identified 33 cancer atlases published on the internet between January 2010 and November 2015. These choropleth maps were mostly published by non-commercial organisations, including not-for-profits, government, research organisations, advocacy groups or government funded partnerships. Only one map was published by a commercial entity.

The cancer atlases covered geographies from all around the world, but only four were global atlases. Most focussed on single nations, the United States was considered by eleven atlases, the United Kingdom by seven, followed by three of Australia, two of Canada, and one of each from Switzerland, Germany, Norway. One atlas covered the European Union. Not all maps had a national focus and ten covered a region or state rather than an entire nation. The states or counties/regions covered were South Australia (AUS), Queensland (AUS), Ontario (CAN), Valencia (Spain), Pennsylvania county Massachusetts (US), New Hampshire (US), Cape Cod (US), Missouri (US), Florida (US), New York State (US) and Arizona (US).

2.3 Supporting statistics in public facing atlases

The primary display of an atlas is often the choropleth map. Cruickshank’s (1947) as cited by Walter (2001), discusses using visuals as ‘formal statistical assessment of the spatial pattern’. Atlases can also utilise bar charts, tables and scatter-plots as useful alternative displays. These displays can present the cancer incidence and mortality rates, as well as the supporting statistics of the atlas. When presenting cancer atlases, d’Onofrio et al. (2016) believes the intuition derived from maps must be ‘validated by rigorous statistical analyses.’ Bell et al. (2006) suggests additional materials such as ‘good tables, graphs, and explanatory text’ support understanding and inference derived from maps, ensuring the message communicated will be consistent across a range of viewers. The interactivity of modern maps enables supplementary information to be incorporated without cluttering the screen, such as in a tool tip feature. The atlases provided additional information to help users understand and interpret the spatial distribution presented. The use of these supports were found in a variety of online map sources. These additional pieces of information can help to validate, explain or explore relationships between cancer incidence and survival rates.

2.3.1 Geographic hierarchies

While atlases are often used to describe differences between areas, statistics may be displayed at different levels of aggregation. The World Health Organisation and UN Regions can also be used to aggregate areas (Ferlay J 2018). World atlases can allow for displays of data aggregated into continents, countries, states, provinces and congressional districts (Group 2019).

2.3.2 Population distribution

It is likely that each population area will have a different amount of people, information regarding the distribution of population levels may be provided in a table or histogram display (“All-Ireland Cancer Atlas 1995-2007” 2011). Atlases have the opportunity to connect the population to the land available to them by communicating population density. Atlases can also connect the population to the land available to them by communicating population density as is shown in the United States map examples.

2.3.3 Statistical uncertainty

Statistical uncertainty is communicated through a Confidence (CI) interval, statistical significance levels, Boxplots, Distribution plots, and reporting the Sample Size and Standard Deviations. The additional statistics often include a measure of the statistical uncertainty of the values of the statistics presented in a choropleth. In the review of atlases in the public domain, atlases were considered to report uncertainty to the non-expert user if they included a measure of statistical uncertainty either within or alongside the map. The maps considered used standard and well known measures including credible intervals and standard deviation, statistical significance, box plots and distributions. The maps employing uncertainty ranged from static pdfs or infographics, to interactive online resources. Close to half of the atlases identified (42%, n=14) included some measure of uncertainty. The most common measure used to represent uncertainty were credible or confidence intervals (CIs).

2.3.4 Demographics

Demographics include information regarding the age and sex distribution of the areas presented. Sex is an important cofactor for cancer atlases. As some cancers are sex specific, and others may be found in both males and females, atlases often specify their use of gender in the displays. Atlases can allow for interaction as users can select between displays for males, females or both depending on the type of cancers explored.

2.3.5 Socio-economic indicators

Socio-economic indicators can explain how the experience of cancer prevalence varies for various members of a society. These indicators include unemployment rates, poverty rates and percentages, remoteness and education levels achieved though only a few atlases also explored the impact of rurality on cancer rates. The Human Development Index can be used to understand the socio-economic experience of a community, as can the Income levels as measured by World bank list of economies (Ferlay J 2018). The areas are usually ranked and allocated to quintiles to be presented as categories describing the ranking.

