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ORIGINAL ARTICLE

Estimating the global incidence of traumatic spinal cord injury

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Study design: Population modelling—forecasting.
Objectives: To estimate the global incidence of traumatic spinal cord injury (TSCI).
Setting: An initiative of the International Spinal Cord Society (ISCoS) Prevention Committee.
Methods: Regression techniques were used to derive regional and global estimates of TSCI incidence. Using the findings of 31 published studies, a regression model was fitted using a known number of TSCI cases as the dependent variable and the population at risk as the single independent variable. In the process of deriving TSCI incidence, an alternative TSCI model was specified in an attempt to arrive at an optimal way of estimating the global incidence of TSCI.
Results: The global incidence of TSCI was estimated to be 23 cases per 1 000 000 persons in 2007 (179 312 cases per annum). World Health Organization's regional results are provided.
Discussion: Understanding the incidence of TSCI is important for health service planning and for the determination of injury prevention priorities. In the absence of high-quality epidemiological studies of TSCI in each country, the estimation of TSCI obtained through population modelling can be used to overcome known deficits in global spinal cord injury (SCI) data. The incidence of TSCI is context specific, and an alternative regression model demonstrated how TSCI incidence estimates could be improved with additional data. The results highlight the need for data standardisation and comprehensive reporting of national level TSCI data. A step-wise approach from the collation of conventional epidemiological data through to population modelling is suggested.
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Keywords: traumatic spinal cord injury; epidemiology; incidence; population modelling; forecasting

BACKGROUND

Global maps have been developed along with an online data repository to present and manage information necessary to inform spinal cord injury (SCI) prevention programmes.[1] The global maps resource has been developed for the International Spinal Cord Society (ISCoS) Prevention Committee and the wider ISCoS membership for the purpose of defining injury prevention priorities.

The first iteration of the traumatic SCI (TSCI), the global map developed by Cripps *et al.*,[1] published in *Spinal Cord*, utilised the published literature as the basis of representing the incidence of TSCI. The TSCI incidence estimates used were those obtained through population-based observation studies, with particular emphasis given to studies using prospective SCI registries and population-based-health data systems. Incidence data were presented as 'green zone' data when drawn from the registry and as population-based data sources or 'yellow zone' data when partial coverage of a country or World Health Organization (WHO) region was available. When no data were available for a WHO region, the term 'red zone' was used. Indeed, Cripps *et al.* stated that 'incidence data was comparable only for regions in North America (39 per million), Western Europe (15 per million) and Australia (16 per million)', but notably, only Australia was attributed the 'green zone' status. Using a large number of studies, Cripps *et al.* were able to describe in terms of percentage the external cause of injury; however, owing to insufficient incidence data, they were unable to provide a TSCI incidence estimate for 11 of the 14 WHO regions.

Following their literature review, Cripps *et al.*[1] noted that a fundamental difficulty in arriving at comparable TSCI incidence rates was the lack of standardisation in outcome measures and measurement practices. In addition, the absence of research activity specific to SCI in a significant number of countries limits the derivation of TSCI incidence and prevalence rates for a number of WHO regions. Given the cost of establishing and maintaining a trauma registry and population-based health data systems,[2] it is thus unsurprising that a global estimate of TSCI incidence has yet to be derived.

In the absence of comprehensive uniform global injury data, population modelling has been used to derive regional and global estimates of injury incidence, and associated mortality and morbidity. Examples include cause of death models as part of the global burden of disease project,[3,4] as well as for specific mechanisms of injury, such as road traffic crashes,[5] or for particular age groups of interest, such as child injury mortality.[6] The estimation of injury incidence generally relies upon survey data of key respondent groups, snap shots of vital registration data and/or studies of hospital presentation and admission rates.

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Given the large gaps in knowledge and consequent inability to establish a global estimate of TSCI incidence based on existing health data systems, population modelling methods can be used to estimate the incidence of TSCI based on observed relationships between TSCI and population—or any other factor (for example, number of registered motor vehicles; alcohol sales and so on) in locations where TSCI incidence studies have been conducted. In the absence of observed TSCI incidence data, estimated TSCI incidence rates based on population modelling permit a broader level of understanding of the magnitude of TSCI and can be used to prioritise injury prevention programs and develop effective health policy. This is particularly important given the significant mortality and morbidity associated with SCI.

