A personalized brain atlas for everyone: unlocking new frontiers for individuals, humanity, science, and artificial intelligence

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Abstract. The brain's enormous complexity, together with the high global prevalence of neurologic disorders, necessitate the development of comprehensive and advanced neuromarkers to enhance both brain understanding as well as disorder prevention, prognosis, diagnosis, and treatment. I propose a combined neuroimaging and neuromodeling multi-purpose, multi-model, multi-dimensional, and multi-modal neuromarker in the form of an electronic brain atlas. This special type of brain atlas is a personalized brain atlas for everyone (*pBAe*), capable of systematically accommodating the condition of one's brain over time.

The *pBAe* is defined as a time series of navigable and quantifiable pairs of (raw brain scans; reconstructed and annotated 3D brain models), and I here address its content, data acquisition and harmonization, software architecture, construction methodology, and development strategy.

The proposed *pBAe* content and functionality are illustrated through the author's personalized brain atlas, demonstrating 3D structure, cerebrovasculature, and cranial nerves fully parcellated by color and labeled.

When deployed globally, the *pBAe* will have a profound impact on individuals, society, science, and AI development. For individuals, it offers deeper insights into brain structure, function, and disorders; quantified brain health; lifestyle modifications; early screening with predictive capabilities; continuous brain status monitoring; and personalized medicine, including targeted therapies. Individual *pBAes* worldwide would collectively form a massive neurodatabase whose analyses could drive new discoveries leading to improved public health and human well-being. Ultimately, the synergy between the *pBAe* initiative and AI can create a self-reinforcing ‘‘virtuous circle’’ accelerating progress in both fields.

Keywords: Human brain, brain atlas, personalized medicine, software architecture, 3D modeling, neurodatabase, computer graphics, AI, NeuroAI.

1 Introduction

A wide range of tests, measurable features, and biomarkers enable to monitor and evaluate a biological state or condition of the human body including anthropometric measurements (e.g., height and weight), physiological measurements (e.g., heart rate, blood pressure, and body temperature), cognitive and psychological metrics (e.g., intelligence

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DOI: 10.1007/978-3-032-29924-6_12

quotient and emotional intelligence), sensory capabilities (e.g., visual acuity and hearing sensitivity), and genetic and molecular biomarkers (e.g., blood type and genetic predispositions), among others. Moreover, some biometric features, such as fingerprints and iris patterns, serve for identification. Many biomarkers are simple, such as the blood type, which is fixed, and the height or pulse rate, which are variable. More advanced biomarkers in the form of biologically based predictive models have been used for screening, diagnosis, staging, prognosis, treatment selection, and monitoring in cancer [1] and heart diseases [2]. These types of biomarkers provide measures that can supplement clinical decision-making.

The human brain is the most complicated organ and neurologic disorders affect a considerable part of the global population. For instance, the Global Burden of Disease Study 2021 estimated nervous system health loss caused by 37 conditions between 1990-2021, founding that 3.4 billion individuals, i.e., 43.1% of the global population, were affected by neurologic disorders [3]. The brain's complexity and such a high prevalence of disorders worldwide demand comprehensive and advanced neuromarkers to enhance both brain understanding and disorder prevention, prognosis, diagnosis, and treatment. Some simple neuromarkers include intelligence quotient, emotional intelligence, memory capacity, and attention span. More advanced neuromarkers are needed in mental disorders and [4] outlines how the development of neuromarkers should occur in this field. A brain scan can be valuable as a neuromarker; however, normally, brain scans are only acquired in cases of head injury or symptomatic neurologic disorders.

