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Cranial Reconstruction After Decompressive Craniectomy: Prediction of Complications Using Fuzzy Logic

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Introduction: Cranial reconstruction after decompressive craniectomy (DC) has been shown to be associated with a relatively high complication rate (16.4%–34%) compared with standard neurosurgical procedures (2%–5%). Most studies that have previously attempted to formulate a multivariate model for identifying factors predictive of postoperative complications of cranioplasty either were unsuccessful or yielded conflicting results. Therefore, fuzzy logic–based fuzzy inference system (FIS), which has proven to be a useful tool for risk prediction in medical and surgical conditions, was used in this study to identify predictors of complications of cranioplasty.

Methods: A retrospective chart review of all the patients who underwent DC followed by elective cranioplasty at Aga Khan University Hospital, during a 10-year period (2000–2010), was carried out to collect data on 24 carefully selected preoperative variables or inputs. The proposed FIS had 24 inputs, 3 outputs, and a set of 7 fuzzy-based rules. All inputs were assigned degrees of membership, and complications were further divided into "severe," "minor," and "least" output classes with each of them representing 2 membership functions: "less" and "more." For each set of inputs, a specific portion of the hypersurface was masked out. The centroid of this subsurface represented the defuzzified output corresponding to 1 percentage value for each output. The maximum of these outputs for each of the 3 output classes was selected to be the final output class. Each output class was compared to the actual outcome of patients, and positive predictive value, negative predictive value, sensitivity, and specificity of FIS for predicting complications were calculated.

Results: A total of 89 patients (mean [SD] age, 33.1 [15.0] y; male-to-female ratio, 3:1) were included in the study. The common postoperative complications included seizures (14.6%), cerebrospinal fluid leak (4.5%), neurologic deficits (3.4%), hydrocephalus (3.4%), superficial wound infection (3.4%), and osteomyelitis (2.2%). The FIS correctly identified all 7 patients who developed severe complications after cranioplasty (true positives) and all 82 patients who did not develop severe complications (true negatives). Thus, the FIS has a sensitivity and specificity of 100% in predicting severe complications.

Conclusions: Our study shows that the procedure of cranioplasty is associated with a high complication rate and that FIS has a 100% sensitivity and specificity in predicting severe complications after cranioplasty. It will prove to be an invaluable tool for clinicians once the results are validated by a similar prospective study with a larger sample size.

Key Words: Cranioplasty, complications, fuzzy logic

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With growing evidence in the support of decompressive craniectomies (DCs) as a management option for traumatic and nontraumatic cranial conditions, it is understandable that the number of DC being performed will also increase.[1,2] Consequently, the number of patients requiring cranioplasty, or replacement of the removed bone flap, a reconstructive procedure essential for the protection of brain, maintenance of normal physiology, and cosmesis is also bound to increase (Fig. 1).

It is interesting to note that, despite cranioplasty being a simple procedure, it has been shown to be associated with a high complication rate (16.4%–34%) compared with standard neurosurgical procedures (2%–5%).[3–5] This high rate includes complications arising because of superficial and deep infections, seizures, surgical site hematoma formation, hydrocephalus, and others. The present data collection was conducted in an attempt to identify preoperative patient-related factors predictive of postoperative complications of cranioplasty after DC. Most studies that have previously attempted to formulate a multivariate model for this purpose used standard statistical tools (such as SPSS) and were either unsuccessful or yielded conflicting results.[3–5] This was not just due to a small data set but also due to the fact that several of the input variables were Boolean type or qualitative in nature and, as such, not suitable for standard statistical tools.

