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Original article

Identifying pre- and posttraumatic brain injury pathways with a multidomain sequence analysis: a retrospective cohort study

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A R T I C L E I N F O

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A B S T R A C T

Background: Traumatic brain injury (TBI) is a major public health issue, associated with significant mortality and long-term disability. Little is known about the typical trajectories of patients with TBI, particularly before and after injury.

Objectives: This study aimed to describe care pathways surrounding TBI and to identify the determinants associated with these trajectories, with the ultimate goal of supporting the development of coordinated and optimized care strategies for patients with TBI.

Methods: A retrospective cohort study was conducted using data from Toulouse University Hospital and the French National Health Data System. People treated for TBI between 2014 and 2018 were identified using ICD-10 codes, and their healthcare trajectories were reconstructed over a period spanning 2 years before and after the injury. A multidomain sequence analysis was conducted across 3 domains: type of care unit, outpatient care type, and mental health status. A multinomial logistic regression model was implemented to analyze the relationship between covariates and care trajectories.

Results: Among the 23 395 people with TBI, 6 distinct care trajectories were identified, 3 per age group. For young individuals aged 10 to 52 years, 4 trajectories ranged from low-complexity and prevention-oriented to high healthcare needs linked with pre-existing mental health vulnerability. Among seniors (aged 53 to 107 years), 3 pathways reflected varying degrees of autonomy loss, reliance on rehabilitation, and psychotropic medication use. Mental health fragility and high hospitalization needs were key discriminants of complex trajectories in both groups. Among the younger group, clustering was largely determined by socioeconomic deprivation, while among the senior group, it was primarily influenced by sex and comorbidity profiles.

Conclusion: This study highlights the heterogeneity of TBI care pathways and underscores the need for age-specific and personalized care strategies. Understanding these trajectories can inform early identification of vulnerable people and guide targeted interventions, ultimately improving equity and continuity of care. The methodology also offers valuable applications for managing other complex health conditions.

List of abbreviations: AAH, French disability benefit; ATC, Anatomical Therapeutic Chemical classification; CCI, Charlson Comorbidity Index; CESREES, French Ethics and Scientific Committee for Research, Studies, and Evaluations in Health; CMU-C, French public complementary health insurance program; CNIL, French Data Protection Authority; EDI, European deprivation index; ICD-10, International Classification of Diseases and Related Health Problems, 10th revision; NIR, French national identification number; OM, Optimal matching; SNDS, French National Health Data System; STROBE, STrengthening the Reporting of OBservational studies in Epidemiology; TBI, Traumatic brain injury; TUH, Toulouse University Hospital

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Introduction

Traumatic brain injury (TBI) represents a major public health challenge due to its high burden in terms of mortality, long-term disability, and socioeconomic consequences. TBI is also a major cause of death, with 31% of fatalities occurring during the initial hospital phase, known as the acute phase [1]. Mortality remains significant even 1 year postinjury, reaching a rate of 27% [2]. Moreover, TBI often results in long-term disability, with persistent impairments observed in 64% of cases at 1 year [3]. These sequelae include functional limitations, difficulties in returning to work, and a marked decline in people's quality of life, despite advancements in physical, cognitive, and functional rehabilitation [4]. Mortality and disability rates vary according to injury severity. Severe TBI is associated with substantially higher mortality rates than moderate forms, as well as a higher proportion of survivors experiencing severe disability or vegetative states [5].

The consequences of TBI extend beyond the medical and social spheres, imposing a substantial economic burden. In France, the healthcare system is based on the principle of solidarity, characterized by universal access to healthcare services funded through income taxation and mandatory social health insurance contributions. These costs are borne by society as a whole, whereas in other healthcare models, such as liberal systems, the financial impact directly affects the patients and their families. A study by Leibson and colleagues reported additional costs associated with TBI of around $22 000 during the acute phase, with significant expenses persisting up to 6 years postinjury [6]. Other studies have highlighted severe financial repercussions for the families of patients with TBI, including the need to take out loans or divide assets to cover trauma-related expenses [7]. These economic challenges, in addition to the medical and social consequences previously highlighted, further underscore the wide-ranging societal impact of TBI.

The management of patients with TBI is particularly complex, requiring rapid intervention within the first 24 hours to limit complications and improve survival outcomes. This care involves highly specialized sectors, including intensive care, neurosurgery, advanced medical imaging, and functional rehabilitation [8]. Rehabilitation begins in the acute phase and often continues until the person returns home [4]. As such, the comprehensive management of patients with TBI is fully integrated within care pathways.

Despite these observations, few studies in France have specifically addressed the characterization of pre- and postinjury phases, as well as the identification of typical care pathways for patients with TBI. Although conducted within the French healthcare system, the methodological approach is transferable to other countries with universal or mixed healthcare systems. Furthermore, understanding how social deprivation shapes care pathways after TBI is relevant across settings, as socioeconomic inequalities in healthcare access and outcomes are widely observed internationally.

The objective of this study is to describe typical care trajectories both before and after TBI, and to identify the determinants associated with these trajectories, with the ultimate goal of supporting the development of coordinated and optimized care strategies for patients with TBI.

Methods

Design

This is a retrospective cohort study.

Regulatory and ethical aspects

This study conformed to the STrengthening the Reporting of OBservational studies in Epidemiology (STROBE) guidelines for the description of study implementation and results, thus facilitating their full and transparent presentation.

The study also complies with the General Data Protection Regulation and received approval from the CESREES (French Ethics and Scientific Committee for Research, Studies, and Evaluations in Health) and authorization from the CNIL (French Data Protection Authority), under authorization request number 921415. All data were selected from the databases of the TUH. Three types of information dissemination were implemented: individual notifications were sent by email when the person's contact information was available in their medical records; collective information was provided through local press announcements; and additional collective information was displayed in high-traffic areas related to TBI care within the TUH.