To bridge this gap, I propose a combined neuroimaging and neuromodeling neuromarker in the form of an electronic brain atlas. This special type of brain atlas shall be a personalized brain atlas for everyone (in brief *pBAe*), progressively monitoring, capturing, and updating the information about the condition of one's brain over time. This work stems from our previous, three-decade-long human brain atlas development efforts, resulting in the creation of over 50 human brain atlas prototypes and 35 commercial products licensed to 67 companies and institutions and distributed in about 100 countries [5]. These atlases have been applied in neurosurgery, neuroradiology, neurology, human brain mapping, and neuroeducation. Here, I propose a novel type of ubiquitous brain atlas as a multi-purpose, multi-model, multi-dimensional, and multi-modal neuromarker applicable in a new niche, namely, serving as a tool for laymen, clinicians, and ultimately the global research community. To my best knowledge, this is a pioneering work as there is no personalized brain atlas yet created for anyone in the sense as defined here; fortunately, my personal 3D brain atlas extended to the head and neck [6,7] partly meets the *pBAe* definition and, as an instance, is employed for illustration.

This work introduces the concept of the *pBAe*, outlines the materials, methods and tools enabling its development, illustrates its content and main functions as well as discusses its potential clinical, social, scientific, and technological impact.

2 Materials and method

Here, I define the *pBAe*, determine its content, software architecture, discuss data acquisition and harmonization, and present the method for *pBAe* construction.

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Definition. The human brain maps and atlases have been developed for more than one hundred years, and the role and definition of brain atlases have evolved over time [8]. The brain atlas is commonly regarded as a neuroimage repository, brain database, or brain template. By several authors, brain atlases are considered: a research tool to make generalizations about localization of function and structure [9]; useful references and analytical tools as well as a framework for data sharing [10]; large-scale neuroimaging databases that capture the mean and variance in the population [11]; and tools to integrate in a topographically meaningful manner diversified information about numerous aspects of the brain [12]. I have earlier defined a multi-purpose, user-extendable, and reference human brain atlas as "a vehicle to gather, present, use, share, and discover knowledge about the human brain with a highly organized content, tools enabling a wide range of its applications, massive and heterogeneous knowledge database, and means for content and knowledge updating and growing by its user" [13].

The *pBAe* is an instance of this general definition. To make the *pBAe* definition more specific and compact, it must reflect that the *pBAe* shall contain time-related brain changes and serve both its owner and his/her healthcare provider (and, in the long term, the global research community). Brain changes over time can be obtained by the acquisition of multiple brain scans. To make these scans more "understandable" by a layman, they shall be converted to 3D models, which are subsequently annotated with structure and function. Hence, the *pBAe* is defined as a *time series of navigable and quantifiable pairs of (raw brain scans; reconstructed and annotated 3D brain models)*.

Atlas content and data acquisition. I propose the *pBAe* to initially include structure, cerebrovasculature, and cranial nerves. The structure contains the main parts of the brain, including the cerebrum with the cerebral cortex, subcortical nuclei, and ventricular system; cerebellum; and brainstem. The cerebrovasculature comprises the arterial and venous systems. The cranial nerves contain twelve pairs of CN I – CN XII nerves.

The cerebral cortex, parcellated (subdivided) into lobes, gyri, and sulci, comprises the primary motor, somatosensory, auditory, and visual cortices as well as the association cortices involved in behavior and intellectual processes. The subcortical nuclei are involved in many functions, including the thalamus relaying sensory information from the body to the cerebral cortex, the hippocampus being involved in memory and learning, and the amygdala determining the emotional, motivational, and social significance of sensory inputs, among others. Moreover, the hippocampus as a neuromarker shows rapid loss of its tissue in the early stages of Alzheimer's disease [14], while the enlargement of the ventricular system is an indicator of brain atrophy or hydrocephalus.

The cerebrovasculature is critical regarding stroke, which is the second leading cause of death worldwide. In the case of ischemic stroke, the standard time window for intravenous thrombolytic treatment is 4.5 hours from the stroke onset to therapy [15]. However, this time window for some individuals may be longer depending on collateral circulation, which provides the auxiliary vascular structures and alternative routes for blood flow to compensate for it when compromised due to stenosis or occlusion of the principal supplying arteries. Conversely, some vascular variants may reduce potential circulatory anastomoses, i.e., connections between blood vessels. Therefore, the knowledge of vascular collaterals and variants is vital. The main circulatory anastomosis is provided by the arterial circle of Willis located at the skull base, which

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DOI: 10.1007/978-3-032-29924-6_12

interconnects the anterior circulation (through the internal carotid artery) with the posterior circulation (via the vertebral and basilar arteries).