Fuzzy logic–based fuzzy inference system (FIS) has proven to be a useful tool for risk prediction in medical and surgical conditions. The tool uses a physician's heuristics combined with available literature to develop mathematical models for identification of risk factors and thus works with both qualitative and quantitative data sets. It has been validated by previous researchers in comparison with multivariate models as well as where multivariate has failed.[6,7] It therefore seemed worthwhile to apply it on data set

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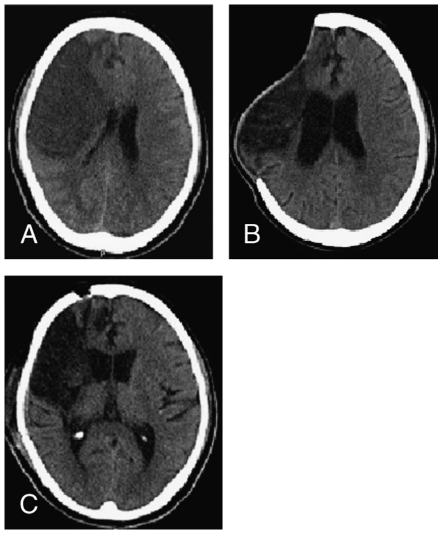

FIGURE 1. Patient before decompressive craniectomy (A), after decompressive craniectomy (B), and after cranioplasty (C).

acquired for patients who underwent cranioplasty after DC to determine possible risk factors for complications.

METHODS

Data Collection

A retrospective chart review of all the patients who underwent DC followed by elective cranioplasty at Aga Khan University Hospital, during a 10-year period (2000–2010), was carried out. Patients with missing or incomplete data were excluded. Data were collected using a predesigned questionnaire including patients' demographics; details of index surgery (craniectomy); complications of index surgery; additional procedures; details of hospital stay; details regarding cranioplasty including preoperative, intraoperative, and postoperative variables; second hospital stay; complications; and follow-up (Table 1). A comprehensive list of 25 carefully selected input variables was thus completed for each patient. These parameters are listed in column 1 of Table 1 under the heading, "Input Parameters." The second column in this table shows various degrees of membership assigned to these input variables and is a critical step in fuzzy logic–based analyses. Because the outcome of interest was the degree of complications, it was further divided into "severe," "minor," and "least" output classes (Table 2), with each of them representing 2 membership functions: "less" and "more." Although some of these complications are severe (and it is these that we intended to predict beforehand), there are cases of minor complications as well as cases with no complications that obviously do not require to be predicted. Hence, to ease the identification process, the minor and the least complicated ones were not subjected to rigorous modeling similar to the severe complication cases. This expected outcome served as the truth class, which was used to compare the results of the prediction. A numeric tag was associated with each type of complication: 3 for severe cases, 2 for minor, and 1 for least or no complication cases.

Fuzzy Logic and FIS Structure

Fuzzy logic was first described in 1965 and was defined as "a class of objects with a continuum of grades of membership."[8] The idea of fuzzy logic has been in the academic as well as research communities since then, and there seems to be more addition to the theory and philosophy of the technique with time. It is an extension to the conventional Aristotelian and Boolean logic as it deals with "degrees of truth" rather than absolute values of "0 and 1" or "true/false." Unlike a computer software, which only understands binary functions or concrete values like 1.5, 2.8, and so on, fuzzy logic is similar to human thinking and interpretation and gives meaning to expressions like "often," "smaller" and "higher." Fuzzy logic takes into account that the real world is complex and there are uncertainties; everything cannot have absolute values and follow a linear function.

The main motivation to use the Fuzzy decision capability in this problem is the fact that a real physician would use similar diagnostic approach by basing it on pure heuristics developed over the years and experience. Although experience is crucial, it also becomes subjective and would deprive a number of patients from a correct diagnosis if they are being treated by a much less-experienced

TABLE 1. Selected Features (Parameters) and Their Fuzzy Set Membership Values

Parameters	Fuzzy Set Memberships
Age	Young, medium, old
Medical problems	Low, high
Reason for surgery	Indication group 1, 2, 3
Location of surgery	At Aga Khan University Hospital, outside
No. procedures	Single, multiple
Flap parameters	Unilateral, bilateral
CSF diversion	No, yes
Preservation	Natural, cryogenic
Post op complication	No, yes
Delay in cranioplasty	Least, less, more, most
Consciousness	Least, less, more
Tracheostomy	No, yes
VP Shunt	No. yes
PEG	No, yes
Antiepileptic medicine	No, yes
Material for plasty	Type 1, type 2, type 3
Bone securing material	Type 1, type 2, type 3
Subgaleal drain	No, yes
Skin closure	Suture, others
Surgery duration	Short, long
Blood loss	Minor, small, large
Transfusion	No, yes
Hospital stay	Short, small, long
Antibiotic duration	Short, long