2.4 Cartograms as an alternative display

A cartogram alters the map base with the intention of improving the presentation of the statistic of interest. For a single variable of interest, each map area is changed to emphasise the distribution by representing the corresponding value, in comparison to the value of the other areas (Dougenik, Chrisman, and Niemeyer 1985). The changes in the map base occur by altering individual areas, by altering the shapes or boundaries.

Australia presents an extreme case of an urban rural divide. The land mass occupied by urban electoral districts is only 10% of Australia, yet 90% of the population live in these urban areas. To present election results on a choropleth map should be ‘unthinkable’, as it means diminishing the visual impact of majority of the electorates. A 1966 cartogram was presented an alternative which uses mostly straight lines, and the result looks very little like the geographical shape of Australia. This issue is felt in any nation which experiences an uneven population distribution. The United States is affect by the different densities of neighbourhoods or states. As this population distribution continues to change the need for cartograms as an alternative to a choropleth map should only increase.

Choropleths may be considered true topological maps, however, if the land mass displayed covers enough of the globe, there must be a transformation or distortion to display the land in 2D. The amount of distortion is related to the distance covered by the landmass displayed Tobler (1963). World map projections reflect the frequent perspectives used to view the earth. Choropleth maps will always be distorted if they cover enough of the globe, just like photographs of the globe from space. Choropleth creation requires choosing a map projection that shows a favourable distortion of the geography for presenting the set of spatial information. Selecting a display can prevent misinterpretation of global statistics, as global maps face the challenge of equitable displays of land mass on maps (Raisz 1963). Maps that do not specify a projection can be considered to have some unknown projection. If the statistic presented on the map base relies on physical distance and is influenced by the topology there is no transformation needed, beyond choosing a reasonable projection.

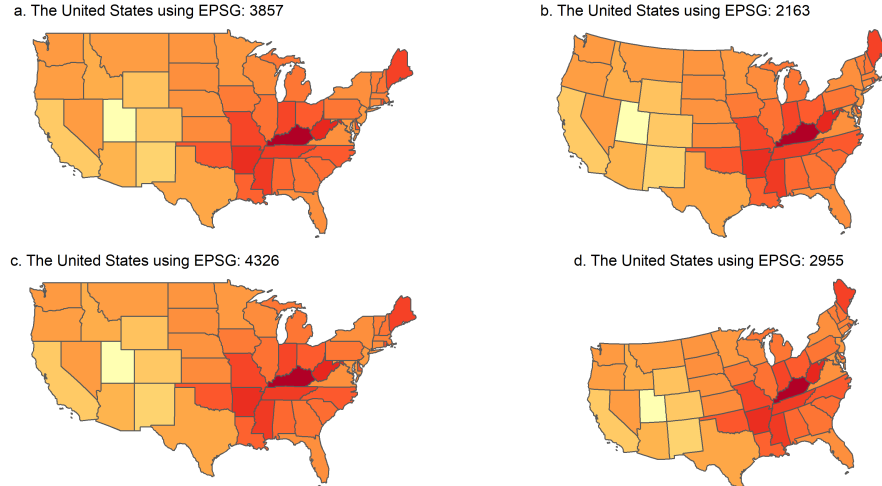


Figure 2: Four choropleth maps of the United States of America using various coordinate reference systems. Each state has been coloured according to the average age-adjusted rate of incidence for lung and bronchus for females and males in the United States 2012-2016. The map projections alter the shapes and angles of the boundaries of each state. Maps a and b are similar in their straight edges, unlike maps c and d which curve on the northern United States border.

The purposeful distortion of the map space, transformed according to population density, is beneficial when a uniform density of the map base is desired. Population then becomes a uniformly distributed background for the statistic presented (Berry, Morrill, and Tobler, n.d.). Dorling (2011) suggests ‘population distribution is often extremely uneven in former British colonies’, this makes the distortion necessary (Griffin 1980). When implementing a distortion of the geographical shape according to population, the resulting display is an area cartogram (Olson 1976), population-by-area cartogram (Levison and Haddon Jr 1965), or iso-demographic map.