The cranial nerves are involved in the senses, such as smell (CN I), vision (CN II), hearing and balance (CN VIII) as well as control of facial expressions (CN VII) and eye movement (CN III, IV, VI), among others.

The structure, vasculature, and cranial nerves can be imaged through magnetic resonance imaging (MRI). There are numerous MRI pulse sequences to image various features and tissues [16-17]. The structure can be imaged employing T1-weighted images, especially MP-RAGE (magnetization-prepared rapid gradient echo), which is a 3D T1-weighted sequence. To image the arterial and venous systems, magnetic resonance angiography (MRA) and magnetic resonance venography (MRV) are employed, respectively. The TOF (time-of-flight) MRA sequence does not require contrast agents, whereas CE (contrast-enhanced) MRA involves contrast agents. SWI (susceptibility-weighted imaging) is suitable for imaging veins without contrast agents [18]. The SPGR (spoiled gradient-recalled echo) sequence images both structure and vasculature and is helpful to spatially register the structural with vascular scans. The cranial nerves can be imaged by employing T1-weighted, T2-weighted, and SSFP (steady-state free procession) sequences [19].

The use of MP-RAGE structural imaging to construct a 3D interactive and stereotactic atlas of the cerebrum, cerebellum, and brainstem is described in [20]. A 3D interactive and stereotactic cerebrovascular atlas reconstructed from TOF, SPGR, and SWI scans is presented and its validation discussed in [21]. A 3D interactive and stereotactic atlas of cranial nerves is featured in [22].

Atlas construction. In general, a brain atlas is created in four major steps: data acquisition, data processing, application development, and validation. Data processing involves image segmentation, multiple scan registration, structure modeling, and structure parcellation (e.g, by color) and annotation or labeling (naming as well as assigning function and/or some parameters, such as vessel diameter). The design and development of human brain atlases have been covered in my previous work [7,13,23-24].

There are many methods and tools developed to support brain mapping, which also facilitate atlas construction, and some of them have been featured in [13]. For example, visualization and registration are supported by the *Visualization Toolkit* (VTK) and the *Insight Toolkit* (ITK), respectively, and these toolkits have been integrated into the *Medical Imaging Interaction Toolkit* (MITK) [25]. *FreeSurfer* is a neuroimaging toolkit for processing, analyzing, and visualizing human brain MR images, including an automation of cortical and subcortical segmentation [26]. *BrainSuite* is a collection of open-source software tools that enable largely automated processing of MR images of the human brain, segment and label grey matter, and provide the ability to create and use custom brain atlases [27]. *FSL* is a library of analysis tools for functional, structural, and diffusion neuroimages [28].

The *pBAe* shall contain the personalized database with the scans and 3D models, prospective and retrospective data harmonization, and be able to convert the scans into 3D models by automatically performing segmentation, registration, modeling, and annotation. It shall be empowered with tools for atlas content navigation, exploration, and quantification by placing the scans and models in a stereotactic coordinate system and

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providing coordinates, distances, areas, and volumes of selected locations, regions, and structures. Besides the personalized database, a common database shall also provide useful information about the brain and its structure, function, and disorders. There are many public brain-related web resources. For example, the *Neuroscience Information Framework* catalogs and surveys the largest searchable collection of neuroscience data with about 2,000 databases, atlases, and the largest ontology for neuroscience on the web [29]. *BrainInfo* comprises 15,000 neuroanatomical terms along with hierarchical relations of each structure to its superstructures and substructures [30]. NOW*in*BRAIN is a repository of more than 8,600 3D reconstructed neuroimages organized in 12 galleries [31-33].

The software architecture of the *pBAe* is presented in Figure 1.

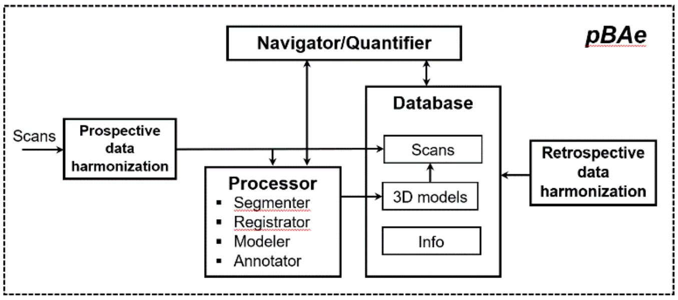

Fig. 1. The software architecture of the *pBAe*.