Participants

The cohort was established based on a list of primary, related, or associated diagnoses of the International Classification of Diseases and Related Health Problems, 10th revision (ICD-10 codes) for TBI, identified from the Hospital Information System database of Toulouse University Hospital (TUH) and emergency department visit summaries at TUH between 2014 and 2018.

Individuals <18 years at the time of notification were excluded, and the age reference (stated in the results) was age at TBI. Toulouse is located in the southwest and is France's fourth most populous city, with over 500,000 inhabitants. This list of diagnostic codes was previously validated by a panel of clinical experts from TUH using a Delphi method (see Appendix A for the list of ICD-10 codes).

The cohort was then linked to the French National Health Data System (SNDS) through direct matching using the French national identification number (NIR). The link enabled the connection of TUH data with national healthcare databases. The available SNDS data covered the period from 2012 to 2020, allowing reconstruction of care trajectories for a minimum of 2 years prior to and 2 years following the initial TBI management for each cohort participant. This database covers more than 98% of the French population, making it one of the largest health databases worldwide, both in terms of historical depth and population size [9].

Determining care pathways

A previous study tested a sequence analysis method based on optimal matching (OM) and clustering in a sample of people with acquired brain injuries [10]. We adapted this method to data from people with TBI, while addressing the limitations identified in the previous study—data on outpatient care and hospitalizations in the private sector were added to the data on hospitalizations in the public sector. Furthermore, following Bernardi, Huinink, and Settersten, the life course can be viewed as a multidimensional process shaped by interdependencies and interactions not only over time but also across different domains [11]. This perspective suggests that if a particular state is absent or unexpressed in one domain for an extended period, it may manifest in another domain. This observation was also noted in the results of the previous study and was identified as one of its main limitations. Therefore, we chose to apply a multidomain sequence analysis method, which allows for the simultaneous consideration of multiple domains.

According to Gauthier, this approach generally involves 3 phases [12]. The first step consists of identifying and justifying the different domains used. Some authors recommend statistical methods to measure the association between domains [13]. However, the empirical method was applied in our study as this approach remains widely used, as clustering yields results even when domains are independent, and when domains are associated, clustering does not always capture these links [14,15]. We identified 3 domains: (i) type of care unit within the healthcare facility (hospitalization, rehabilitation, etc.), (ii) type of outpatient care, and (iii) an approximation of mental health status. The empirical method was applied; these choices were based on the results of the previous study [10], particularly regarding the type of care unit. This was

complemented by outpatient care, which was considered one of the main limitations of the previous study, as it was not included, but is also well described in the literature [16]. The choice of the third domain, "mental health," was based on the typical profile of people with TBI, as described in both the literature and by clinicians, highlighting the importance of psychoaffective disorders and related medication use [17,18].

The second step involves making choices about how the analysis is conducted: selecting the approach, choosing a dissimilarity measure, and selecting the clustering algorithm [19,20]. The multidomain sequence analysis approach was favored. Another approach found in the literature, the extended alphabet method, would have resulted in an excessively large alphabet, making the sequences overly complex and difficult to interpret in graphical representations. Dissimilarity was measured using the commonly used OM metric [21,22], with substitution costs based on transition rates. Insertion and deletion costs were set at half the highest substitution cost, thereby favoring state transitions/substitutions with lower costs over insertion or deletion operations. Finally, Ward's method, widely used in OM, was applied for clustering, allowing the grouping of similar sequences and the identification of trajectory typologies [23].

The third step includes the selection of typical clusters. Graphical methods, including the dendrogram and the inertia jump plot, were used to determine the optimal number of clusters to consider. It is essential that the clustering solution aligns with theoretical and clinical considerations. Indeed, a grouping may exhibit strong statistical properties while lacking practical or interpretative relevance [24]. Since the analysis was stratified by age, using the median age (52 years) as the cutoff, the graphical methods consistently suggested a common solution of 3 clusters across both groups, "young" (10 to 52 years) and "senior" (53 to 107 years), with an interpretable structure that made clinical sense.

Considered states

For Domain 1: Type of care unit, 3 states were considered: outpatient procedures and consultations (including emergency department visits); hospitalizations in medical and rehabilitation care units; and hospitalizations in departments such as medicine, surgery, obstetrics, psychiatry, or home-based hospitalization programs.

For Domain 2: Type of outpatient care, 4 states were considered: consultations with general healthcare providers (including general practitioners, midwives, gynecologists, dentists, and pediatricians); consultations with professionals specialized in TBI (such as physical medicine and rehabilitation specialists, trauma surgeons, orthotists, speech therapists, neurologists, neurosurgeons, and maxillofacial surgeons); use of physiotherapy services; and use of nursing home services.

For Domain 3: Mental health, 3 states were considered, based on the use of 5 psychotropic drug classes identified via Anatomical Therapeutic Chemical classification (ATC codes): antidepressants, anxiolytics, hypnotics, neuroleptics, and mood stabilizers. State 1 was defined when at least one psychotropic drug class was consumed during the month (corresponding to at least 2 purchases of the same class on different dates). State 2 was defined when 2 or more different psychotropic drug classes were used during the same month; people without psychotropic drug use were assigned a "no-use" state.

As injury mechanisms are strongly associated with age (ie, road traffic accidents are predominantly observed among younger individuals, while falls are more frequently associated with older individuals [25,26]), care trajectories were modeled separately for 2 groups. We used the median age (52 years) as the cutoff: "young" (10 to 52 years) and "senior" (53 to 107 years).

Covariates

We selected from the literature variables likely to influence care trajectories.

We then collected information on sex, comorbidities, initial hospital episode severity, psychotropic medication, psychiatric disorder, neighborhood-level deprivation from the European Deprivation Index, EDI. We gathered information on low-income health coverage from CMU-C, a French public complementary health insurance program providing free coverage for low-income individuals. Disability benefits were obtained from AAH, a French disability benefit program that provides income support to adults with long-term disability or reduced work capacity. AAH is a proxy for social vulnerability applicable to both working and non-working individuals. CMU-C and AAH were received annually, either before or after injury. These variables are therefore identified annually on the SNDS.