Cartograms provide an alternative visualisation method for statistical and geographical information. The key difference between a choropleth and a cartogram is the desirable augmentation of the size, shape or distance of geographical areas (Dorling 2011). Cartograms may be seen as an extension of map transformations and projections. The favourable distortion is proportional to a value other than actual earth size area (Olson 1976). A disadvantage of the conventional map is that sparsely populated rural areas may be emphasized, whereas the areas representing cities are very small, making interpretation of spatial patterns very difficult. The distortion of a cartogram accounts for the population density, preventing it from obscuring the spatial patterns (Levison and Haddon Jr 1965). The spatial transformation of map regions relative to the data emphasises the data distribution instead of land size (Kocmoud and House 1998). When visualising population statistics Dorling (2011) considers this equitable representation design ‘more socially just’, or honest (Dent 1972), giving due attention to all members of the population and reducing the visual impact of large areas with small populations (Walter 2001). Howe (1989) suggests that ‘cancer occurs in people, not in geographical areas’ and Griffin (1980) believe that spatial socio-economic data, like cancer rates, are best presented on a cartogram for urban areas as the population map base avoids allocating ‘undue prominence’ to rural areas. Jahan et al. (2018) encourage the use of cartograms to highlight small areas and uncover local-level inequalities.

The creation of cartograms was historically in the hands of professional cartographers (Kraak 2017). Early approaches including John Hunter and Jonathan Young (1968) and Durham’s wooden tile

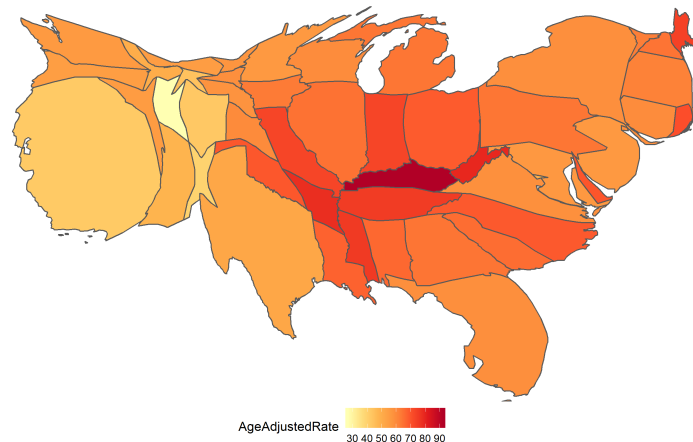


Figure 3: A contiguous cartogram map of the United States of America. Each state has been coloured according to the average age-adjusted rate of incidence for lung and bronchus for females and males in the United States 2012-2016. Each state shape has been distorted according to the population of the state in 2015. The state of California has become much larger due to its large population density. This draws attention to the densely populated North East region, and detracts from the Mid West.

method, Skoda and Robertson’s (1972) steel ball bearing approach and Tobler’s (1973) computer programs (Dorling 2011). Geographical information systems allowed map users, and researchers to implement their own cartograms, but these systems are utilised depending on ‘the effectiveness, efficiency, and satisfaction of the map products (Nielsen 1994)’ (Kraak 2017). Howe (1989) discusses the impact of electronic computer-assisted techniques.

There are many alternatives to consider, the intended audience of the map, and its purpose are key points in cartogram use and creation. Dorling (2011) reiterates: ‘There is no “best” cartogram or method of creating cartograms just as there is no “best” map’ (Monmonier and Schnell, 1988). There have been many algorithms presented, Nusrat and Kobourov (2016) provided a framework to investigate implementations and the “statistical accuracy, geographical accuracy, and topological accuracy”.

2.4.1 Contiguous

A contiguous cartogram maintains connectivity of the map regions while areas are resized according to a statistic. This transformation often occurs at the expense of the shape of areas (Kocmoud and House 1998, @NAC, @TAAM). From a computer graphics perspective, Min Ouyang and Revesz (2000) explain the application of ‘map deformation’ to account for the value assigned to each area, they provide three methods for creating value-by-area cartograms. Examples include Tobler’s Pseudo-Cartogram Method, Dorling’s Cellular Automaton Method (2011), Radial Expansion Method of Selvin et al., Rubber Sheet Method of Dougenik et al., Gusein-Zade and Tikunov’s Line Integral Method, Constraint-Based Method (Kocmoud and House) (1998).