This paper introduces techniques to derive TSCI incidence using available data. This approach permits the estimation of TSCI in regions where Cripps *et al.* were unable to establish a TSCI incidence rate (that is, 'red zone' regions). Hence, the aim of this paper is to estimate the global incidence of TSCI, and in doing so provide TSCI incidence rates for all WHO regions.

MATERIALS AND METHODS

Using past studies the relationship between observed TSCI and population can be determined using linear regression methods.[7] The incidence values of TSCI were obtained from 31 research papers from the global data repository described in Cripps *et al.*, which described the incidence rate and the proportion with tetraplegia and paraplegia.[1,8–38] Where the population at risk (that is, number of people in the country or the study catchment area) was not reported, the stated number of TSCI cases combined with the incidence rate was used to derive the population 'at risk'. The 31 studies were those conducted from 1990 onwards, however, exception was made for the two studies[28,30] as they were the only two studies from Sub-Saharan Africa, both of which contained incidence data commencing in 1988. The 31 studies were set:Japan (observed TSCI incidence rate: 40.2 per million persons[32]), China (23.7[24]; 60.6[22], Vietnam (13.9[38]), Australia (14.9[13]; 14.5[25]), Estonia (27.9[31]), Russia (29.7[33]; 44[20]), France (19.4[8]), Greece (33.6[14]), Ireland (13.1[26]), Italy (20[27]; 14.3[11]), The Netherlands (7.5[35]), Iran (62.2[29]), Turkey (21.1[19]; 16.9[18]; 12.1[17]), Canada (35[30]; 52.5[15]; 24[12]; 38[16]; 42.4[28]), the USA (40[23]; 83[37]; 27.1[10]; 77[34]; 56[9]), South Africa (13.9[36]) and Zimbabwe (11.7[21]). The population for each of the 31 studies was either reported or calculated from information by the authors of this paper.

Using the data from the 31 research papers noted above, a linear regression model was fitted using the known number of TSCI cases as the dependent variable and the population at risk as the single independent variable (see Box 1; known as the population-only model). Linear regression assumes that the relationship between the dependent variable (TSCI) and the independent variable (population at risk) is linear; however, this was shown not to be the case by model testing using fractional polynomials. Hence, the use of fractional polynomials improved the 'fit' of the model and in this instance population values were expressed as two separate yet additive terms; the end result is that specifying population as two additive terms better explains the observed TSCI incidence in each of the 31 studies (refer Box 1).[8–38] The adjusted-r^2 for the model was 99% and the model was highly statistically significant ($P<0.001$). Analysis was performed in STATA (version 12/MP; Statacorp, Austin, TX, USA).

Using the regression equation in Box 1, an estimate of TSCI can be made for each country using reported population. In total, population data was known for 178 countries with 2007 population data being used.[5] For example, Australia had a population of 20 743 179 in 2007, and by means of substitution into the formula presented in Box 1, the TSCI incidence was estimated to be 402, with the 95% confidence intervals (CIs) stating that this could range from 333 to 472; this translates to a TSCI incidence rate of 19.4 per million persons (95% CI: 16.1–22.7). The same process was undertaken for each country where population was known, with the known population value being represented as '*X*' in equation (7) to then obtain values for population1 (equation 5) and population2 (equation 6). The two values derived using are then substituted in equation (1) with values presented in equations (2–4) to obtain the TSCI estimate for that individual country. The only parameter to change in the estimation of TSCI is the population of the country in question. This step was performed in MS Excel (Microsoft, Redmond, WA, USA) following estimation of the regression equation in STATA as described above.