TABLE 2. Classification of Complications After Cranioplasty

Moderate Complications	Severe Complications
Superficial wound infection	New-onset neurologic deficits
Seizures	Deep wound infection (brain abscess, osteomyelitis)
Hydrocephalus	Hemorrhage requiring surgical intervention
CSF leak	Death

physicians. By incorporating a vast and diversified experience in this decision engine, a powerful tool has been developed for assisting neurosurgeons in making crucial decisions related to cranioplasty.

The FIS has been developed using MATLAB's Fuzzy Logic tool box. The proposed FIS has 24 inputs and 3 output as shown in Figure 2 and is composed of the following:

- Twenty-four input membership descriptors (representing the feature space),
- Three output membership descriptors for the 3 types of complications' classification, and
- A set of 7 rules that connects various degrees of memberships to the outputs.

The way these memberships were assigned various degrees is outlined in Figure 2. From the parameter values for each range of values of input space, certain groups were defined based on the available literature and experience of senior neurosurgeons with interest in trauma. Keeping in mind that each range is defining a different class without concerning the overlap regions between the feature classes. The groups were then plotted against the sample values, and depending on the occurrences of their peaks, they were assigned the degrees of membership. The actual values of the features were calculated using custom routines written in MATLAB 7 and provided a range of values for each parameter for each class. The output variables corresponded to the 3 classes of complications for each of which 2 Gaussian distributions memberships were selected for each class corresponding to "less" and "more." The data values, which were assigned artificial numeric values as a replacement for the actual qualitative values, were weighed higher for known severe complication cases. For instance, more than 6 categories of typical pathologies identified and were given simple numeric indices from 1 to 6. However, the indices 2, 4, and 5 (corresponding to some pathologic conditions) were noted to be related to severe complications. Hence, their indices were changed to 21, 24, and 25 to weigh them more compared with the other parameters. The same was repeated for every input parameter space. Some of the resulting memberships are shown in Figure 3. The membership degrees were also assigned in such a way that the rightmost degree (Table 1, column 2) was favorable for severe complications. The set of rules is an intuitive collection of antecedents and their consequents that most humans will agree with. In this case, a set of 7 rules was established based on an intriguingly simple logic.

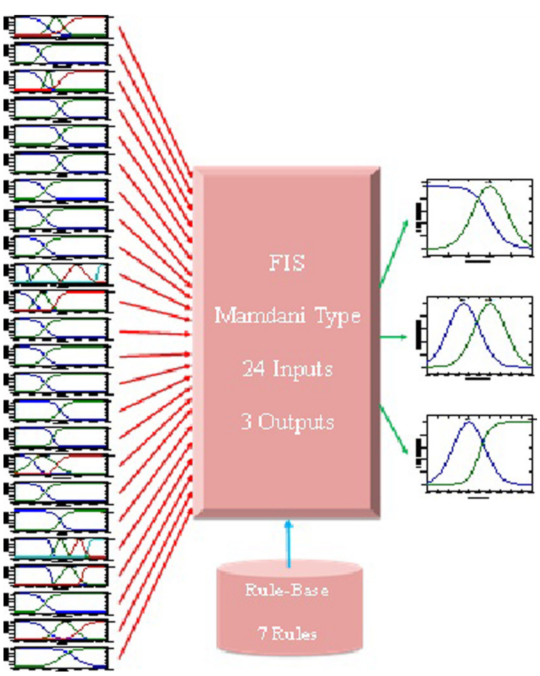

FIGURE 2. Fuzzy inference system structure.