An intentional goal when creating the 1966 Census population cartogram for Canada was to maintain contiguity, while attempting to keep the actual shape of places. The end result was a ‘very

accurate isodemo-graphic map of Canada’. This intentional design goal coincided with the rising interest in urban geography and presentation of social statistics.

To be able to recognise the significant changes, a reader will usually have to know the initial geography to find the differences in the new cartogram layout (Olson 1976). Tobler’s Conformal mapping means to preserve angles locally so that the shapes of small areas on a traditional map and a cartogram would be similar. Kocmoud and House (1998) presents this issue as conflicting tasks or aims, to adjust region sizes and retain region shapes. Cano et al. (2015) define the term ‘mosaic cartograms’ for hexagonal tile displays, where the amount of tiles for each area can be used to communicate the statistic of regions. The complexity of the boundaries can be adjusted in the resulting display, as the size of the tiles used allows a trade-off be made between boundary complexity and simplicity.

2.4.2 Non-Contiguous

Non-Contiguous cartograms succeed in maintaining the shape of the areas presented. Each area stays in a similar position to their location on a choropleth map. The choropleth map base is often also plotted as a comparison point to highlight the change in area. The addition is the gap between areas, created as each individual area shrinks or grows according the associated value of the statistic. Olson (1976) discusses creation of these maps, the significance of the empty areas left between the geographic boundaries and the new shape, and the ‘degree of difference from the original map that is the real message’ of these displays.

As the trade-off regarding boundaries approaches simplicity, the distortion of region shapes on the contiguous cartogram presents an additional hurdle to visual recognition and this hurdle is not only eliminated on the noncontiguous cartogram but is replaced by the meaningful empty-space property (Olson 1976, @ECGC). The shapes are valuable for recognition and allows users to orient themselves on the display. Map creators can efficiently communicate with this kind of map by keeping the outlines or particular elements of the original in the new shape (Dent 1972). The scale of the areas does not impact on the shape recognition. However it may impact on the visibility of all areas if small areas expand beyond their boundaries.

2.4.3 Alternative Displays

Daniel Dorling presented an alternative to highlight the spatial distribution and neighbourhood relationships without complex distortions of borders and boundaries. This approach opposes preserving the intricate shape details. This concept is founded in the simple question put forward by Daniel Dorling (2011):

“If, for instance, it is desirable that areas on a map have boundaries which are as simple as possible, why not draw the areas as simple shapes in the first place?”

He answers this with his implementation of maps created with ‘the simplest of all shapes’. He acknowledged the sophistication of contiguous cartograms but critiqued their ‘very complex shapes’. Circular cartograms use the same simple shapes for every region represented, and size the shapes according to the statistic represented or the population for a base map. This familiar shape may be more effective for understanding the spatial distribution than contiguous cartograms, as the

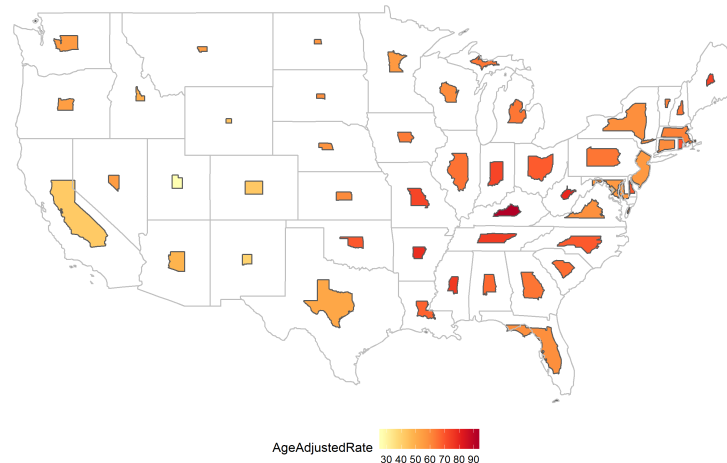


Figure 4: A Non - contiguous cartogram map of the United States of America. Each state has been coloured according to the average age-adjusted rate of incidence for lung and bronchus for females and males in the United States 2012-2016. Each state shape has been maintained, but the size has altered according to the population of the state in 2015. The state of California has remained closer to it's original size than it's surrounding states. The North East states have remained closer to their geographical size, in the case of Massachusetts and Connecticut. This draws attention to the densely populated North East region, and the sparse Mid West.

