International Journal of Computing and Digital Systems
ISSN (2210-142X)
Int. J. Com. Dig. Sys. 13, No.1 (Jan-2023)

http://dx.doi.org/10.12785/ijcds/130123

Optimal Brain Structural Biometric Authentication through Medical Imaging

Shaleen Bhatnagar[1] and Aditya Kishore Saxena[2]

[1,2]*Department of Computer Science Engineering,Presidency University, Bangalore, India*

Received 14 Feb. 2022, Revised 16 Dec. 2022, Accepted 12 Jan. 2023, Published 31 Jan. 2023

Abstract: Brain is an organ which defines individuality of a human being. It is quite evident to make use of it for human biometric identification. The electrical impulses generated by the human brain while performing various tasks and showing behavior have been studied conventionally for human biometric authentication. But researchers have shown that the behavioral biometrics are very unstable and cannot guarantee successful authentication all the time. Thus, it is necessary to devise biometric features from the brain structure which is comparatively stable at macro level. Brain structural information can be identified from magnetic resonance imaging (MRI) images but for biometrics we require portable and low-cost machines for MRI imaging. Feasibility of the brain structural biometrics in near future has been established through a ladder of review of portable MRI machines. We have proposed a novel secure approach covering optimal structural information of the 3D brain which mitigates the unaddressed problems by previous approaches of brain biometric using structural information of the brain. The robustness and scalability of the template has been investigated thoroughly and found to be optimistic to establish a novel biometric modality in near future.
Keywords: 3D brain, Authentication, Brain structural biometrics, Hidden biometrics, Portable MRI, Security.

1. Introduction

Biometric analysis of the human body has been proved to be one of the safest mechanisms of authentication mechanisms. Conventionally, the security depended upon secret codes, keys, etc. which are susceptible to theft. Involvement of human biometrics personalizes the security to guarantee better reliability, security, and authentication [1]. Since biometrics belongs to identification of a human subject based on bodily unique features, there is one to one correspondence between the features and the human being leading to unique identification of a human subject. Biometric features can be structural in nature such as fingerprint, iris, etc. where specific structures on the external body parts are used, or they can be behavioral where the behavior or any activity performed by the subject is used for identification. In structural category, the biometric features can be superficial located on the external view of body such as fingerprint, ear biometric, etc. as well as it can be hidden such as retina, veins, brain signal or structure [2]. However, the visible biometric modalities are prone to spoofing and copying attacks which limit their application for high security areas [3]. Human brain is the most important part of the human body. A person's individuality entirely depends on the brain. We argue that mapping uniqueness among the brains of different persons should be established as biometric modality. Biometric information from the brain can be extracted either in the form of electrical signals [4] generated from the brain or the structural features of the brain [5]–[9]. Brain biometrics conventionally has been considered under the behavioral category since the electrical impulses are emitted by the brain while the human subject performs some activities, displaying emotions and thoughts. It has been observed that these impulses show unique features with respect to behavior shown by the subject [10]. Systems have been trained to identify the signal features and their uniqueness relative to behavioral activities by human subjects. However, faking the thoughts and feelings for particular situations lead to incompleteness of this biometric modality for high security areas [8] [9]. Brain structure is another important candidate feature for biometrics. The 3D brain has a unique structure and can be used to identify individuals. The reason for choosing structural features of the brain is that it is impossible to alter the structure of the brain nor can it be copied. So, this approach is immune to spoofing and copying attacks. The brain structure can be obtained by Magnetic Resonance Imaging (MRI) and Computing Tomography (CT) scans, which provide 3D, 2D high-resolution clinical images that can be analyzed to extract unique structural features from brain for biometric applications [5] [6] [7]. In this paper, we specifically talk about brain structural biometrics, its feasibility through portable MRI and demonstrate how we developed a strong and secure biometric template in comparison to the available schemes.

Graphical abstract of this paper is shown in figure 1.

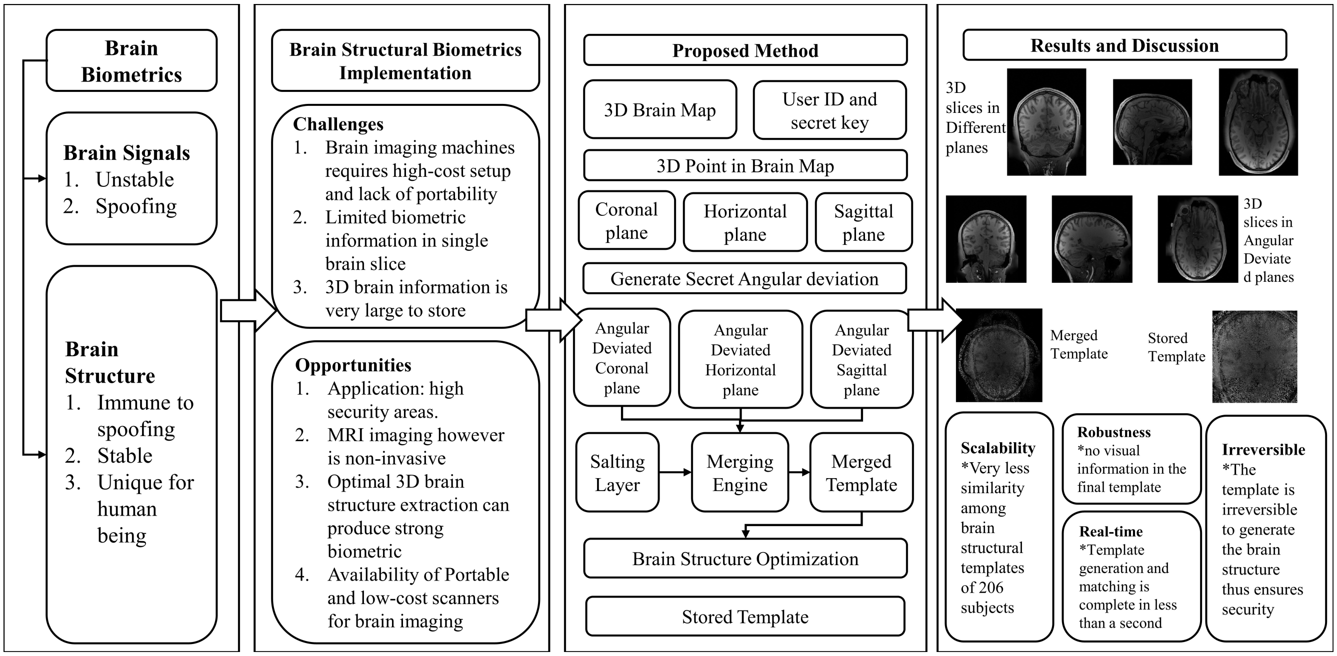


Figure 1. Schema of the proposed hypothesis and results

Four blocks in this figure from left to right depicts four major sections of this paper. First section is dedicated to introduction to brain biometric as a strong hidden biometric trait and how it outcasts the traditional biometric modalities. In the second block, the challenges and opportunities to implement brain structural biometrics have been shown. The proposed framework has been designed to counteract and provide solutions to the identified challenges by exploring the opportunities in this area. The third block of this figure is the top down flow diagram of the proposed work. Various entities taken as input or obtained during algorithm processing of the brain 3D structure have been sequentially displayed. The final block of this figure displays a glimpse of the results of template creation, how the final templates look while it also displays the scalability, robustness, real-time nature and irreversibility properties of the proposed work.