Box 1 Formula for the estimation of TSCI used for each country

$$\text{SCIest} = \text{constant} + \beta1\times(\text{population1}) + \beta2\times(\text{population2}) \quad (1)$$

where

$$\beta1 = 3596.208(95\%\ \text{CL}: 3292.678\ \text{to}\ 3899.737)\dagger \quad (2)$$

$$\beta2 = -2130.132(95\%\ \text{CL}: -2433.23\ \text{to} -1827.035) \quad (3)$$

$$\text{constant} = 373.4508(95\%\ \text{CL}: 304.2426\ \text{to}\ 442.659)\dagger \quad (4)$$

$$\text{And where: population1} = X^2 - 0.0381500612 \quad (5)$$

$$\text{population2} = X^2{*}\ln(X) + 0.0623033975 \quad (6)$$

$$(\text{where}: X = \text{pop}/100000000) \quad (7)$$

Note: †, $P\leqslant 0.05$

Alternative model specifications

It is accepted thatalthough population can be used as the basis of estimation in its most basic form, other variables have an important role in the incidence of injury. At the outset it was anticipated that using a more complex estimation model with a broader set of development and economic indicators would yield more robust TSCI estimates.

The modelling process commenced using population and economic indicator data gathered for 178 countries cited in the WHO global status report on road safety.[5] As per the World Bank classification, based on the gross national income per capita (GNI, Atlas method[39]), 42 jurisdictions were classified as high-income countries (⩾\$11 456, HIC), 91 were middle-income countries (\$936–11 455, MIC) and 45 were low-income countries (⩽\$935, LIC). These 178 jurisdictions represented 91.2% of all member and associate member states (refer Table 2, p. 10 in *World Health Organization. Global status report on road safety: time for action*[5]); the 19 non-participating countries and territories comprise 1.9% of the global population.

For each of the 178 countries, a range of economic and development indicators using various sources were linked to the WHO population and income status variables. These additional variables included unemployment rate, urbanisation (of the population)[40,41] and the United Nations Human Development Index (HDI).[42] The HDI is a comprehensive development composite index that incorporates life expectancy, education, income, infrastructure and associated measures of inequality, measures of environmental sustainability, well being and happiness, demographic trends, health, physical and media infrastructure and access to information and communication technology. The HDI was available for 157 countries for the 2005 calendar year, whereas all other values related to 2007.

The alternative regression model used population, income, urbanisation, unemployment and the United Nation's HDI, rather than population alone (Box 1), to estimate the incidence of TSCI for each country and is presented in Box 2 (that is, alternative model). The adjusted-r^2 for the model was 97% and the model was highly statistically significant ($P<0.001$). Analysis was conducted in STATA. The application of the formula is the same as for Box 1.

RESULTS

Population-only model

Using the population-based regression model, the calculation of a TSCI incidence estimate was able to be performed for 131 of the 178 countries (74%) (Appendix Table 1 for detail on each country in Supplementary Material).

Box 2 Formula for the estimation of TSCI (alternative model)

$$\mathrm{SCIest} = \mathrm{constant} + \beta 1 \times (\mathrm{population}) + \beta 2 \times \mathrm{WHO\ income\ classification} + \beta 3 \times \mathrm{Unemployment} \times (\%) + \beta 4 \times \mathrm{Urbanisation} + \beta 5 \times \mathrm{Human\ Development\ Index} \quad (1)$$

where:

$$\beta 1 = 0.0000401 (95\ \%\mathrm{CL}: 0.0000385\ \mathrm{to}\ 0.0000416)\dagger \quad (2)$$

$$\beta 2 = \mathrm{Income\ level\ 1\ (middle)} = 762.1305 (95\%\ \mathrm{CL}: -53.48418\ \mathrm{to}\ 1577.745)$$
$$\mathrm{Income\ level\ 2\ (high)} = 495.0312 (95\ \%\ \mathrm{CL}: -665.669\mathrm{to}1655.753) \quad (3)$$

$$\beta 3 = \mathrm{Unemploymentpercent} = 20.32637 (95\ \%\mathrm{CL}: 0.2088747\ \mathrm{to}\ 40.44387)\dagger \quad (4)$$

$$\beta 4 = \mathrm{Urbanisation} = -17.34702 (95\ \%\mathrm{CL}: -31.53629\ \mathrm{to} -3.157744)\dagger \quad (5)$$

$$\beta 5 = \mathrm{Human\ Development\ Index} = 4033.327 (95\%\ \mathrm{CL}: -275.043\ \mathrm{to}\ 8341.696) \quad (6)$$

$$\mathrm{constant} = -2485.609 (95\%\ \mathrm{CL}: -5651.86\ \mathrm{to}\ 680.6419) \quad (7)$$