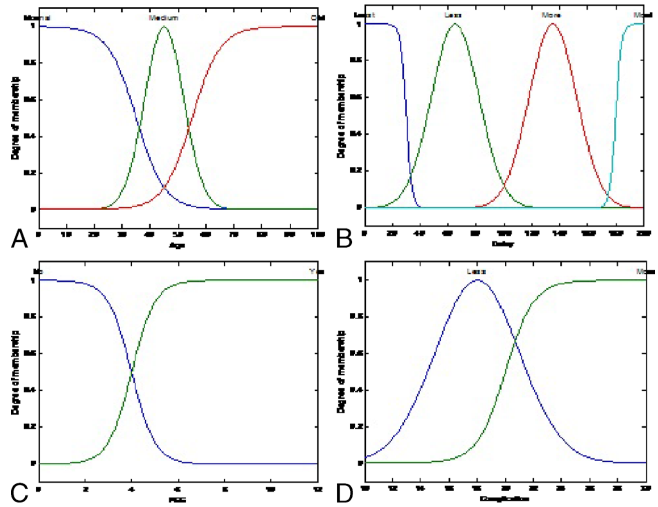

FIGURE 3. Membership functions: age (A), delay (B), PEG (C), and severe complications (D).

Each rule was developed based on the degree of membership for those known cases of severe complications. For instance, the first rule was formulated as a string of numbers that appears as follows:

1 1 1 1 1 1 1 2 1 3 2 2 1 2 1 2 1 2 1 4 2 1 1 1

This corresponds to a condition where including 1st membership function of the first 7 inputs, 2nd membership function of the 8th, then 1st for the 9th, 3rd for the 10th and so on, uses the Boolean "and" function. Hence, the resulting rule can be read as:

> If (Age is Normal) and (Comorbid is Low) and (Path is Least) and (Location is Inside) and (NProc is Single) and (Flap is Unilap) and (EVD is No) and (BoneFLP is Cryo) and (PostOpComp is No) and (Delay is More) and (GCS is Less) and (Trach is Yes) and (VPShunt is No) and (PEG is Yes) and (AntEpil is No) and (MatCP is Most) and (BoneSec is Type 1) and (GalDrain is Yes) and (Skin is Sutur) and (SurgDuration is Long) and (BloodLoss is Small) and (Transfusion is No) and (Stay is Short) and (ABX is Long) then (Complication is More)

These rules are outlined as a matrix of the following type:

1 1 1 1 1 1 1 2 1 3 2 2 1 2 1 2 1 2 1 4 2 1 1 1
1 1 1 1 2 1 1 2 2 2 1 1 1 1 1 1 1 1 1 3 3 1 1 1
3 2 1 1 2 1 1 2 1 2 1 1 1 1 2 1 1 1 1 3 3 2 1 1
1 1 1 1 1 1 1 1 2 2 1 1 1 1 2 1 1 2 1 4 2 2 2 2
1 1 1 1 2 1 1 2 2 1 1 1 1 1 1 1 2 1 2 3 2 1 3 1
2 2 1 1 1 1 2 2 2 2 1 1 1 1 1 1 1 1 2 2 1 1 2 1
3 2 1 1 1 2 1 2 2 2 2 2 2 1 1 1 1 1 1 1 2 2 1 1

TABLE 3. Results of Applying FIS to the Patient Data

	For Least Complicated		
	57 (Actual Positive)	**32 (Actual Negative)**	
Predicted positive	49 (true positive)	18 (false positive)	73.1% (PPV)
Predicted negative	8 (false negative)	14 (true negative)	63.64% (NPV)
	85.96% (sensitivity)	43.75% (specificity)	
	For Minor Complications		
	25 (Actual Positive)	**64 (Actual Negative)**	
Predicted positive	7 (true positive)	18 (false positive)	28% (PPV)
Predicted negative	18 (false negative)	36 (true negative)	66.6% (NPV)
	28% (sensitivity)	56.25% (specificity)	
	For Severe Complications		
	7 (Actual Positive)	**82 (Actual Negative)**	
Predicted positive	7 (true positive)	0 (false positive)	100% (PPV)
Predicted negative	0 (false negative)	82 (true negative)	100% (NPV)
	100% (sensitivity)	100% (specificity)	

The main decision related to which condition is more favorable for complication in the cranioplasty procedure was based on the following:

- Available truth classes showing the complications for these input arrangements and
- Discussion with senior neurosurgeons to confirm and/or affirm certain assertions appearing in the truth class of the data set.