In the next section, firstly, we discuss the various techniques developed for brain biometrics with their advantages and scope of improvement to increase practicality and security. Next, we discuss how the portable MRI scans of brain structure can be used to ensure feasibility of the proposed brain structural biometric information.

2. Brain Structural Biometrics Challenges and Opportunities

Utilizing the brain structure as biometric is better than other biometric methods such as face, iris, hand, and fingerprints. The two main reasons are first, the brain defines individuality so its structure is unique and second, it is hidden so the brain structure cannot be copied or spoofed [5]–[9]. The original brain is a 3D structure, but it can be divided into many slices according to its generated slice size and thickness. Many features are extracted from the brain's 3D image like gyrification index, cortical surface curvature, brain gray and white matter volumes etc. [5] [6]. These areas can be obtained through segmentation of the brain images. Literature of feature extraction on brain images has been thoroughly reviewed by us but majority of the approaches [11] which extracts the brain signatures in the terms of medical features to distinguish normal areas from the abnormal areas for disease diagnosis. Segmentation in medical images targets to distinguish the pixels of a region with lesions from the pixels of the background and healthy tissues. In such approaches, feature extraction of the tumors or abnormal part of the brain is done and feature difference from the normal part is estimated. But in our case both these segmentation methods and feature extraction methods would not work as we assume the subject to be healthy and we need absolute brain structure instead of a comparison between normal and unhealthy parts of the brain. So, adding these reviews is out of scope of our paper.

A. *Review of Brain Biometric Methods*

Like general biometrics, the brain biometric also works in two modes of operation, first, the enrolment phase where geometric features of the brain were extracted and stored as templates. Second is the identification phase where the query template is compared with stored templates. In [6], brain shapes have been extracted using a segmentation approach involving 3D level sets. The structural parameters like isoperimetric ratio, the cortical surface curvature and the gyrification index are extracted. Gray matter and white matter volumes were evaluated in a volumetric study of the brain. The slice selection algorithm has been used to choose which brain slice is going to be analyzed. This algorithm includes steps to select a slice number, where the secret key is required to be entered by user and secret key along with a global key feed into a pseudo random key generator. To extract biometric features the first brain's region of interest is separated which is not optimal currently. Brain segmentation is performed by using Otsu's method to ignore extra parts of the brain and to extract biometric features. Brain print is a compact and lightweight representation of brain morphology which takes memory less than 9K bytes for a scan. It contains the shape information of brain anatomy. Brain-print based biometric approach is potentially robust for identifying individuals. The Sulco-Gyral structures and brain folds are unique to each person. Instead of storing image intensities directly, the main advantage of taking brain print is to store shape representation. The differences between brains can be calculated with brain prints which is very useful in neuroimaging [7]. The main problem with both of these approaches is that it uses the original brain structure and stores it in the form of a brain biometric template, so once this template is stolen then brain structural information can be compromised so it is necessary to store the template in a secure manner.

Authors in [8] created an artificial brain microstructure and did feature extraction from 2D brain MRI images. System showed good results at the time of verification but the challenge with all these linear approximation approaches is that the quantity of curve information available was limited as they considered a single slice. Focusing on geometrical characteristics of the brain's macro structures, authors in [9] presented a technique for extracting non-linear curves from MR images. Authors also considered only a single slice for feature selection which can create problems in the long term as brain plasticity is not taken into consideration. It is necessary to involve a complete 3D brain so that representation of maximum amount of brain structural information can be embedded in the brain template.

It is evident from the research works that a brain biometric template extracted from the structural features of the brain using MRI brain imaging is a promising method of implementing hidden biometrics. However, the main application of this biometric modality system revolves around the high security applications due to the need for MRI imaging. MRI imaging however is non-invasive and does not impact on human health but extraction of MRI scans of the whole brain using conventional MRI machines requires high-cost setup and lack of portability. It also takes time to scan the brain in comparison to the conventional biometric sensors. Using a single slice of the brain for biometric validation has limited structural information. The approaches for the brain biometrics discussed above have two major concerns which inhibits their use for practical and large-scale brain biometrics. First, there is a need for portable and low-cost devices and techniques which can deduce the brain structure in comparatively less time. Second, brain biometric template creation needs to be done such that it optimizes the structural information of the brain in the template, which increases the security, robustness and scalability of the brain biometric. 3D volumetric features of the brain have been used earlier but again full brain scan is required for the same which involves complex 3D volume and brain surface area estimation. Let us now summarize the existing low-cost and portable brain imaging methods which are actual enablers of the proposed work.

B. Review of Low-cost Portable Brain MRI Devices and Techniques

For over four decades, body MRI has been used in healthcare. It uses Fourier transfer imaging technique, which needs a homogeneous static magnetic field and linear gradient fields in the field of view. Although MRI has transformed healthcare but being expensive and sophisticated the MRI scans are still not in approach of many. MRI equipment generally needs specially constructed rooms with magnet quench vent pipes, entrance systems that check for metals attracted to magnets, and specialized protective measures. As a result, patients must be taken to the MRI scanners rather than vice versa. Applications which motivate the development of low cost and portable MRI include bed-side MRI facility for ICU patients, reduce the overall time, complexity, power requirements, noise, explore the scanning feasibility through low power magnets and permanent magnets with comparatively lower magnetic field exposure. Ultimately such research may lead to availability of brain scans to smaller health clinics rather than current availability at big hospitals of major cities only. To ensure utility of medical brain imaging for biometric extraction even in high security areas, it is essential to explore the availability of the portable brain scanners.