Comorbidities were assessed using the Charlson comorbidity index (CCI). Initial hospital episode severity was categorized as "hospital stay" vs "emergency department visit" according to French Diagnosis-Related Group classifications. Psychotropic medication use was identified based on the dispensing of at least 3 prescriptions of antidepressants, mood stabilizers, antipsychotics, anxiolytics, or hypnotics (according to their ATC classes) during the year of interest, in the absence of any recorded psychiatric diagnosis. Psychiatric disorders were identified through a validated algorithm combining long-term illness status, ICD-10 psychiatric diagnoses and/or hospitalization for psychiatric conditions, and the dispensing of at least 3 psychotropic medications (antidepressants, mood stabilizers, or antipsychotics) during the year of interest. EDI is a composite index measuring socioeconomic deprivation at the neighborhood level, based on census and survey data. Higher EDI quintiles correspond to higher levels of deprivation.

Analysis of factors associated with care trajectories

A multinomial logistic regression model was implemented to analyze the relationship between covariates and care trajectories. Prior to model estimation, interaction terms were tested, considering potential interactions between sex and age, comorbidities and age, as well as EDI and age. Only the interaction between comorbidities and age was retained in the final models. A stepwise inclusion strategy was used to facilitate the interpretation of the relative contribution of the social variables.

The first model, referred to as the minimal model, included individual characteristics (age and sex, coded as a binary variable). These structural variables provide an initial estimate of the associations. This base model was then compared with 2 extended models that progressively incorporated other confounders related to socioeconomic position: the EDI (5 ordered classes), CMU-C (binary variable), and AAH (binary variable).

In the fully adjusted model, medical characteristics which may be influenced by socioeconomic disadvantage and the interaction term were included: comorbidity level, categorized into 2 ordered classes; and severity of the initial hospital episode, dichotomized as "hospital stay" vs "emergency department visit".

Results

Cohort and baseline characteristics

A total of 41 073 people were initially identified at TUH based on ICD-10 codes: 4 427 from the Hospital Information System and 36 646 from emergency department records. After verifying person identifiers (NIR, date of birth, and sex) and removing duplicates (n = 1 700), several exclusions were applied: people with provisional or missing NIRs (n = 200), minors without a recorded beneficiary NIR (n = 6 700), individuals still underage at study notification (n = 8 137), and records linked to a relative's insurance card (n = 800). People who declined participation (n = 68) were also excluded. The final TUH cohort included 23 468 adults with valid NIRs as of November 29, 2022. Of these, 23 395 (99.6%) were successfully matched in the SNDS database, forming the final TBI cohort (Figure 1).

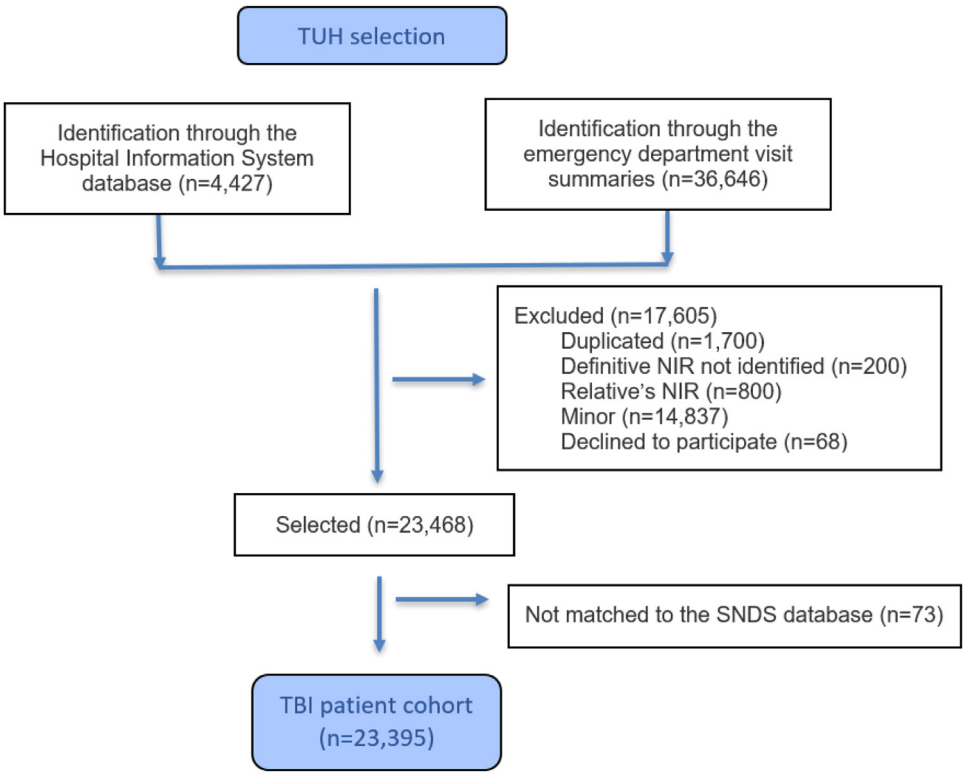


Figure 1. Participant flow diagram

Participants characteristics, according to age, are presented in Table 1. The "young" subgroup (median age 25 years old) comprised predominantly men (n = 7 916; 68%), whereas the "senior" subgroup (median age 81 years old) included a majority of women (n = 6 263; 54%). Seniors exhibited a higher burden of comorbidities than younger participants (CCI = 1: 9% vs 2%). The severity of the initial hospitalization was also greater among seniors (36% vs 27% among the young group). Young individuals were more socioeconomically disadvantaged,

Table 1
Baseline characteristics.