The resulting decision surfaces are hyperdimensional and cannot be displayed as 1 hypersurface. However, for each set of inputs, a specific portion of the hypersurface was masked out. The centroid of this subsurface represented the defuzzified output corresponding to 1 percentage value for each output. The maximum of these outputs for each of the 3 output classes was selected to be the final output class.

Once all the structures were set up, all the inputs from 89 patients were fed to the FIS to calculate the output. For each output class, the known outputs were listed under Actual Positives and Actual Negatives for that class. The FIS predicted a specific input set into one of these output classes. If the Predicted output was True for Actual Positive, it was called True Positive (a). Similarly, if FIS predicted an Actual Negative then it was called True Negative (d). On the other hand, if prediction was Positive but actual was negative, it was termed as False Positive (b) and vice versa for False Negative (c). Using these 4 parameters, the following figures of merit are calculated[4] and are listed in Table 3:

- Sensitivity = $a/(a + c)$
- Specificity = $d/(b + d)$
- Positive predictive value (PPV) = $a/(a + b)$
- Negative predictive value (NPV) = $d/(c + d)$

RESULTS

A total of 89 patients were included in the study. The mean (SD) age of the patients was 33.1 (15.0) years, and the male-to-female ratio was 3:1. The most common indication for DC in these patients was blunt traumatic brain injury, followed by penetrating traumatic brain injury and tumors. The overall complication rate of DC was 38.2%, with 37 patients requiring more than a single procedure, including reoperations, external ventricular drain placements, tracheostomy, and others.

All cranioplasties were done electively and performed during the same admission in 19 patients, whereas the rest were done during a new admission. The mean delay for cranioplasty from the index surgery was 90 days (range, 30–348 d). The materials used for reconstruction of defect included autologous bone (66.29%), polymethylmethacrylate (PMMA) (16.85%), autologous bone modeled with PMMA (11.23%), and autoclaved bone flap (5.61%). To secure the flap, silk sutures (33.70%), Vicryl (29.21%), wires (20.22%), and plates (15.73%) were used. Sutures were used for closure of skin flap in 61 (68.53%) patients, while staples were used in 28 (31.46%) patients. Subgaleal drain was placed in 23 patients, lumbar drain in 11 patients and external ventricular drain in 3 patients.

The mean duration of cranioplasty procedure was 185 minutes (range, 67–381 min) with mean blood loss of 344 mL (range, 100–1300 mL) and 17 patients requiring blood transfusion. The mean hospital stay of the patients was 11.5 days (range, 2–84 d), and the mean duration of follow-up was 6 months (range, 1–36 mo). The common postoperative complications included seizures (14.6%), cerebrospinal fluid (CSF) leak (4.5%), neurologic deficits (3.4%), hydrocephalus (3.4%), superficial wound infection (3.4%), and osteomyelitis (2.2%). Twelve of these patients required corrective interventions including repeat surgery (25.0%), insertion of ventriculoperitoneal shunt (9.38%), and subgaleal needle aspiration of collected fluid (3.13%).

Death, new-onset neurologic deficits, deep wound infections (brain abscess and osteomyelitis), and postoperative hemorrhage requiring repeat surgery were classified as severe complications (Table 2) and were the main subject of our analysis. The FIS correctly identified all 7 patients who developed severe complications after cranioplasty (true positives) and all 82 patients who did not develop severe complications (true negatives). Only 7 (true positives) of 25 patients who developed minor complications were identified, whereas 36 (true negatives) of 64 patients who did not develop minor complications were correctly identified. Thus, the

FIS has a sensitivity and specificity of 100% in predicting severe complications and sensitivity and specificity of 28.0% and 56.25%, respectively, in predicting minor complications (Table 3).

DISCUSSION

The FIS has been developed using MATLAB's Fuzzy Logic tool box. It was first introduced in 1965 and was defined as "a class of objects with a continuum of grades of membership."[8] The idea of Fuzzy Logic has been in the academic as well as research communities since then, and there seems to be more addition to the theory and philosophy of the technique with time. Fuzzy logic manifests the idea to associate degrees of memberships to the values within a subset of possibilities instead of a hard yes/no–type decision. Interestingly, human beings operate on similar principle. For instance, the size of an object will be defined as "small," "big," and "huge" by a human observer instead of exact numerical values.