A device named **Hyperfine** now exists which can be wheeled to patient's bed [12] and uses **microwave imaging** and magnetic field intensities in **low field ranging** from 0.25 to 1T. The **Hyperfine Swoop™**, the world's first portable MRI scanner, went on sale in the US in 2020, because of its unique design and **ultra-low field** of view (0.064T). The bi-planar, three axis gradient system deployed in the point-of-care (POC) MRI has a peak amplitude of 26 mT/m and 25 mT/m, respectively [13] [14]. A **permanent magnet** is an alternative source of magnetic field. It is an artificial device constructed of magnetized ferromagnetic material that produces a continuous magnetic field and exhibits sudden magnetization in the absence of an extrinsic magnetic field below Curie temperature. **Permanent magnet arrays** that are smaller and lighter scan a greater volume encompassing organs like the skull. They can be a low-to mid-field system with no cryogenics, a definite fringe field, and no electrical power or heat dissipation requirements. It opens the possibility of building a genuinely portable, low-cost MRI scanner. MRI imaging has employed permanent magnet arrays that provide dipolar magnetic fields.

A unique configuration of permanent magnets is known as a **Halbach permanent magnet array**. On one side of the array, there is a high magnetic field distribution, while on the other side, the magnetic field distribution is reduced. A Halbach array can be single dimensional also known as **linear Halbach array**, two dimensional also known as **Halbach cylinder**, or three dimensional also known as **Halbach sphere**. The innovation of Halbach is mostly used to concentrate particle accelerator beams. The Halbach cylinder was utilized for Nuclear Magnetic Resonance and Magnetic resonance imaging applications. The Halbach array, in which flux is directed on one end and can be zero on the other end, allows an MRI system to fit into a tiny area, like an ambulance, without de-metaling in the area beyond the imaging volume [15]. The MRI system has been developed using an optimized **Halbach array of permanent rare-earth magnet made of neodymium** of around 120 kg including the gradient coils and radio frequency (RF) coils. The design is to fit around the head for brain scans. The power requirement is about 800W [16] [17].

An IO ring-pair aggregate made up of two identical annular magnets, based on an **Aubert ring pair**, was suggested to supply a spatial encoding magnetic field for head imaging [15] [18]. Patrick McDaniel et.al deployed a 2D generalized projection imaging with a lightweight Halbach magnet designed for brain imaging, and then improved the magnetic field pattern for better **rotational encoding** [19]. The portable scans from cylindrical Halbach arrays have been optimized and enhanced using **genetic algorithm (GA)** [20]. Thomas O'Reilly et.al proposed a cost - effective, lightweight permanent magnet-based MRI device. For operating at 50 mT, they constructed a **discretized Halbach permanent magnet array** with a bore diameter of 27 cm. On phantoms and in-vivo, custom-built gradient coils, RF coils, gradient amplifiers, and RF amplifiers were integrated and evaluated. **In a span of around 2 minutes, 3D in-vivo images of the brain of a healthy subject were obtained by a turbo spin-echo sequence with a spatial resolution of 4 × 4 × 4 mm**. **Tissue contrast was excellent** in both T1-weighted and T2-weighted images [21] [22]. This research has demonstrated that a low-field, portable and cost-effective MRI system can be built using hardware devices capable of acquiring human scans in-vivo in an acceptable amount of time [23].

Constructing an **organ-specific imaging system** either by permanent magnets or superconducting magnets will effectively minimize the size of the system [15]. Here, to build a compact scanner, the magnet and associated gear like gradient coils, radio frequency coils, and detecting coils must be constructed around the organ being scanned. Pissanetzky of the University of Houston proposed in a patent in 1995 that a magnet can be built around the organ being imaged such as **bagel shaped for breasts** and a **helmet-shaped magnet for head imaging**. Recently, Vaughan and his colleagues have suggested a half-sized liquid nitrogen-cooled magnet for head imaging [15]. **O-scan from Esaote** [24] is a portable MRI which provides optimum patient comfort and uses a small permanent magnet array and a convenient patient chair to scan all limbs and joints, including the knee, calf, foot, hands, ankle, wrist, forearm, and elbow. Zimmerman et.al created a tiny, cost effective, open-interface tabletop MRI scanner for educational usage and tested twenty of these **scanners in a teaching lab at MIT**. Fully functioning scanners were created after simplification and downscaling to a 1 cm field of view. It has **customizable GUIs**, pulse sequences, and reconstruction code, which made it easier to customize the scanner as per the demands of the project [20].

Other than MRI, there are other modalities available such as **Electrical impedance tomography (EIT)** which translates the electrical resistivity of the body into image intensities non-invasively. A portable and cost-efficient system has been implemented using signal processing on raspberry pi resulting in an increased temporal resolution. Working principle is to inject the current to all the electrodes concurrently at various frequencies. Thus, the fast changes in impedance can be captured to reconstruct real-time 2D images. Target is to monitor those imaging applications where the impedance varies quickly up to 70 frames/sec [25]. Another is **microwave imaging** which is helpful in identifying fatal diseases such as stroke and cancer at an early stage and has several advantages, including non-invasiveness, cost effectiveness, speed, and non-ionization. It has a wearable microwave head imaging system. An array of adjustable ultra-wide band antennas is built into the wearable gadget, which is shaped like a hat [26]. These scanners have open design that allows interventional brain imaging to be performed on the patient, they have relatively smaller footprints with sufficient bores, and various configurations due to the employment of permanent and resistive magnets, which optimize patient comfort and reduce claustrophobia.

In this subsection, we performed an exhaustive review of various low-cost and portable methods for brain MRI imaging of medically challenged subjects. During the review we have not encountered any significant research working on structural biometric features extraction with the use of portable brain scans. We deduce that as the research is on-going and recently promising devices have also been tested with patients. This imposes an optimistic opportunity to explore the brain biometric modality based on brain structural information. This structural information must be soon available for portable and practical use for day-to-day biometric applications instead of only applying it for medical purposes. This review also enables us with clear motivation of developing more secure and having optimal brain structural information.

In the next section, we describe how we extract optimal brain structural information and create a secure and scalable biometric template.

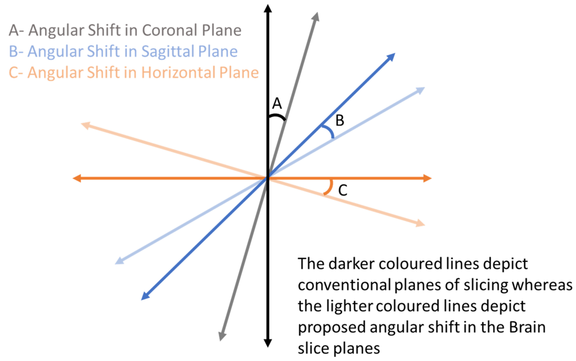


Figure 2. Idea of Secure Angular Shift of Brain slice planes

3. Proposed Method

We discussed various approaches which utilize the brain's structural information to create biometric templates in section 2A. The scope of improvement of these approaches have also been mentioned there as an opportunity to establish robust and scalable brain biometric modality.