	TBI n = 23 395		
	young (10-52 yr) n = 11 697	senior (53-107 yr) n = 11 698	***P-value***
Sex			*P <0.05*
Women	3 780 (32%)	6 263 (54%)	
Men	7 916 (68%)	54 35 (46%)	
Age median (IQR)	25 (19–36)	81 (69–88)	*P <0.05*
CCI			*P <0.05*
0	11 401 (97%)	10 492 (90%)	
1	261 (2%)	1 076 (9%)	
2	15 (<1%)	84 (1%)	
3	20 (<1%)	46 (<1%)	
Initial hospital episode severity			*P <0.05*
Hospital stay	3 174 (27%)	4 236(36%)	
Emergency department visit	8 524 (73%)	7 462 (64%)	
Psychiatric disorder*	876 (8%)	1844 (16%)	*P <0.05*
Mental health treatment*,¤	581 (5%)	404 (3%)	*P <0.05*
Death post-TBI	410 (4%)	6 192 (53%)	*P <0.05*
EDI*			*P <0.05*
1	1 700 (15%)	1 871 (16%)	
2	1 621 (14%)	1 658 (14%)	
3	2 106 (18%)	2 280 (20%)	
4	2 134 (18%)	2 362 (20%)	
5	2 903 (25%)	2 413 (21%)	
NA	*1 231 (11%)*	*1 114 (10%)*	
CMU-C*	2 170 (19%)	367 (3%)	*P <0.05*
AAH*	564 (5%)	238 (2%)	*P <0.05*

n (%), median (IQR)
CCI = Charlson comorbidité index - Bannay revision, **EDI** = European Deprivation Index, **CMU-C** = French public complementary health insurance program, **AAH** = French disability benefit
* measurement during the TBI year
¤ treatment without a diagnosed pathology

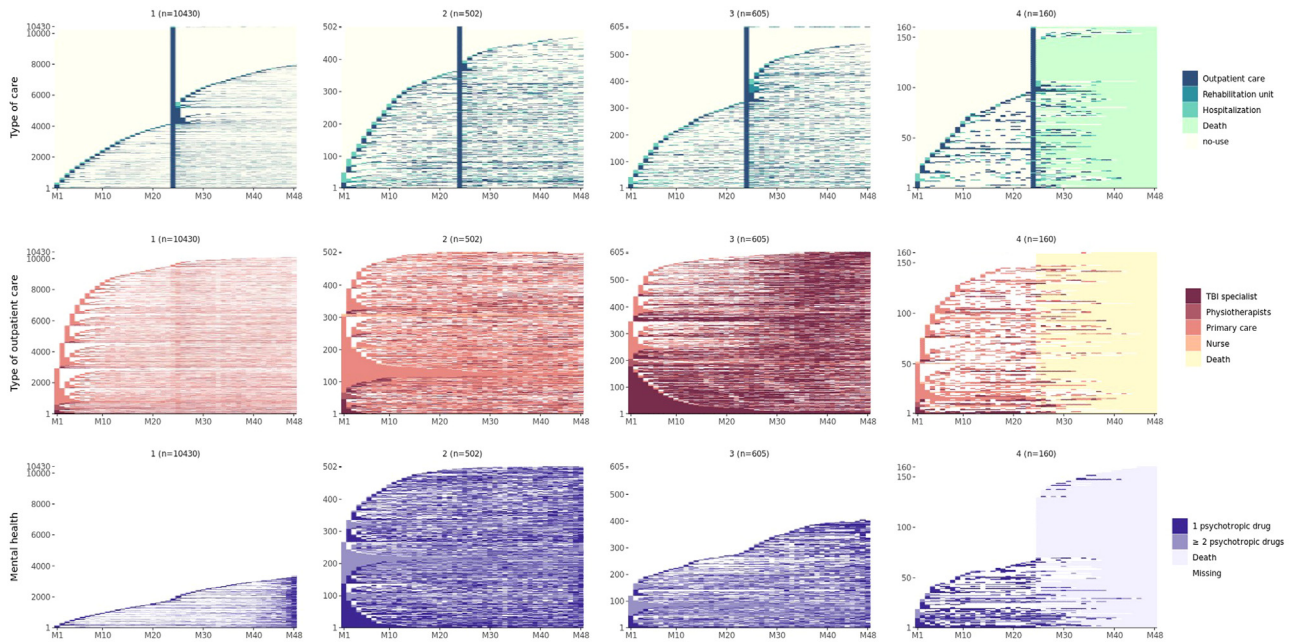


Figure 2. Typical care pathways for the young group

Participants are displayed on the y-axis, while the time scale is shown on the x-axis. Each line represents the trajectory of a single person. Time is represented on a monthly scale, with the TBI occurring at month 24 (M24), at which point information is available for each person in Domain 1. The 2 years preceding the TBI correspond to the interval from M1 to M24, and the 2 years following the TBI correspond to the interval from M25 to the end of follow-up. Each cluster can be identified in the column panels, while each domain is represented in the row panels.

with higher proportions in the most deprived EDI quintile (EDI 5: 25% vs 21% in the senior group), and more frequent beneficiaries of CMU-C (19% vs 3% in the senior group) and AAH (5% vs 2% in the senior group).

Description of care pathways

When examining the sequences by age categories, young (10−52 years) and senior (53−107 years), we observed distinct care trajectories (Figures 2 and 3). Participants are displayed on the y-axis, while the time scale is shown on the x-axis. Each line represents the trajectory of a single participant. Time is represented on a monthly scale, with the TBI occurring at month 24 (M24), at which point information is available for each participant in Domain 1. The 2 years preceding the TBI correspond to the interval from M1 to M24, and the 2 years following the TBI correspond to the interval from M25 to the end of follow-up. Each cluster can be identified in the column panels, while each domain is represented in the row panels.

Clusterization

The inertia jump plots and dendrograms (Appendix B) showed significant jumps at 4 clusters, among the young group, and at 3 clusters, among seniors. A clustering solution with 4 trajectory types for young people and 3 trajectory types for senior people, resulting in a total of 7 clusters, was selected based on its clinical relevance and interpretability.