3 Results

To illustrate the potential of the *pBAe*, I use my personalized brain atlas [6], as to my best knowledge, this is the only existing advanced personalized brain atlas developed so far with about 3,000 3D components. Although it does not fully meet the atlas definition proposed here, it is sufficiently advanced to serve as an illustration.

The main components of the *pBAe* in 3D, i.e., the structure, cerebrovasculature, and cranial nerves, parcellated by color are shown in Figure 2.

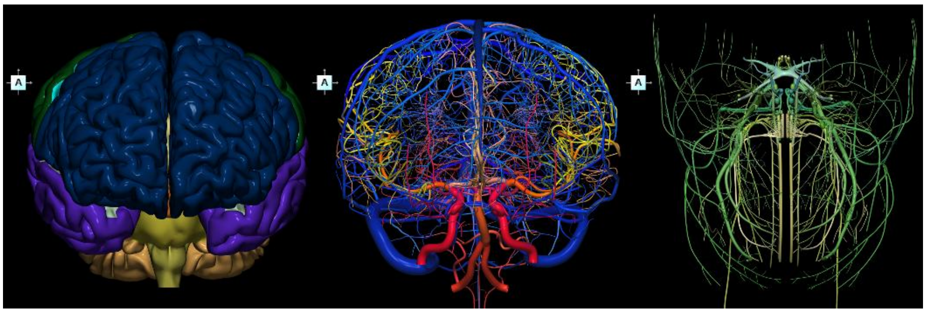

Fig. 2. Anterior view of the main components of the *pBAe* in 3D parcellated by color. Left) Structure. Center) Cerebrovasculature. Right) Cranial nerves.

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The structure, cerebrovasculature, and cranial nerves together parcellated by color and partly labeled with names are illustrated in Figure 3.

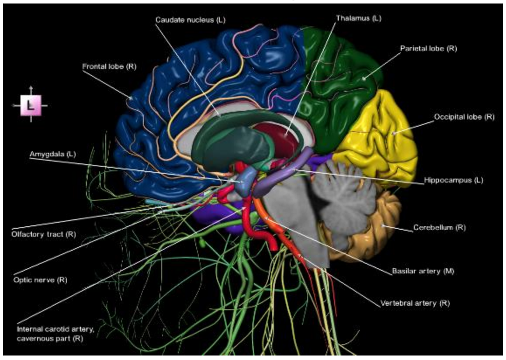

Fig. 3. Left view of the right structure (including the left subcortical nuclei), cerebrovasculature, and cranial nerves parcellated by color and partly labeled with names.

The primary motor, somatosensory, and visual cortices parcellated by color and labeled with structure and function are demonstrated in Figure 4.

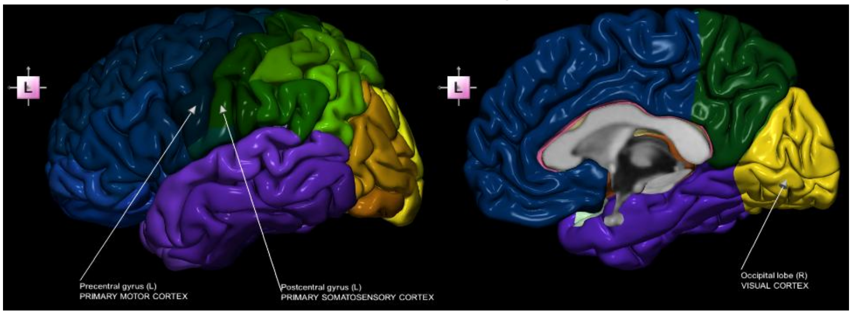

Fig. 4. Left view of the primary motor, somatosensory, and visual cortices parcellated and labeled with anatomic names and function. Left) The cerebral cortex parcellated into gyri with the precentral gyrus (the primary motor cortex) and the postcentral gyrus (the primary somatosensory cortex) labeled with names and functions. Right) The right cerebral hemisphere parcellated into lobes, and the occipital lobe (the visual cortex) labeled with name and function.