A. Problem Formulation and Novel Solutions

3D volumetric features of the brain have been used in [5] but full brain scan is required for the same which involves complex 3D volume and brain surface area estimation. The approaches [7] [8] [9] use a single brain slice of specific thickness which may not have sufficient biometric details since they represent only one-dimensional brain structure. Moreover, single dimensional slices which are either coronal, sagittal or horizontal, depict limited structural information as it traverses the brain structure in a straight line parallel to these axes. We envision using the 3D structure of the brain by using slices in all the planes. In approach [8], an artificial polygon has been created using the brain curves but here matching of exact coordinates of brain curves may not be possible in some cases. Transformation of the brain's original structure is desired to maintain its secrecy [27]. However, multidimensional structural information must be used to increase robustness and scalability. We propose to use angular slices inclined to the coronal, sagittal or horizontal, directions as shown in figure 2. This may enhance the brain biometric template due to larger traversal of the brain structure. This also ensures the transformation of the original brain slices in natural planes to secret angular planes but still the actual brain structure is there. We also plan to apply low-complexity yet strong cryptography over the merged template. This will irreversibly transform the brain template and secure the original structure. Let us now understand the angular template creation method. Various data structures and their symbols used for proposed algorithm implementation have been explained in table I.

B. Proposed Angular Template Creation Method

Complete 3D brain map in Neuroimaging Informatics Technology Initiative (NII) format (BM) is taken as input along with a unique user ID (U) and a secret key (S) from the registering user. The secret key and user ID are used to generate a seed for a pseudo-random generator for the whole system. This key is used as the seed of a pseudo-random number generator. A 3D point is selected at random anywhere in 3D brain mass using this seed. Three slices, one in each plane, are extracted named as Coronal plane (N_SLC_COR), Sagittal plane (N_SLC_SAG), Horizontal plane (N_SLC_HOR) passing through this point with coordinates (px, py, pz). Now we generate secure angular deviations (xshift, yshift, zshift) from the secret key in all planes respectively as shown by A, B and C in figure 2. Each of these planes at 3D point is transformed with respective angular deviation. Angular interpolation is done to generate angular transformed

TABLE I. Various Symbols used in Proposed Algorithm

Sr. No.	Symbol	Use
1	BM	3D brain map in NII image format
2	U	User ID
3	S	Secret Key
4	K	Generated secret
5	Seed	PN generator seed
6	(px, py, pz)	3D point coordinates inside brain
7	N_SLC_COR N_SLC_SAG N_SLC_HOR	Normal Brain Slice Coronal plane Sagittal plane Horizontal plane
8	A_SLC_COR A_SLC_SAG A_SLC_HOR	Angular Transformed Brain Slice Coronal plane Sagittal plane Horizontal plane
9	Salt	2D matrix of salt with values {0, 1, 2}
10	merged_template	Brain biometric template obtained by merging of Angular transformed slices
11	ROI_template	Region of Interest Extracted from merged_template to be stored as final template

slices $A\_SLC\_COR, A\_SLC\_SAG, A\_SLC\_HOR$ in each plane respectively. The collective biometric information is created by merging these transformed slices such that the brain structural information remains secure. The slices are overlapped so that slices become layer 1, layer 2, and layer 3 respectively and create a brain cube. This brain cube has structural features of the brain overlapped from slices of all transformed planes. Overlapping causes an increase in structural information but yet the information is available in its original form. Also the brain cube is 3D in shape so it has larger size to be processed and stored for real-time security applications. So it is necessary to apply a second layer of transformation to reduce size and increase security. We apply salt cryptography to generate the final overlapped template.

C. Salt Cryptography

Cryptography is done to transform a secret information to an unreadable form so that the secret cannot be revealed. However, generally, cryptography is reversible and has steps such as encryption and decryption. However, we believe that security of the brain structural template would be optimal when the final generated and stored template is irreversible. Salt cryptography is once such a candidate that works in the sense of one-way encryption. The original data is salted with some random sequences generated using a secret code known to the user only. Salt can be used in many ways, such as mixing it to the original data to change its original form. It can also be used as a guiding sequence to transforming the data without actually getting mixed with it. We are using it in the latter way. Salt Cryptography has less complexity than other encryption methods having comparative attack complexity [28]. We create a salt using the same pseudo-random generator seeded initially. The generated salt is of the size of the individual 2D angular transformed slices i.e. $(320, 320)$ having $salt(i, j)\epsilon\{0, 1, 2\}$. i, j represents the pixel at i^{th} row and j^{th} column of slices and salt. This matrix of 0, 1 and 2 is used to merge the brain cube layers 1, 2 and 3 as per the logic described in algorithm 1 step 9 to create a merged template named as secure salted brain template. This salted brain slice is now stored for each subject as a template to transform the data. We are using it in the latter way.

D. Brain Region of Interest Extraction

The stored brain template has structural features of the brain but in secured form which is irreversible to obtain the brain structural information. However, this merged template has a surrounding area also as shown in figure 5a which should not be part of the template and may create unnecessary positive matches. To remove the surrounding area which does not depict brain structures, we run a region of interest (ROI) extraction algorithm to extract a 200 by 200 uniform template from the center of the brain. Algorithm 1 gives formal steps of the proposed method.

Algorithm 1: Proposed Secure Optimal Brain Structural Biometric Cube

Input:

1) Complete 3D brain map in NII format (BM)
2) User ID (U) and secret key (S) of the user

Steps:

1) Generate secret key $K = mod(U, S)$
2) Set pseudorandom generator (PNgen) seed= K
3) Generate a 3D point from secret key with Coordinates (px, py, pz)
4) Extract 3 slices at selected 3D point in the form of pixel matrices
   a) Coronal plane (N_SLC_COR)
   b) Sagittal plane (N_SLC_SAG)
   c) Horizontal plane (N_SLC_HOR)
5) Generate angular deviation from the secret key in all planes respectively using PNgen (xshift, yshift, zshift)
6) Transform each template with respective angular deviation
   a) Interpolating each row of normal slice with the corresponding row in the new angular plane $A\_SLC\_COR, A\_SLC\_SAG, A\_SLC\_HOR$
7) Secure merging of angular transformed slices
   a) Overlap angular transformed slices $A\_SLC\_COR, A\_SLC\_SAG, A\_SLC\_HOR$ as layer 1, layer 2, and layer 3 to create a brain cube
8) Create a 2D salting layer using PNgen
   a) Salt(320,320) with $salt(i, j)\epsilon\{0, 1, 2\}$, i,j represents the pixel at i^{th} row and j^{th} column of slices and salt
9) $mergedTemplate$=Apply salt cryptography security layer over brain cube
   a) if salt(i,j)==0
      i) $mergedTemplate(i, j) = layer1(i, j)$
   b) else if salt(i,j)==1
      i) $mergedTemplate(i, j) = layer2(i, j)$
   c) else if salt(i,j)==2
      i) $mergedTemplate(i, j) = layer3(i, j)$
10) Extract ROI from the mergedTemplate of size 200 by 200

Output:

1) Proposed secure optimal Brain structural biometric template of size 200 by 200

In the next section we present the results of the implementation of the proposed brain structural biometric template creation. We also discuss various performance parameters which proves the scalability of the proposed system.