‘nonsense’ shapes used have ‘no meaning’ after distortions are applied Dent (1972). To produce a compelling map, a gravity model is applied to avoid overlaps, and keep spatial relationships with neighbouring areas over many iterations. This implementation can work for up to ‘one hundred thousand’ areas.

The groundwork for the simplistic approach had been laid in the mid 1930's by Raisz. Tobler (2004) quotes the official definition of Value-Area Cartograms, the simplistic displays which represent each area as a single rectangle, sized according to the value of the statistic. This rectangular display also allows for tiling, where geographic neighbours also share rectangle borders.

3 A discussion of mapping methods

“designing a map tailored to precise goals [is] easier than forcing a single map to accommodate diverse objectives” Bell et al. (2006)

Waldo Tobler (2012) explores many graphical techniques, and suggests there are particular methods for particular purposes. To choose an appropriate map display, the map creator must consider the intended user, and message the map will communicate. It is the objectives of the investigator that will drive the choice of representation (Bell et al. 2006).

There are two keys presented by Moore and Carpenter (1999) to drive the choice of display: - the properties of the visualisation, and - the ease or accuracy of information extraction for map users

Visualisation properties have been explored across several disease mapping displays. Choropleth displays utilise more traditional cartographic methods, this means they are usually true to the

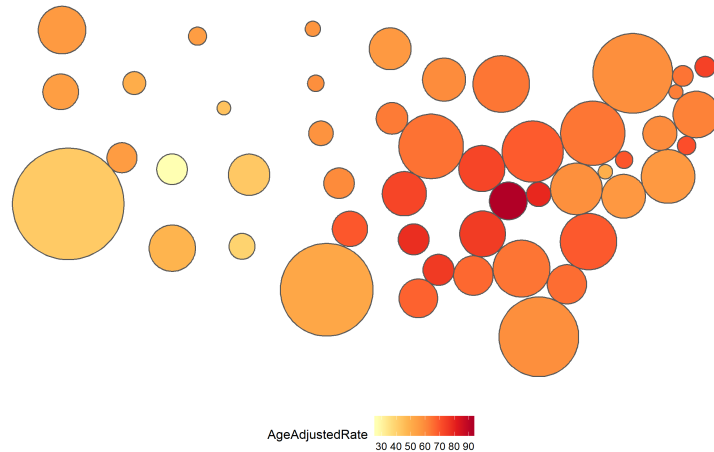


Figure 5: A dorling cartogram of the Unites States of America. Each state has been coloured according to the average age-adjusted rate of incidence for lung and bronchus for females and males in the United States 2012-2016. Each state has been represented by a circle, but the size was determined by the population of the state in 2015. The North East states remain closer to their neighbours, and may be displaced from their geographic location. The sparsity of the population in the Mid West is highlight by the distance between the circles, located at the geographic centroids.

topography. Tobler’s work highlights the need for consideration of the transformation of the globe to a 2D space. When there is a relationship between the cancer type being mapped and geographical features, a choropleth map would pair this information visually. These maps are best used when the geography is of importance to the data in the display. Users can identify the areas relevant to them by the familiar boundaries, and can easily contrast the experience of geographic neighbours.

Pairing geography and cancer data was historically the work of epidemiologists, however it did not require them to be the map designer. This was expected as cartographers were the creators of geographic displays, and epidemiologists utilised the maps that had been prepared in advance. This disconnect did not allow the map to be prepared with the data in mind. Cartogram methods began exploring the concept of diagrammatic cartograms, displays that highlighted the importance of data, as well as the geography. This approach began a shift in the focus and responsibility of map creators. Cartogram displays began incorporating the statistics and population into the design of the display. Shifting and sometimes sacrificing familiar boundaries to draw attention to outliers in the data space or population density. The difference between the familiar map display helps highlight the impact of the disease on communities.

By removing the unexpected boundaries and shapes, the spatial distribution is the primary concept communicated by the display. Areas that are geographically close will maintain connectedness in some way, but the population and the statistic will take precedence. These alternatives are especially helpful for data aggregations where administrative boundaries break populations into groups. The experience of each collective may be worth considering as their experiences may be similar in terms of the services and facilities they share. Population affects are highlighted by these displays, as this display allows a more equitable view of each community, and does not minimise those that operate on a smaller geographic scale.