The concept of fuzzy logic is well established in mathematics and engineering, but its usefulness in medicine has been recently acknowledged and medical publications on fuzzy logic are increasing at a significant pace.[6,9] Fuzzy logic provides a suitable answer to complex medical problems because the grades and severity of disease are defined as "mild," "moderate," or "severe" and do not have specific numerical values that are analyzed by Aristotelian or binary logic. The FIS uses if-then-else–style rules combined with different membership functions for decision making. For example, in the case of cranioplasties, "If the GCS [Glasgow Coma Scale] is low preoperatively, the age is old, and the flap was bilateral, then rate of postsurgical complications will be high," and "If the age is young, blood loss during surgery is less, then the rate of postsurgical complications will be low."

Although cranioplasty is a straightforward and commonly performed procedure, it has a significantly high complication rate including seizures, hydrocephalus, infection, bone resorption, hematoma formation, and others. The complication rate in our study was found to be 36%, which is comparable to the complication rates reported in literature.[3–5] There are several studies discussing technical details about cranioplasty, but very few studies that have addressed clinical outcomes and complications after cranioplasty. Results of studies aimed at finding predictive factors related to complications after cranioplasty have not been conclusive. Stephens et al[5] reported a high complication rate, but none of the factors including type of injury, CSF leakage, prosthesis material, and initial GCS was significantly associated with the frequency of complications. Gooch et al[3] found bifrontal cranioplasty as the only significant predictive factor of reoperation after cranioplasty ($P < 0.01$). Guresir et al[10] reported the presence of ventriculoperitoneal shunt to have an association with formation of extradural or subdural hematoma ($P = 0.003$). Cheng et al[11] showed that patients' demographics (age, sex), mechanism of injury, swab culture results, prosthesis material, and GCS are not significantly associated with infection, although PMMA has a lower risk of infection compared with cryopreserved bone grafts. In contrast from these studies, a significantly higher rate of infection was seen in patients who underwent multiple procedures or if there was insufficient time interval between index surgery and cranioplasty.[11] Tumors[4] and use of HA as the graft material have also been associated with a significantly higher rate of complications.[12] Although the results of the aforementioned studies are contradictory and inconclusive, the FIS proposed in our study proved to be a very sensitive and highly specific tool for predicting severe complications after cranioplasty. This is probably because such data mostly contain qualitative variables and very few quantitative variables, and fuzzy logic best interprets these variables compared with multivariate analysis and logistic regression.

The proposed FIS has demonstrated the algorithmic structure and its feasibility for making human-like decisions for the risk classifications. Results clearly show that for the procedure of cranioplasty after DC, the application of fuzzy logic provides a reasonably accurate preoperative identification of cases not expected to have any complications, and a precise identification of cases expected to have serious complications, although it is not a useful means for the prediction of minor complications. However, in clinical practice, a prediction of minor complication does not change the management and therefore, such a prediction is of little significance. It is mainly the likelihood of serious complication, which needs to be identified preoperatively, to be able to discuss preemptive management strategies, including the option of delaying surgery until conditions are more suitable. For this reason, given its 100% sensitivity, specificity, PPV, and NPV, fuzzy logic seems to be an invaluable tool if the results of the current study can be validated prospectively and on a larger sample size. Although the results are not absolute and not the only tools available, they will facilitate the physician's correct anticipation and management plan. Moreover, these conclusions are based on 11 rules that are heuristically formulated based on the physician's experience and available literature and can surely improve as the number of rules and their combinations are experimented with more structural and logical variants.

CONCLUSIONS

Our study shows that the procedure of cranioplasty is associated with a high complication rate and that FIS has a 100% sensitivity and specificity in predicting severe complications after cranioplasty. It will prove to be an invaluable tool for clinicians once the results are validated by a similar prospective study with a larger sample size.

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