Identified typical care pathways

For the young group—Figure 2: Cluster 1 included 10 430 participants (or sequences) (89%). In Domain 1 (type of care unit), there was limited healthcare use prior to the TBI event. The TBI was marked in Domain 1 at month 24 (M24), as all participants were admitted to TUH, either through the emergency department or via hospitalization. Prior to the TBI, the main type of healthcare use in Domain 1 was outpatient consultations, with a slight increase in hospital admissions observed after the TBI. This group quickly ceased hospital visits following the initial care period. In Domain 2 (use of outpatient healthcare professionals), there was regular but spaced use of general medical services (general practitioners, pediatricians, dentists, gynecologists, midwives) prior to the TBI, which slightly intensified at the time of the TBI. Domain 3 (psychotropic medication use) showed low psychotropic consumption before the TBI, which further decreased after the injury. This care pathway, characterized by few general medical services, was summarized as "Prevention". In this context, the term "Prevention" is a simplified representation of the pathway to facilitate reading of the results; it refers to dominant patterns within pathways rather than formal clinical programs.

Cluster 2 included 502 participants (4%). In Domain 1, frequent hospitalizations were observed prior to the TBI, with further increases afterward. Domain 2 showed significant use of general healthcare services before the TBI and an increase in the use of rehabilitation professionals after TBI. In Domain 3, substantial and continuous psychotropic consumption was observed prior to the TBI, with a notable increase in both intensity and the number of psychotropic classes used following the injury, indicating a complex mental health profile. This care pathway, characterized by significant use of healthcare services and a complex mental health profile, can be summarized as "Complex". In this context, the term "Complex" is a simplified label that reflects dominant care patterns, not formal clinical programs.

Cluster 3 included 605 participants (5%). Domain 1 presented a pre-TBI pattern similar to Cluster 1 but with a more pronounced increase in hospital visits after the TBI. In Domain 2, there was already intensive use of rehabilitation professionals prior to the TBI, particularly physiotherapists and rehabilitation specialists. This use intensified further after the TBI, with consistent and sustained engagement with both types of professionals. In Domain 3, psychotropic use was low before the TBI, followed by a clear increase post-TBI, though limited to a small subgroup. This care trajectory, characterized by the use of rehabilitation professionals, can be summarized as "Rehabilitation". The term "Rehabilitation" is a simplified label that reflects dominant care patterns, not formal clinical programs.

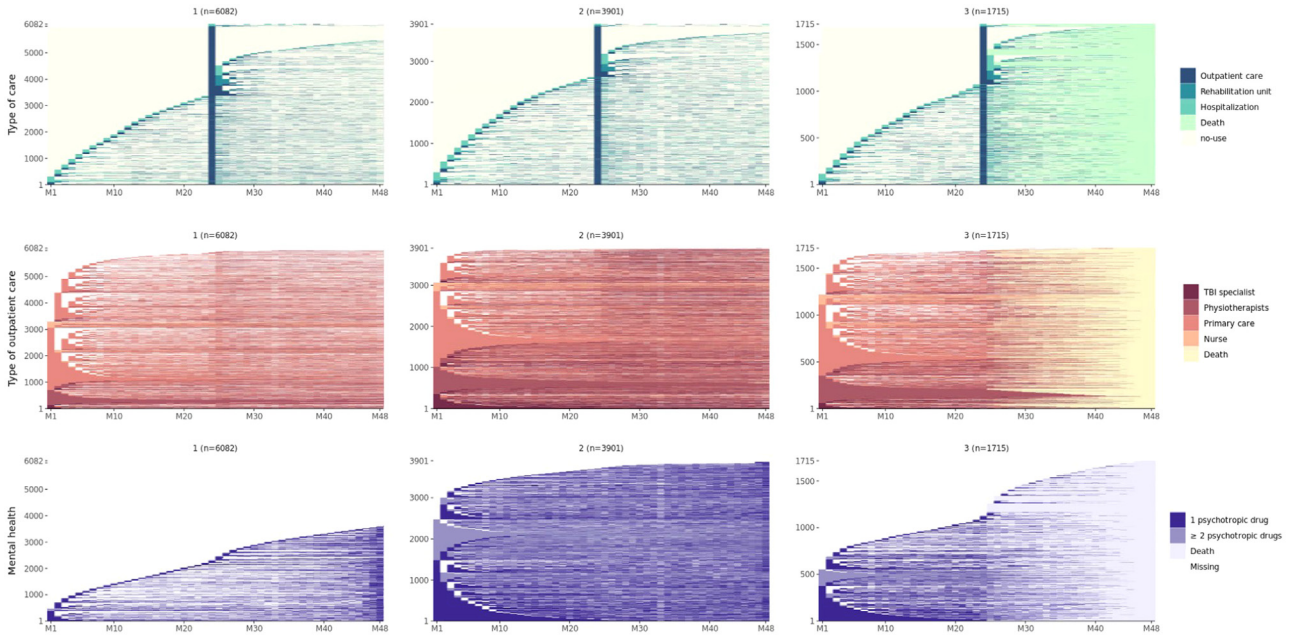


Figure 3. Typical care pathways for the senior group

Participants are displayed on the y-axis, while the time scale is shown on the x-axis. Each line represents the trajectory of a single person. Time is represented on a monthly scale, with the TBI occurring at month 24 (M24), at which point information is available for each person in Domain 1. The 2 years preceding the TBI correspond to the interval from M1 to M24, and the 2 years following the TBI correspond to the interval from M25 to the end of follow-up. Each cluster can be identified in the column panels, while each domain is represented in the row panels.

Cluster 4 includes 160 participants (1%). This cluster is characterized by death occurring in the immediate aftermath of TBI. It can be summarized as representing "severe injury"; this simplified label reflects dominant care patterns, not formal clinical programs.

For the senior group—Figure 3: Cluster 1 included 6 082 participants (52%). Domain 1 was similar to the previous cluster but showed a more pronounced increase in hospitalizations immediately after the TBI, lasting only 2 to 3 months. In Domain 2, there was moderate utilization of general medical care prior to the TBI, with a slight increase in physiotherapy use afterward. Domain 3 indicated lower psychotropic use compared to the other clusters, though a slight increase was noted after TBI, affecting only a small subgroup. This pathway, characterized by moderate utilization of general medical care, can be summarized as "Simple", a simplified label that reflects dominant care patterns, not formal clinical programs.