4 Animation and Interactivity

Recent developments in technology allowed interactive web atlases.

“Where control of the message is important, static maps will continue to be the most effective, although good tables, graphs, and explanatory text are still needed in order to ensure that different people will see the same thing in the maps” Bell et al. (2006)

The intention of interactivity and animation is to allow users to answer their own questions.

5 Acknowledgements

6 References

Wickham (2017) for data analysis, Bivand, Nowosad, and Lovelace (2019) and Pebesma (2018) to implement plotting of spatial data. Kobakian and Cook (2019) to create hexagon tessellation. Arnold (2019) to enhance plot displays. Jeworutzki (2018) for contiguous and non-contiguous cartogram displays.

“All-Ireland Cancer Atlas 1995-2007.” 2011.

Arnold, Jeffrey B. 2019. *Ggthemes: Extra Themes, Scales and Geoms for 'Ggplot2'*. <https://CRAN.R-project.org/package=ggthemes>.

Bell, B Sue, Richard E Hoskins, Linda Williams Pickle, and Daniel Wartenberg. 2006. “Current Practices in Spatial Analysis of Cancer Data: Mapping Health Statistics to Inform Policymakers and the Public.” *International Journal of Health Geographics* 5: 49. <https://doi.org/10.1186/1476-072X-5-49>.

Berry, Brian J. L., Richard L. Morrill, and Waldo R. Tobler. n.d. “GEOGRAPHIC Ordering of Information: NEW Opportunities” 16 (4): 39–44. https://doi.org/10.1111/j.0033-0124.1964.039_q.x.

Bivand, Roger, Jakub Nowosad, and Robin Lovelace. 2019. *SpData: Datasets for Spatial Analysis*. <https://CRAN.R-project.org/package=spData>.

Brewster, Mark B., and S. V. Subramanian. 2010. “Cartographic Insights into the Burden of Mortality in the United Kingdom: A Review of ‘The Grim Reaper’s Road Map’” Journal Article. *International Journal of Epidemiology* 39 (4): 1120–2. <https://doi.org/10.1093/ije/dyp395>.

Cano, R. G., K. Buchin, T. Castermans, A. Pieterse, W. Sonke, and B. Speckmann. 2015. “Mosaic Drawings and Cartograms.” *Computer Graphics Forum* 34 (3): 361–70.

Cramb, Susanna, Kerrie L Mengersen, and Peter Baade. 2011. “Developing the Atlas of Cancer in Queensland: Methodological Issues.” *International Journal of Health Geographics* 10 (January): 9. <https://doi.org/10.1186/1476-072X-10-9>.

Dent, Borden D. 1972. “A Note on the Importance of Shape in Cartogram Communication.” *Journal of Geography* 71 (7): 393–401. <https://doi.org/10.1080/00221347208981697>.