Note: †, $P \leqslant 0.05$

In 2007, it was estimated there were 179 312 TSCI incident cases, with the 95% CIs stating that the number of TSCI incident cases would potentially range between 132 967 and 225 658 incident cases. The overall incidence rate was estimated to be 27.5 TSCI incident cases per million persons in the population (population for 131 countries: 6.250 billion). The estimated TSCI incidence rate ranged from 18.3 per 1 million persons (nine countries) to 42.9 per 1 million persons (Brazil). These estimates are based on individual country estimates. Regional estimates by WHO classification and income category are presented in Table 1.

As noted, an estimate of TSCI incidence was achieved for 131 countries, with 47 countries deemed to have implausible TSCI estimated values. These instances included the incident rate being artificially high (>80 per million), as well as the lower confidence bound being less than zero. Consequently, these estimates were excluded from the results.

Alternative model specification

Application of the enhanced population model (Box 2) yielded TSCI estimates for 105 countries. The estimates for China and India represented statistical outliers at 4.5 and 3 million TSCI cases, respectively, and thus were deleted from the output. Hence, the alternative model specification using additional input variables permits estimation of the incidence of TSCI for 103 of the 178 countries where the population was known (that is, 57.8%), this being 28 countries less than the population-only model.

The alternative model estimates the incidence of TSCI to be 189 111 persons for an overall incidence rate of 47.1 TSCI cases per 1 000 000 persons (population 4 billion, excluding China and India). By contrast, the population-only model estimated 116 387 persons would sustain a TSCI per annum for a TSCI incidence rate of 31.9 TSCI cases per million persons (also excluding China and India). The mean TSCI incidence rate among the 103 countries was 34.4 per million persons (model 2), whereas the comparable incidence rate using the same 103 countries by the population-only model (Box 1) was 25.8 TSCI incident cases per million persons. Owing to the large number of countriesthat an estimate could not be derived, aggregated summary statistics by WHO region as per Table 1 are not presented. For thoroughness, the TSCI incidence estimate (number of cases, rate) is presented in Appendix Table 1 (Supplementary Material).

DISCUSSION

Using population modelling, and based on the observed relationships between TSCI and the population at risk in each of the studies cited in Materials and Methods, it was possible to present a model that estimates TSCI for 131 countries. The derived TSCI estimates represent the expected number of TSCI cases given the observed relationship between TSCI and the population reported in research studies. It was the case though that estimates for 47 countries in the population-only model were unsatisfactory. This appeared to affect small island countries in particular, and this highlights that the model is only as robust as the studies upon which it is based, in this case, 31 studies, none of which were undertaken in small populations.

A most likely explanation for this limitation is that the TSCI population-only model used known incidence and population data from only 31 studies that were set in only 17 countries, with only 10 representing national estimates. None of the studies were set in small island populations, only 2 in low-income countries, 10 in middle-income countries and 19 in high-income countries with Australia, Canada and the USAcollectively accounting for 12 original studies. The need for additional population-based TSCI across a broad range of countries is clear.

The accuracy of the TSCI incidence rates derived by the population model can be assessed by examining the estimated TSCI incidence and the reported TSCI incidence in the original studies. By way of example, the original Australian studies reported the TSCI incidence to be 14.5[25] and 14.9[13] cases per million persons, whereas the population-based model estimated the incidence to be 19.4 per million persons (95% CI: 16.1–22.7). For the USA, the National Spinal Cord Injury Statistical Center (NSCISC)[23] reported a TSCI incidence of 40 per million persons, whereas the population-based model estimates the incidence of TSCI to be 37.5 per million persons (95% CI: 17.6–56.4 TSCI cases per million persons).

It is noteworthy that the TSCI estimates for Australia given by the two models was similar (population-only model: 402 TSCI cases, rate: 19.4 per million persons; alternative model: 421 TSCI cases, rate: 20.3 per million persons). It is likely that this result reflects the strength of the input data, particularly as 2 of the 31 studies from which the relationship between TSCI incidence and population are reported were population-based Australian studies. Similarly, the USA TSCI incidence estimate 95% CI range captures the actual TSCI incidence reported by three of the five USA studies,[9,10,23] with the actual incidence being higher for two (Alaska (77 per million persons);[34] Mississippi (83 per million persons)[37]) studies; importantly, the average TSCI incidence reported by the five studies was 56.6 per million persons, approximately equivalent to the upper 95th% CI.