4. Results and Discussions

As the dataset and imagery of brain structures from portable MRI scanners is not available for public research. We have used the Human Connectome Project, WU-Minn HCP Data - 1200 subjects [29] for the validation of the proposed algorithm. This dataset has structural Unprocessed

3D brain scans of 1,113 of 1,206 subjects. This package contains the Neuroimaging Informatics Technology Initiative (NIFTI) formatted T1 and T2 weighted scans, the associated scans necessary to construct field maps, and a .csv containing scan acquisition details. We implemented the proposed algorithm in MATLAB v2021a. In this paper, we present the preliminary result of development of secure biometric template creation. We tested the algorithm on 209 subjects randomly chosen from the dataset. The algorithm has been run on an Intel core i7 system with 16 GB of RAM, however the maximum processing required only 4GB of RAM as per CPU statistics during the execution.

A. Normal and Angular Transformed Slices

The 3D brain is scanned for specific slices in all three planes at the 3D point. The original slices at 3D point are shown in figure 3. These slices are angular transformed and interpolated. The angular transformed slices are shown in figure 4. It can be seen that these slices cover larger brain areas and curves in comparison to the normal slice. Moreover, these are very different in structure than normal slices.

B. Generation of Salted Brain Cube Template

The angular transformed slices contain the brain data which cannot be directly stored due security reasons. It has the brain structural information and to increase safety of the template it is necessary to encrypt the information and minimize it for storage. We perform salt encryption to produce encrypted templates. This encrypted template is an overlapped slice of all the three slices as shown in figure 5a. The actual brain template used here for storage also has another layer of security. A 200 by 200 brain image ROI template is selected from this overlapped slice. This template is chosen because it has a center from the densest part of the brain slices as shown in figure 5b.

C. Robustness of the Brain Template

To ensure that the template is secure and robust enough to be used for practical differentiation among human subjects, we analyze the generated brain cube template on the following three parameters.

1) No visual Information

First, there is no visual information in the final template about the actual brain structure as shown in figure 5a of the final salted brain cube template. Figure 5b shows the ROI extracted from the merged template. The ROI has size 200 by 200 and is selected such that it contains the maximum part of the brain slices and not the surrounding area.

2) Irreversibility to Recreate Actual Brain Structure

Due to the use of salt cryptography, the three angular transformed planes of the brain are merged into a single plane. The pixels in the resultant plane are chosen based on salt sequence. Even if the salt is known to the attacker, the three original planes having the brain structural information cannot be generated again from the salted brain cube template. The resultant image as shown in figure 5b, it is evident that from this image it is impossible to generate original brain slices. The process of template creation is irreversible to create original brain structure from it.

3) Template Uniqueness and Scalability

Brain slices should be unique since biologically no two subjects have the same physical and mental traits, both of them are governed by different parts of the brain. The structures of sulci and gyri create a unique macro structure. Due to choosing a 3D point in the brain mass and merging all the three angular transformed planes passing through this point to create the biometric template, it is desired that the merged template is unique for each subject so that there is significant difference between biometric templates of any two subjects. We estimate inter-subject template correlation which is a measure of the similarity between the templates. If correlation is high (maximum 1) then the templates are completely same otherwise they are unique. The correlation has been estimated for the worst case when ID and passwords are the same for all subjects, making the secret key same for all subjects. The best case has been chosen when all the user IDs and passwords are different, so the secret key is different for all. The proof of uniqueness is available in figure 6 and 7 where correlation between all the resultant templates of 209 subjects in the worst case has been shown. The diagonal line in figure 6 shows correlation between the templates of the same subject. Only this line is bright yellow in color, other than this correlation between templates of any two subjects is very less than this as depicted by greener and bluer areas. It is evident from the figure 6 that the correlation among the subjects is very less even in the impossible worst condition. Figure 7, indicates a histogram of correlation values of the stored templates for the worst case. A threshold correlation to distinguish genuine matches from other matches can be identified from this figure. In figure 7, a clear separation between the actual and false match proves that there is sufficient difference among angular transformed slices thus they are unique for every subject. For worst and best case the parameters are in table II. We present a worst case analysis to demonstrate the robustness of the proposed system in the worst case scenario. The peak in histogram is from 0.6 to 0.75 and most correlations less than 0.8 for worst case. Bar at correlation 1 has height of 209 which means diagonal matching in both histograms.

A biometric modality is said to be strong if the templates are unique as proved by correlation results. This is also necessary to make the biometric scalable to make a global biometric. Various performance metrics for worst case without ROI and best case are given in table II. The results shown proves the scalability of the system for a large population since the matching among the templates is very less.

D. Comparison with Previous Approaches

Proposed brain template extraction method is the first work to utilize 3D brain structure. Earlier only 3D brain

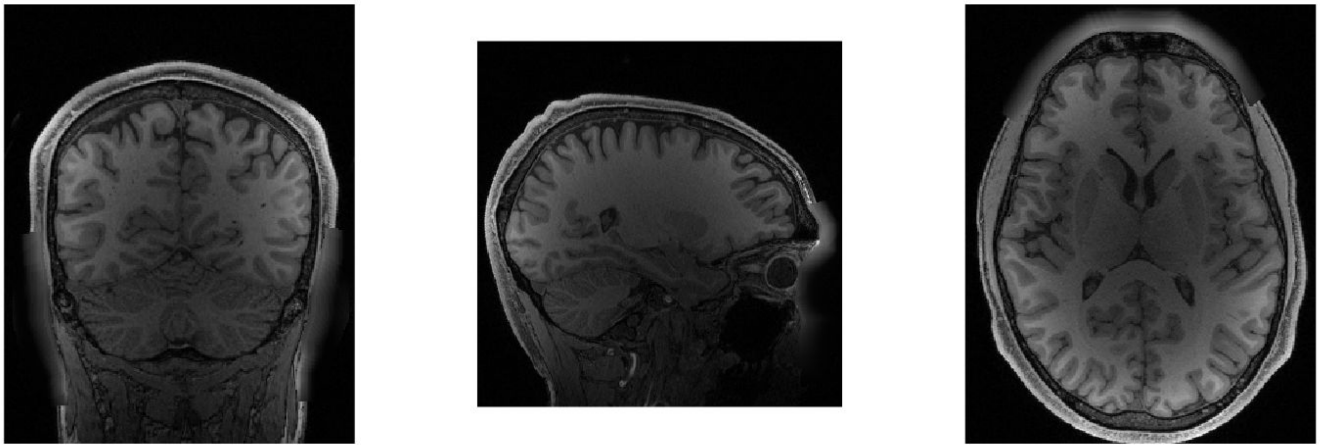


Figure 3. Normal Brain slices in coronal, sagittal and horizontal planes at 3D point