Cluster 2 included 3 901 participants (33%). In Domain 1, hospitalizations were already somewhat more frequent before the TBI, with a clear increase afterward. Domain 2 was characterized by extensive use of general medical care and nursing services prior to the TBI, which further increased after the injury, along with a higher reliance on rehabilitation specialists and physiotherapy. Domain 3 showed fragile mental health profiles, with higher consumption of psychotropic drugs before and after TBI. In summary, this pathway, characterized by intense rehabilitation care and physiotherapy, can be described as "Rehabilitation". This simplified label reflects dominant care patterns, not formal clinical programs.

Cluster 3 included 1 715 participants (15%). In Domain 1 (type of care unit), some hospitalizations were observed prior to the TBI, followed by a clear increase after the injury. Domain 2 showed very frequent use of general medical care and significant physiotherapy use. It can be hypothesized that these participants were already experiencing a loss of autonomy prior to the TBI. After the injury, physiotherapy intensified and continued to increase over time. Domain 3 indicated substantial psychotropic medication use prior to the TBI, which appeared to increase progressively over time. A substantial number of deaths occurred within the 2 years following TBI. This care pathway, characterized by death occurring post-TBI, can be summarized as "Complex". This simplified label reflects dominant care patterns, not formal clinical programs.

Factors associated with care pathways

Among young individuals, women had higher odds of belonging to the "Complex" (OR 1.59, 95% CI 1.31−1.92) and "Rehabilitation" clusters (OR 1.40, 95% CI 1.18−1.66) compared with the "Prevention" cluster, while they had lower odds of belonging to the "Severe injury" cluster (OR 0.60, 95% CI 0.41−0.88, Table 2, Model 1).

Age was positively associated with belonging to all clusters compared with the "Prevention" cluster (OR 1.10, 95% CI 1.09−1.11 for "Complex"; 1.03, 95% CI 1.02−1.03 for "Rehabilitation"; and 1.06, 95% CI 1.04−1.07 for "Severe injury").

In Model 2, socioeconomic deprivation with individuals in EDI quintile 4 had higher odds of belonging to the "Complex" (OR 2.41, 95% CI 1.70−3.43) and "Severe injury" clusters (OR 5.23, 95% CI 2.67−10.26) but lower odds of belonging to the "Rehabilitation" cluster was not statistically significant (OR 0.76, 95% CI 0.57−1.02). Similarly, individuals in EDI quintile 5 had higher odds of belonging to the "Complex" (OR 1.53, 95% CI 1.08−2.17) and "Severe injury" clusters (OR 2.25, 95% CI 1.12−4.52). CMU-C recipients had higher odds of belonging to the "Complex" cluster (OR 2.47, 95% CI 2.01−3.04), but lower odds of belonging to the "Rehabilitation" cluster were not statistically significant (OR 0.89, 95% CI 0.71−1.11). AAH recipients had higher odds of belonging to all clusters (OR 6.29, 95% CI 4.91−8.06 for "Complex", and OR 4.87, 95% CI 3.76−6.30 for "Rehabilitation", and OR 2.60, 95% CI 1.56−4.34 for "Severe injury").

In Model 3, the initial hospital episode type was associated with pathway assignment. Compared with participants hospitalized during the initial episode, those with an emergency department visit only had substantially lower odds of belonging to the "Rehabilitation" cluster (OR 0.80, 95% CI 0.67−0.97) and "Severe injury" cluster (OR 0.19, 95% CI 0.14−0.27).

Table 2
Multinomial GLM modeling of care pathways based on socioeconomic and medical characteristics, stratified by age.

	Young group				Senior group		
	Prevention	Complex *OR (95%CI)*	Rehabilitation *OR (95%CI)*	Severe injury *OR (95%CI)*	Simple	Rehabilitation *OR (95%CI)*	Complex *OR (95%CI)*
Model 1	Reference				Reference		
Sex							
Men							
Women		**1.59[b] (1.31–1.92)**	**1.40[b] (1.18–1.66)**	**0.60[b] (0.41–0.88)**		**1.93[b] (1.77–2.11)**	**0.67[b] (0.60–0.75)**
Age[c]		**1.10[b] (1.09–1.11)**	1.03 (1.02–1.03)	1.06 (1.04–1.07)		1.02 (1.02–1.03)	**1.08[b] (1.07–1.08)**
Model 2[a]							
EDI[c]							
1							
2		1.16 (0.77–1.75)	1.04 (0.78–1.39)	1.71 (0.77–3.79)		1.03 (0.89–1.20)	1.19 (0.97–1.46)
3		1.00 (0.69–1.44)	0.83 (0.64–1.08)	1.25 (0.60–2.61)		1.01 (0.89–1.15)	**1.20[b] (1.01–1.43)**
4		**2.41[b] (1.70–3.43)**	0.76 (0.57–1.02)	**5.23[b] (2.67–10.26)**		**1.25[b] (1.09–1.43)**	**1.26[b] (1.04–1.52)**
5		**1.53[b] (1.08–2.17)**	0.80 (0.61–1.04)	**2.25[b] (1.12–4.52)**		1.03 (0.90–1.18)	1.00 (0.83–1.21)
CMU-C[c]		**2.47[b] (2.01–3.04)**	0.89 (0.71–1.11)	**1.69[b] (1.18–2.41)**		0.80 (0.62–1.03)	0.95 (0.62–1.47)
AAH[c]		**6.29[b] (4.91–8.06)**	**4.87[b] (3.76–6.30)**	**2.60[b] (1.56–4.34)**		**3.92[b] (2.93–5.25)**	**4.72[b] (2.95–7.54)**
Model 3[a]							
CCI[c]							
0							
1		0.59 (0.05–6.61)	1.09 (0.29–4.14)	4.24 (0.60–30.14)		2.09 (0.83–5.30)	**18.78[b] (5.22–67.60)**
Initial hospital episode severity[c]							
Hospital stay							
Emergency department visit		0.99 (0.80–1.23)	**0.80[b] (0.67–0.97)**	**0.19[b] (0.14–0.27)**		1.08 (0.99–1.17)	**0.81[b] (0.72–0.91)**
Age[b]CCI		1.02 (0.97–1.08)	1.01 (0.98–1.05)	1.00 (0.95–1.05)		1.00 (0.98–1.01)	**0.97[b] (0.96–0.99)**

CCI, Charlson comorbidité index - Bannay revision; EDI, European Deprivation Index; CMU-C, French public complementary health insurance program; AAH, French disability benefit.