The above highlights the point that the strength of the TSCI estimations relies upon the input data in determining the relationship between actual incidence and the known population. That the TSCI incidence estimate for the USA was close to that reported by the NSCISC national TSCI incidence rate is unsurprising as the population model reflects the average occurrence. Where the actual data is reported from a sub-national location, such as a specific city or region, higher or lower incidence rates than the national estimate would be expected. In such cases, TSCI incidence rates would be dependent on—and more senstive to, the nature of the population at

Table 1 Traumatic SCI incidence estimates by WHO region

WHO region	*Estimated incidence of SCI (number persons)*	*LCL of SCI incidence (number persons)*	*UCL of SCI incidence (number persons)*	*Estimated median incidence of SCI (95% CI) (per million persons)*	*Number of countries with estimate*	*Number of countries without estimate*
Africa						
Medium income	2101	1790	2413	23 (15–26)	4	7
Low income	17 979	14 911	21 046	20 (13–26)	26	4
Regional subtotal	20 080	16 702	23 459	20 (13–26)	30	11
Americas						
High income	12 336	6104	18 569	30 (18–49)	3	3
Medium income	18 049	14 347	21 751	22 (13–30)	20	6
Regional subtotal	30 385	20 450	40 320	23 (13–32)	23	9
Eastern Mediterranean						
High income	741	521	962	28 (13–45)	3	2
Medium income	8258	7140	9375	24 (15–35)	12	0
Low income	7954	6521	9387	21 (19–24)	3	0
Regional subtotal	16 953	14 182	19 724	24 (16–35)	18	2
Europe						
High income	11 850	10 098	13 603	21 (12–31)	19	6
Medium income	12 841	10 528	15 154	27 (12–38)	18	3
Low income	857	638	1076	22 (11–33)	3	0
Regional subtotal	25 549	21 264	29 834	25 (12–32)	40	9
Southeast Asia						
Medium income	12 127	8842	15 412	31 (28–33)	3	3
Low income	32 478	22 064	42 892	24 (22–29)	4	0
Regional subtotal	44 605	30 906	58 304	27 (25–29)	7	3
Western Pacific						
High income	7081	6070	8093	28 (16–45)	5	1
Medium income	31 047	20 278	41 817	28 (16–33)	4	11
Low income	3611	3115	4108	23 (12–35)	4	1
Regional subtotal	41 740	29 463	54 017	27 (13–36)	13	13
Global estimate	179 312	132 967	225 658	23 (13–30)	131	47

Abbreviations: LCL, lower confidence level; SCI, spinal cord injury; UCL, upper confidence level.

risk, manifested in the nature of the economy, local industry and other contexual factors.

An alternative TSCI population incidence model was developed with the expectation that additional variables would improve the model and produce TSCI incident numbers (and rates) more specific to the prevailing economic context apparent in each country. The alternative model included a broader range of economic and development indicators including unemployment, income status (high, middle and low), HDI and the percentage of the population residing in an urban population. Although conceptually useful, an estimate of TSCI could not be obtained for 73 countries (excluding China and India). This was the result of one or more factors such as unemployment, urbanisation or the HDI value being unknown.

The two estimation models produced different TSCI incident rates (model 1: 25.8 per million persons; model 2: 34.4 per million persons), with this difference being driven in large part by the significantly higher TSCI estimate for the USA, this being 4.9 times higher (that is, 56 199 TSCI cases in model 2 (rate, 183 per million) vs 11 468 TSCI cases (rate, 37.5 per million) in model 1). The alternative model resulted on average a 33% higher TSCI incidence than the population-only model, and excluding the USA that reduced nominally to 29% more TSCI cases. The inclusion of additional socio-economic variables in model 2 adds complexity to the estimation model, and then relies on the relationship between these and the original 31 studies upon which the regression equation is based. As per the population model, this small number of studies (31) formed the basis of the relationship between population, and the limitation of this is noted above. Put simply, the small number of studies constrains the accuracy of the TSCI estimates and this represents a limitation to the current analysis; indeed, only a larger number of epidemiological field-work studies would overcome this limitation.