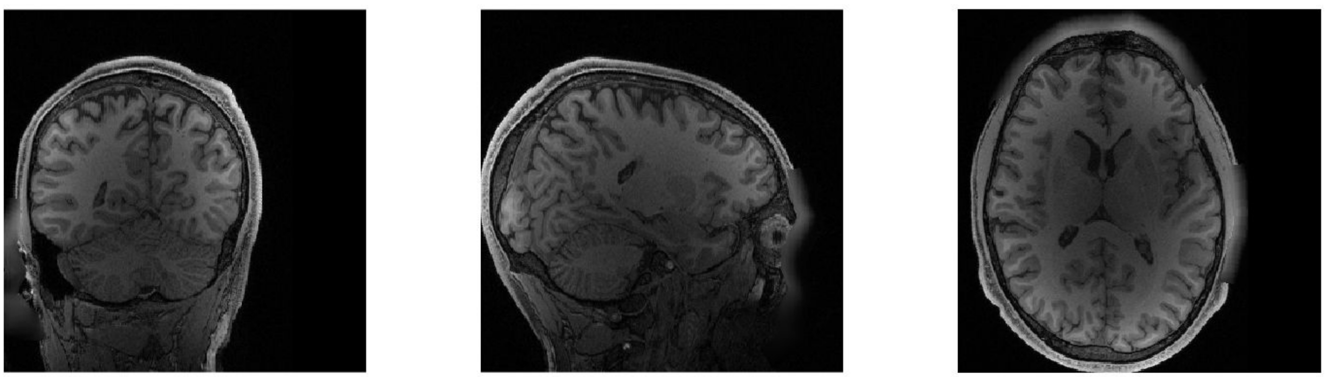
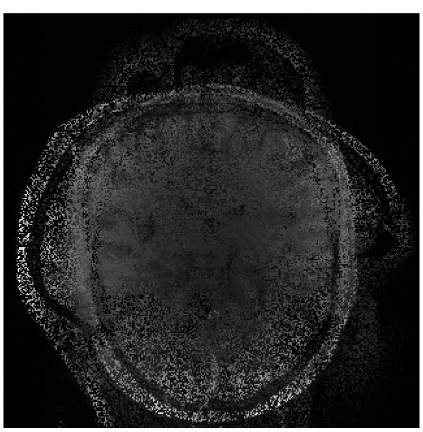
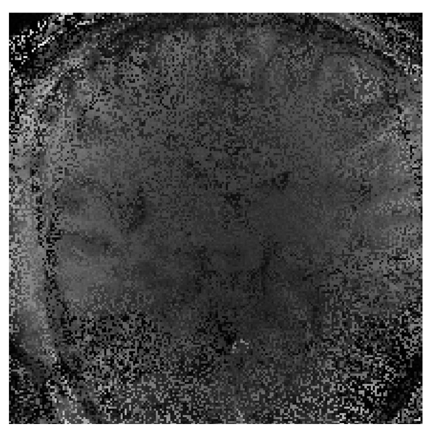


Figure 4. Angular transformed Brain slices in coronal, sagittal and horizontal planes at 3D point



(a) Salted irreversible brain biometric template



(b) ROI extracted from the merged template of size 200 by 200.

Figure 5. Resultant Brain Biometric Templates

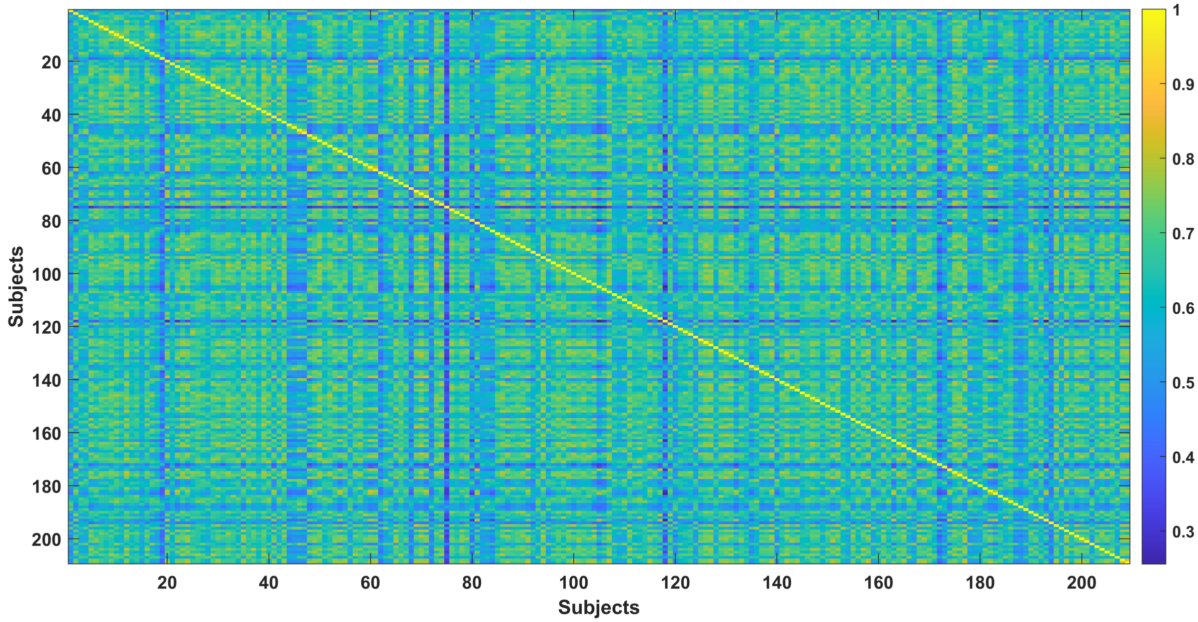


Figure 6. Image representation of correlation matrix among the 209 brain templates for worst case, the figure represents that the templates are sufficient different from each other

volumetric parameters have been used [5] [7]. We optimally extracted brain structure by using angular slices which covers more features of brain structure than normal straight slices. We represent the brain using 3 slices in different planes unlike approaches which use a single slice with insufficient biometric details since they [8] [9] represent only one-dimensional brain structure. We use correlation for matching of templates which is better than matching of exact coordinates of brain curves as they may fail in some cases [8]. Angular slices inclined to the coronal, sagittal or horizontal directions may enhance the brain biometric due to larger traversal of the brain structure and better than transformations described in [8] [9].