[a] Adjusted on sex, age, CCI, initial hospital episode severity, socioeconomic variable included in the previous model, and age.

[b] CCI.

[c] At the time of the TBI.

Among the senior group, women had higher odds of belonging to the "Rehabilitation" cluster (OR 1.93, 95% CI 1.77−2.11) and lower odds of belonging to the "Complex" cluster (OR 0.67, 95% CI 0.60 −0.75) compared with the "Simple" cluster (Table 2, Model 1). Age was positively associated with the "Rehabilitation" clusters (OR 1.02, CI 1.02−1.03).

In Model 2, socioeconomic deprivation showed limited associations among seniors compared with the young group, with individuals in EDI quintile 4 having higher odds of belonging to the "Rehabilitation" (OR 1.25, 95% CI 1.09−1.43) and "Complex" cluster (OR 1.26, 95% CI 1.04 −1.52). AAH recipients had higher odds of belonging to both the "Rehabilitation" (OR 3.92, 95% CI 2.93−5.25) and "Complex" clusters (OR 4.72, 95% CI 2.95−7.55).

In the fully adjusted model, the interaction between age and comorbidity was significant only for the "Complex" pathway, indicating decreasing odds with increasing age among those with comorbidities. In other words, the "Complex" cluster was more commonly observed among "younger" seniors with comorbidities, as each additional year of age was associated with only a modest 5% increase in the odds of belonging to this cluster among patients with comorbidities. Emergency department visits were associated with lower odds of belonging to the "Complex" cluster (OR 0.81, 95% CI 0.72−0.91).

Discussion

TBI is associated with complex healthcare needs and frequently exposes people to inequalities in access to care and continuity of follow-up. Individuals who have experienced a TBI often accumulate more disabilities, chronic diseases, and unmet healthcare needs, particularly women [27] and older adults [28]. Currently, post-TBI care trajectories are highly heterogeneous, reflecting this complexity, and no prior study has modeled care pathways both before and after TBI. In this work, we identified 6 distinct care trajectories among people with TBI, strongly influenced by age. Three trajectories were identified among the young group and 3 among the senior group. For young people: (1) "Prevention," which accounts for the vast majority of cases, comprising 89% of young people, and 3 other much smaller clusters: (2) "Complex rehabilitation," (3) "Rehabilitation center," and (4) "Serious injury," in which participants die as a result of the trauma. For seniors, the distribution across the clusters was relatively more balanced: (1) "Simple" which was the main cluster comprising more than 50% of seniors, (2) "Rehabilitation", and (3) "Complex". The clusters in the young group were primarily driven by socioeconomic deprivation, whereas in the senior group they were mainly explained by sex and comorbidities.

This study, based on the SNDS for patients with TBI, presents several limitations inherent to the use of healthcare databases. First, the absence of clinical data (such as Glasgow Coma Scale scores or imaging results) limits the ability to precisely characterize the severity of TBIs. This limitation is well-documented in the literature [29,30]. Nevertheless, injury severity currently guides care pathways [31]. We therefore approximated injury severity using hospitalization-related clinical criteria, considering the type of injury, which integrates age, diagnostic information, length of stay, discharge status (including death), selected procedures, and any admission to critical care. Based on these elements, we classified participants into 2 severity groups: a mild TBI group (stays <24 hours, consisting of an emergency department visit without hospitalization) and a moderate-to-severe TBI group (all hospitalizations, with possible critical care involvement and high-intensity procedures).

The CCI, commonly used in SNDS-based studies, does not account for psychiatric disorders, with the exception of dementia. Yet, individuals with TBI frequently present with psychiatric conditions and addictions [32,33]. To address this lack of information, we sought additional descriptive elements within the SNDS to capture psychiatric disorders, but no standardized evaluation scales were available. Dementia was identified using both the CCI and the "psychiatric disorders" variable. This dual identification strategy may have contributed to an overrepresentation of dementia at the time of TBI, due to potential overlap between comorbidity-based and psychiatric coding. Nevertheless, dementia remains a particularly relevant condition in this population, as TBI is known to increase the risk of developing dementia, especially following repeated injuries [34−36]. In addition, early diagnoses observed within the 2-year follow-up period may reflect the unmasking of

preclinical neurodegenerative conditions or increased medical surveillance after TBI, rather than incident dementia in all cases. These elements should be taken into account when interpreting the findings, and future studies should aim to isolate and characterize dementia more precisely.

French expert consensus for behavioral disorders after TBI explicitly recommends a non-pharmacological approach in first intention, combining psychotherapeutic, environmental, rehabilitation, and activity-based strategies. These recommendations are consistent with international and European dementia and TBI guidelines [37], explaining how the observed psychotropic medication use may reflect clinical complexity, comorbidities, or insufficient access to non-pharmacological resources.

Another limitation of the SNDS is that it only records healthcare reimbursed by the national health insurance system. Services covered exclusively by complementary health insurance, as well as non-reimbursed health products (eg, certain medical devices sold in pharmacies), are not captured, potentially underestimating total healthcare consumption [29,38]. Future research could integrate data from complementary health insurers or non-reimbursed pharmacy records to improve data completeness, although it should be noted that a substantial volume of care is already captured by the national health insurance system, which covers most services compared with other healthcare models.