Despite the poorer performance of the alternative TSCI estimation model, the current method of basing TSCI incident estimates on the simple regression relationship between known TSCI and population is also not without limitations, particularly given the complex nature of SCI. Recognition of this led to the development of a more sophisticated model that sought to account for a range of economic and development indicators, although the lack of complete global coverage for these additional indicators meant that the incidence of TSCI was estimated for fewer countries. The analysis reported here highlights the ongoing need for the further development of the alternative model. Future work will be focussed on refining the current method by examining a broad range of variables (for example, population age distribution, alcohol sales, fuel consumption) that could influence the incidence of TSCI injury in society. This work is, however, wholly dependent upon new studies being published that examine the epidemiology of SCI in the field, as this will permit the TSCI regression model to be more robust. Finally, the source data inputs in the regression models must be matched to a single calendar year (for example, 2007 as used here) as the basis of estimations. Although more recent input data were available for a number of independent variables, the 2007 calendar year was used as the full range of source data was available at the time of analysis. It does however remain important that revised estimates of TSCI are published regularly.

Integration of these estimation methods within the ISCoS prevention committee global mapping project

The initial global mapping work by Cripps *et al.*[1] highlighted the paucity of available TSCI incidence data. By representing TSCI incidence in a graphical manner it was readily apparent that significant gaps exist in our understanding of the global incidence of TSCI. These gaps were presented as 'red zones' in the original global mapping work;[1] however, using the estimates of TSCI incidence reported here, these 'gaps' can be closed. The estimation of TSCI incidence and associated incidence rates as reported here form an important part of expanding the reach of the ISCoS global mapping project, particularly in light of the relatively few population-based TSCI studies undertaken globally.

On the basis of the work undertaken here, there is a clear need for additional studies to be undertaken. Although recognising the significant financial costs and resource requirements in establishing population-based surveillance systems, it is recommended that standardised collection and reporting of TSCI data be adhered to. In lieu of this, it can stated that the ISCoS Prevention Committee has developed and implemented the following step-wise approach to mapping global data:

1. Standardised conventional methods of evaluating and mapping existing published data in order to identify data deficits within an area.
2. Encourage the use of the ISCoS core data set[43] and the International Classification of External Causes of Injury inherent in the ISCoS prevention committee's data collection tool,[44] the purpose of which is to provide a platform for a coordinated TSCI prevention programme. It is expected that these strategies will assist ISCoS members in facilitating the exploration, extrapolation, implementation and evaluation of appropriate prevention strategies.
3. Where underlying (that is, input) data are available and robust, use population modelling to better estimate SCI incident data for each of the WHO global regions,[4] so as to provide improved global statistics for incidence.[45]

The analysis undertaken here was purposely designed to estimate the incidence of TSCI. There is an opportunity to use the same methods to derive estimates of non-TSCI (NTSCI). At present though, it can be stated that there are insufficient source data to derive an estimating regression model for NTSCI. Consequently, no global estimate of NTSCI can be made at this time. It is notable, however, that data extrapolation is being used to estimate NTSCI prevalence between two socioeconomically similar countries (Canada and Australia),[46] which it is expected will shed light on the extent of morbidity associated with NTSCI. Furthermore, the establishment of NTSCI data standards in this area currently in draft form (http://www.iscos.org.uk/page.php?content=20) and the ISCoS global data repository will assist in improving NTSCI data to a level where the derivation of global NTSCI estimates are possible using the regression techniques described here in relation to TSCI.

CONCLUSION

Overall, using published research incidence data, population data and population modelling procedures, an estimate of TSCI incidence was derived for 131 of the 178 countries. This information is useful in filling known gaps in our understanding of the incidence of TSCI, and is of value in guiding injury prevention priorities and health service provision. The fact that the estimation of TSCI by population modelling was necessary reinforces the need for TSCI incidence data derived from original and well-designed epidemiological studies. It is recommended that future studies adopt standardised data collection instruments and reporting standards.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Supplementary Information accompanies this paper on the Spinal Cord website (http://www.nature.com/sc)