5. Conclusion and Future Work

This paper describes three important aspects of brain structural biometrics. First, it finds a research gap in the available brain structural biometric template creation methods. Previous brain templates required optimization in terms of structural information and security. Next, it explores the feasibility of low-cost and portable MRI brain imaging methods. These devices are essential for practicality of brain structural biometric in near future. Lastly, the paper proposed a secure brain biometric template creation which ensures that the brain structural information is kept safe. It also optimizes the brain structural information content by considering the novel angular 3D slices to create biometric templates. The time taken for template creation is less than a second thus, the method enables real-time applications. The similarity among the templates of different subjects is very less which indicates the scalability of the system. There is clear separation between the correct and false matches. The present work is an important step of a developing ladder to a complete brain structural biometric authentication system based on portable brain imaging devices.

In future, we look forward to developing a complete authentication system based on the proposed approach through portable brain imaging devices. Since these portable scanning devices have different image formats, standardization so bench-marking of the brain imaging is required to make the brain biometrics universally useful. This can be done through collaboration with the portable brain imaging device pioneers. The proposed work presented in this paper has been tested for scalability for the brain templates of 209 subjects. However, to establish this as a universal biometric modality like fingerprints, the proposed method needs to be tested on more subjects. Considering the optimistic results, we are looking forward to collaborating with various brain imaging centers and data repositories to test the method on a higher number of human brain maps. Currently, the time taken for brain scan has not been considered which may be high using state of the art systems, so research is also required in the direction of fast brain scans improving the chances of being used as day to day biometric modality.

References

[1] S. Bhatnagar, "Cooperative biometric multimodal approach for identification," in *International Conference on Information and Communication Technology for Intelligent Systems*. Springer, 2017, pp. 13–19.

[2] S. Bhatnagar and N. Mishra, "Conventional biometrics and hidden biometric: A comparative study," in *International Conference on Information and Communication Technology for Intelligent Systems*. Springer, 2020, pp. 473–481.

[3] A. Nait-Ali, "Hidden biometrics: Towards using biosignals and biomedical images for security applications," in *International*

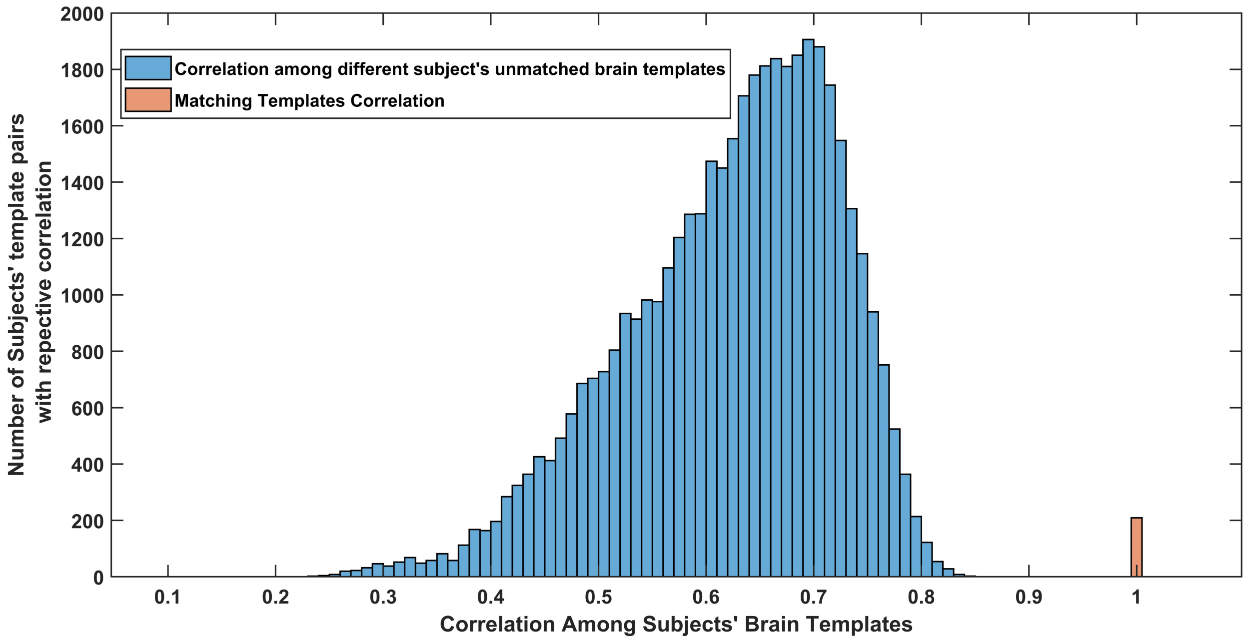


Figure 7. Histogram of correlation among the templates with most correlations less than 0.8 for worst case without ROI extraction. Templates have correlation 1 with themselves only.

TABLE II. Performance Metrics for Worst Case Scenario of the Proposed Method

Sr. No.	Parameter Name	Value	Significance
1	Average Correlation (Worst case without ROI) Average Correlation (Best case) Max Correlation (Best Case)	0.63 0.49 0.72	This value depicts the average matching among the stored brain templates. Lesser the average correlation more robust is the approach.
2	Average Max Correlation (Worst Case without ROI) Average Max Correlation (Best Case)	0.78 0.65	This value depicts the average of maximum extent of matching among the stored brain templates depicting that each template does not match with others more than this on average. (Here, the template has not been correlated with itself.)
3	Average template processing time (Worst Case)	0.46 sec	This depicts the processing time required for creation of brain structural biometric template from the 3D brain map. Time less than 1 sec depicts the real-time nature of the proposed algorithm.
4	Average template matching time (Worst Case)	0.23 sec	This depicts the average processing time required for matching a query template to all $N = 209$ stored brain structural biometric templates to determine the best correlating match.
5	Complexity of angular transformation and template creation	$O(n^2)$	Size of each normalized brain slice (nxn) pixels, we use 3 slice planes and $n >> 3$
6	Complexity of template matching	$O(Nn^2)$	Here N is the number of registered subjects. Ideally target $N > n$

Workshop on Systems, Signal Processing and their Applications, WOSSPA, 2011, pp. 352–356.

[4] Q. Gui, M. V. Ruiz-Blondet, S. Laszlo, and Z. Jin, "A survey on brain biometrics," *ACM Comput. Surv.*, vol. 51, no. 6, feb 2019. [Online]. Available: https://doi.org/10.1145/3230632

[5] K. Aloui and A. Na, "A new useful biometrics tool based on 3d brain human geometrical characterizations," 2012.

[6] K. Aloui, A. Naït-Ali, and M. S. Naceur, "New biometric approach based on geometrical humain brain patterns recognition: Some preliminary results," in *3rd European Workshop on Visual Information Processing*. IEEE, 2011, pp. 258–263.