The classification of people into 2 age categories presents notable methodological limitations, including threshold effects and loss of information regarding mechanisms specific to intermediate age groups. Arbitrary cutoffs can result in misclassification and potentially misinterpret the risks or injury mechanisms in TBI [39]. Current recommendations suggest moving beyond arbitrary age thresholds, favoring continuous or multi-category models that incorporate clinical, anatomical, and biomarker data to better capture the complexity of injury mechanisms and optimize TBI management [40]. In our study, age groups were defined using the median age of the participants, resulting in 2 groups with approximately symmetrical distributions, as illustrated in Appendix C. This age stratification represents a clinical and methodological compromise between the identification of highly specific care pathways and the need to provide a clear and interpretable visualization for this initial modeling of innovative care trajectories. Nevertheless, age was treated as a continuous variable in the statistical models, alongside other relevant personal characteristics.

Despite these limitations, several strengths of this study should be emphasized. First, the methodological approach was rigorous, starting with a comprehensive scoping review to develop the hypotheses [41], followed by the validation of the clustering methodology using a separate study on ischemic stroke [10], and finally, a large-scale analysis of national healthcare database data on TBI. This structured approach supports the robustness of our findings. Additionally, this TBI study benefits from a substantial volume of data with a long historical depth (2012−2020), allowing for an in-depth longitudinal analysis of both pre- and post-TBI care trajectories. The ability to investigate these trajectories beyond the acute phase provides a valuable perspective.

Death was treated as a competing event, and individuals were censored at the time of death; this aspect is important when interpreting care trajectories, as mortality—particularly among older adults—may contribute to reduced healthcare use during follow-up.

The study focused not only on post-TBI care but also on pre-injury care trajectories. This topic remains underexplored in TBI research, and future work on social and medical determinants, as well as pathway costs, would better identify their implications.

Finally, in France, several studies have developed individual-level deprivation indices based on variables such as entitlement to CMU-C, lack of personal housing, living without a partner, or foregoing healthcare for financial reasons. These indices capture a dimension of social vulnerability that goes beyond monetary income alone and are strongly associated with healthcare access, delays in follow-up, and poorer health outcomes. In other countries, different schemes play a comparable role. These include means-tested health coverage for low-income populations (eg, Medicaid or other social health protection programs), used as Yproxies for low income and vulnerability [42]; publicly funded supplementary or "safety-net" health insurance schemes that are functionally similar to CMU-C; and disability benefits, which serve as markers of both disability and economic deprivation [43]. In addition, multidimensional deprivation or poverty indices based on housing conditions, employment, education level, insurance status, and related factors are widely used [44]. Consequently, international comparisons are feasible when reasoning in terms of types of social protection rather than country-specific institutional labels.

These results emphasize the need for tailored post-TBI care pathways based on age, sex, socioeconomic deprivation, and vulnerability in younger individuals, or comorbidities in seniors. These factors define the profiles associated with the most complex trajectories. Uniform care risks failing to meet subgroup-specific needs and may worsen inequalities. Further analyses should identify "optimal" pathways and people at risk of deviation, enabling early, targeted interventions to prevent care disruptions and lost opportunities.

Beyond the scientific and methodological contributions, this work has important operational and clinical implications. It underscores the need to raise awareness—among healthcare professionals, both hospital-based and community-based—about specific TBI trajectories and the particular needs of these people. A better understanding of these care pathways could lead to more appropriate clinical practices, particularly in care coordination and post-acute follow-up. Within this framework, nurses play a pivotal role in coordinating these complex care pathways and guiding people through the healthcare system. Nurses' strategic position, at the interface of various healthcare providers, places them at the heart of care continuity and pathway fluidity, particularly in the early identification of people at risk of care disruption and in organizing timely and appropriate interventions.

This methodology and approach also hold potential for application to other chronic or acute conditions. The ability to identify typical trajectories and at-risk profiles could significantly benefit the management of other complex diseases, such as neurodegenerative disorders, diabetes, or severe psychiatric conditions.

Care pathways for individuals with TBI are highly heterogeneous and shaped by injury severity, age, comorbidities, and socioeconomic determinants, resulting in substantial inequalities in access to care and outcomes. Identifying these pathway typologies is essential for guiding policies toward greater equity and more tailored models of care. Social and economic inequalities persist across all stages of the TBI care trajectory, contributing to greater injury severity, higher costs, and poorer recovery. Although few studies have examined in detail the interaction between costs, care effectiveness, and social disparities, available evidence indicates that socioeconomic vulnerability increases both the complexity and the financial burden of care [41,45]. The literature increasingly calls for care models that incorporate social determinants in order to promote equity and improve recovery in people with TBI.

Conclusions

Our results highlight the importance of developing differentiated care pathways based on age profiles. A one-size-fits-all organization of post-TBI care risks failing to meet the specific needs of each subgroup and could exacerbate healthcare disparities. Socioeconomic deprivation was the main determinant of care pathway clusters among young individuals, while sex and comorbidities predominantly shaped clusters in the senior group. Future efforts should focus on identifying "optimal" trajectories and detecting people at risk of deviating from them. Early identification of these "at-risk" or "disengaged" people could enable personalized and targeted interventions to prevent care disruptions and loss of opportunities. Evaluating these "optimal" trajectories could also benefit from distributional cost-effectiveness analyses, which would not only measure overall health gains but also assess how these gains are

distributed across different social groups. Such analyses would support healthcare decisions aimed at improving equity and ensuring that the benefits of implemented strategies are not limited to the least vulnerable people.

Authors' contributions

NC and CD jointly supervised the work. FC, NC, LM, and XB were involved in the design of the study. HD, OA, and LM did the TUH data collection. XB was involved in the Delphi process. FC and RD did the data management and analyses. FC, RD, NC, XB, and CD interpreted the data. HD and MM contributed to the interpretation of data. FC drafted the initial manuscript. All of the authors contributed to the review of the results and the initial manuscript.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used DeepL Write to translate the article. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Data availability

Data can be made available upon request to the French Health Data Hub (HDH).

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Declaration of competing interest

None.

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Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.rehab.2026.102148.

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