- d’Onofrio, Alberto, Chiara Mazzetta, Chris Robertson, Michel Smans, Peter Boyle, and Mathieu Boniol. 2016. “Maps and Atlases of Cancer Mortality: A Review of a Useful Tool to Trigger New Questions.” Journal Article. *Ecancermedicalscience* 10: 670–70. <https://doi.org/10.3332/ecancer.2016.670>.
- Dorling, Daniel. 2011. “Area Cartograms: Their Use and Creation.” In *Concepts and Techniques in Modern Geography (CATMOG)*, 59:252–60. <https://doi.org/10.1002/9780470979587.ch33>.
- . 2012. *The Visualisation of Spatial Social Structure*. John Wiley & Sons Ltd.
- Dougenik, James A., Nicholas R. Chrisman, and Duane R. Niemeyer. 1985. “AN Algorithm to Construct Continuous Area Cartograms.” *The Professional Geographer* 37 (1): 75–81. <https://doi.org/10.1111/j.0033-0124.1985.00075.x>.
- Elliott, Paul, Jon Wakefield, Nicola Best, and David Briggs. 2001. *Spatial Epidemiology: Methods and Applications*. Book. Oxford University Press: Oxford.
- Exeter, Daniel J. 2017. “Spatial Epidemiology.” Journal Article, 1–4. <https://doi.org/10.1002/9781118786352.wbieg0283>.
- Ferlay J, Lam F, Ervik M. 2018. “Global Cancer Observatory: Cancer Today.” <https://gco.iarc.fr/today>.
- Griffin, T.L.C. 1980. “Cartographic Transformation of the Thematic Map Base.” *Cartography* 11 (3): 163–74. <https://doi.org/10.1080/00690805.1980.10438102>.
- Group, U.S. Cancer Statistics Working. 2019. “U.S. Cancer Statistics Data Visualizations Tool, Based on November 2018 Submission Data (1999–2016).” www.cdc.gov/cancer/dataviz.
- Howe, G. M. 1989. “Historical Evolution of Disease Mapping in General and Specifically of Cancer Mapping.” In *Cancer Mapping*, edited by Peter Boyle, Calum S. Muir, and Ekkehard Grundmann, 1–21. Berlin, Heidelberg: Springer Berlin Heidelberg.
- Jahan, Farzana, Earl Duncan, Susanna Cramb, Peter Baade, and Kerrie Mengersen. 2018. “Making More of Spatial Maps: A Bayesian Meta-Analysis Approach.” In.
- Jeworutzki, Sebastian. 2018. *Cartogram: Create Cartograms with R*. <https://CRAN.R-project.org/package=cartogram>.
- Keim, D.A, S.C North, C Panse, and J Schneidewind. 2002. “Efficient Cartogram Generation: A Comparison.” In *IEEE Symposium on Information Visualization, 2002. INFOVIS 2002*, 2002:33–36. IEEE.
- Kobakian, Stephanie, and Dianne Cook. 2019. *Sugarbag: Create Tessellated Hexagon Maps*. <https://CRAN.R-project.org/package=sugarbag>.
- Kocmoud, Christopher J., and Donald H. House. 1998. “A Constraint-Based Approach to Constructing Continuous Cartograms.” In.
- Kraak, M. J. 2017. “Cartographic Design.” In *The International Encyclopedia of Geography : People, the Earth, Environment, and Technology*, edited by D. Richardson, 1–16. United States: Wiley.
- Levison, M. E., and W. Haddon Jr. 1965. “THE Area Adjusted Map. AN Epidemiologic Device.” Journal Article. *Public Health Reports* 80: 55–59.

- Min Ouyang, and P. Revesz. 2000. “Algorithms for Cartogram Animation.” In *Proceedings 2000 International Database Engineering and Applications Symposium (Cat. No.PR00789)*, 231–35. <https://doi.org/10.1109/IDEAS.2000.880581>.
- Moore, Dale A., and Tim E. Carpenter. 1999. “Spatial Analytical Methods and Geographic Information Systems: Use in Health Research and Epidemiology.” *Epidemiologic Reviews* 21 (2): 143–61. <https://doi.org/10.1093/oxfordjournals.epirev.a017993>.
- Nusrat, Sabrina, and Stephen G. Kobourov. 2016. “The State of the Art in Cartograms.” *CoRR* abs/1605.08485. <http://arxiv.org/abs/1605.08485>.
- Olson, Judy M. 1976. “NONCONTIGUOUS Area Cartograms.” *The Professional Geographer* 28 (4): 371–80. <https://doi.org/10.1111/j.0033-0124.1976.00371.x>.
- Pebesma, Edzer. 2018. “Simple Features for R: Standardized Support for Spatial Vector Data.” *The R Journal* 10 (1): 439–46. <https://doi.org/10.32614/RJ-2018-009>.
- Raisz, Erwin. 1963. “Rectangular Statistical Cartograms of the World.” Journal Article. *Journal of Geography* 35 (1): 8–10. <https://doi.org/10.1080/00221343608987880>.
- Tobler, Waldo. 1963. “Geographic Area and Map Projections,” January, 59–78. <https://www.jstor.org/stable/212809>.
- . 2004. “Thirty Five Years of Computer Cartograms.” *Annals of the Association of American Geographers* 94 (1): 58–73.
- Tufte, Edward R. 1990. *Envisioning Information*. Graphics Press.
- Walter, S. D. 2001. “Disease Mapping: A Historical Perspective.” Book.
- Wickham, Hadley. 2017. *Tidyverse: Easily Install and Load the 'Tidyverse'*. <https://CRAN.R-project.org/package=tidyverse>.