[7] C. Wachinger, P. Golland, and M. Reuter, "Brainprint: Identifying subjects by their brain," in *International Conference on Medical Image Computing and Computer-Assisted Intervention*. Springer, 2014, pp. 41–48.

[8] S. Maheshwari and P. Choudhary, "Hidden biometric security implementation through human brain's artificial macro structure," *Procedia Computer Science*, vol. 78, pp. 625–631, 2016.

[9] M. Bassi and P. Triverbi, "Human biometric identification through brain print," in *2018 Second International Conference on Electronics, Communication and Aerospace Technology (ICECA)*. IEEE, 2018, pp. 1514–1518.

[10] Y. S. Soni, S. Somani, and V. Shete, "Biometric user authentication using brain waves," in *2016 International Conference on Inventive Computation Technologies (ICICT)*, vol. 2. IEEE, 2016, pp. 1–6.

[11] S. Saman and S. J. Narayanan, "Survey on brain tumor segmentation and feature extraction of MR images," *International Journal of Multimedia Information Retrieval*, vol. 8, no. 2, pp. 79–99, Dec. 2018. [Online]. Available: https://doi.org/10.1007/s13735-018-0162-2

[12] M. Editors, feb 2020. [Online]. Available: https://www.medgadget.com/2020/02/worlds-first-portable-mri-cleared-by-fda.html

[13] A. D. Elster., jan 2021. [Online]. Available: https://mriquestions.com/advantages-to-low-field.html

[14] K. N. Sheth, M. H. Mazurek, M. M. Yuen, B. A. Cahn, J. T. Shah, A. Ward, J. A. Kim, E. J. Gilmore, G. J. Falcone, N. Petersen *et al.*, "Assessment of brain injury using portable, low-field magnetic resonance imaging at the bedside of critically ill patients," *JAMA neurology*, vol. 78, no. 1, pp. 41–47, 2021.

[15] S. Huang, Z. H. Ren, S. Obruchkov, J. Gong, R. Dykstra, and W. Yu, "Portable low-cost mri system based on permanent magnets/magnet arrays," *Investigative Magnetic Resonance Imaging*, vol. 23, no. 3, pp. 179–201, 2019.

[16] J. M. Tyszka, "Compact brain mri," *Nature Biomedical Engineering*, vol. 5, no. 3, pp. 201–202, 2021.

[17] P. C. McDaniel, "Computational design and fabrication of portable mri systems," Ph.D. dissertation, Massachusetts Institute of Technology, 2020.

[18] Z. H. Ren, W. C. Mu, and S. Y. Huang, "Design and optimization of a ring-pair permanent magnet array for head imaging in a low-field portable mri system," *IEEE Transactions on Magnetics*, vol. 55, no. 1, pp. 1–8, 2018.

[19] P. McDaniel, C. Z. Cooley, J. P. Stockmann, and L. L. Wald, "3d imaging with a portable mri scanner using an optimized rotating magnet and 1d gradient coil," *Proceedings of the International Society for Magnetic Resonance in Medicine. Paris*, p. 0029, 2018.

[20] C. Z. Cooley, M. W. Haskell, S. F. Cauley, C. Sappo, C. D. Lapierre, C. G. Ha, J. P. Stockmann, and L. L. Wald, "Design of sparse halbach magnet arrays for portable mri using a genetic algorithm," *IEEE transactions on magnetics*, vol. 54, no. 1, pp. 1–12, 2017.

[21] C. Z. Cooley, P. C. McDaniel, J. P. Stockmann, S. A. Srinivas, S. Cauley, M. Sliwiak, C. R. Sappo, C. F. Vaughn, B. Guerin, M. S. Rosen *et al.*, "A portable brain mri scanner for underserved settings and point-of-care imaging," *arXiv preprint arXiv:2004.13183*, 2020.

[22] C. Z. Cooley, P. C. McDaniel, J. P. Stockmann, S. A. Srinivas, S. F. Cauley, M. Śliwiak, C. R. Sappo, C. F. Vaughn, B. Guerin, M. S. Rosen *et al.*, "A portable scanner for magnetic resonance imaging of the brain," *Nature biomedical engineering*, vol. 5, no. 3, pp. 229–239, 2021.

[23] T. O'Reilly, W. M. Teeuwisse, D. de Gans, K. Koolstra, and A. G. Webb, "In vivo 3d brain and extremity mri at 50 mt using a permanent magnet halbach array," *Magnetic resonance in medicine*, vol. 85, no. 1, pp. 495–505, 2021.

[24] "O-scan," july 2014. [Online]. Available: http://thznetwork.net/index.php/thz-images

[25] S. Anand, B. Lall, A. Srivastava, V. Singh *et al.*, "A low-cost portable wireless multi-frequency electrical impedance tomography system," *Arabian Journal for Science and Engineering*, vol. 44, no. 3, pp. 2305–2320, 2019.

[26] M. S. R. Bashri, T. Arslan, W. Zhou, and N. Haridas, "Wearable device for microwave head imaging," in *2016 46th European Microwave Conference (EuMC)*. IEEE, 2016, pp. 671–674.

[27] S. Bhatnagar and N. Mishra, "A review of mri brain print as hidden biometric," *TEST Engineering & Management*, vol. 83, p. 28571 – 28578, jun 2020.

[28] S. Khandelwal and G. prakash, "Multitier biometric template security using cryptographic salts and personal image identification," *ELCVIA: electronic letters on computer vision and image analysis*, vol. 13, no. 3, Oct. 2014. [Online]. Available: https://raco.cat/index.php/ELCVIA/article/view/284234

[29] V. J. W. B. Rosen, A. W. Toga, "Human connectome project (hcp) database," jan 2010. [Online]. Available: https://ida.loni.usc.edu/login.jsp

Shaleen Bhatnagar has completed BE in information Technology in 2009 and M.Tech in computer science & Engineering in 2013 from Rajasthan, India. Currently, she is pursuing Ph.D. from Presidency University Bangalore India while working there as Assistant Professor. She has teaching experience of 11 years. Her research interests include Biometrics, Computer Vision, Pattern Recognition, Image Processing, Image Analysis and Machine Learning.

Dr. Aditya Kishore Saxena received the bachelor's degree in Computer Science from the UP Technical University, in 2007. He has done the master's degree in Information Security from IIIT Allahabad. He was awarded Silver Medal for securing overall 2nd Position in the University. He completed Ph.D. degree from the Department of Computer Science, IIIT Allahabad, India, in 2017. He is presently working as Asst. Professor in Presidency University, Bangalore India. His research interests primarily focus on understanding how the behavior of individuals affects the overall mechanism of Biometric based authentication and classification.