The atlas guides and enhances scan interpretation, as illustrated in Figure 5, where a 2D coronal MRI image is labeled with the hippocampus, which is also visualized in 3D.

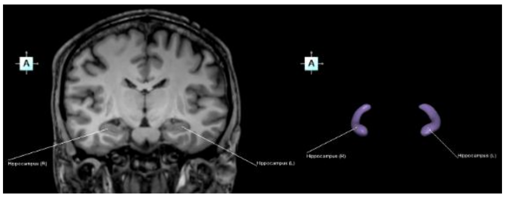

Fig. 5. Anterior view of the hippocampus. Left) An MRI coronal image with the hippocampus labeled by the atlas. Right) The hippocampus in 3D labeled.

The atlas is located in the stereotactic coordinate system and its structures can be quantified as illustrated in Figure 6, where, e.g., the distance between the left and right temporal horns of the lateral ventricles is measured.

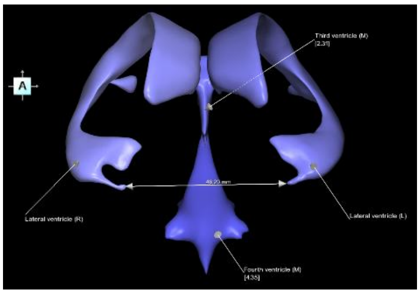

Fig. 6. Quantification of the ventricular system. The volume of the third and fourth ventricles (in cm^3) and the distance between the lateral ventricles' left and right temporal horns are measured.

The complete and incomplete arterial circle of Willis is illustrated in Figure 7.

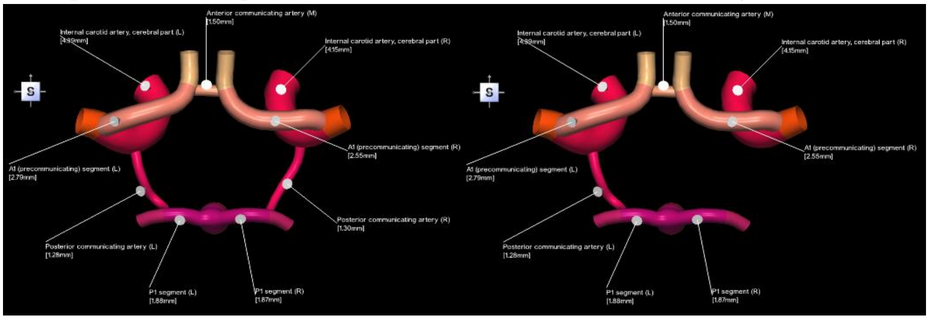

Fig. 7. The arterial circle of Willis. Left) The complete circle parcellated and labeled with vessel names and diameters. Right) An incomplete circle (absent right posterior communicating artery).

An unruptured aneurysm of the basilar artery compressing the oculomotor nerve CN III and causing the oculomotor nerve palsy is presented in Figure 8.

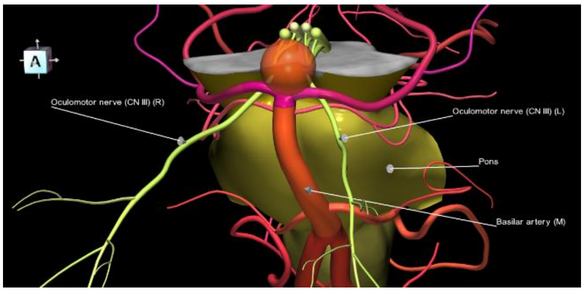

Fig. 8. The oculomotor nerve (CN III) compressed by an unruptured aneurysm (modeled as a ball) of the basilar artery causing oculomotor nerve palsy.

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DOI: 10.1007/978-3-032-29924-6_12

4 Discussion

I discuss the *pBAe* in terms of the feasibility of building, content extension, and impact. **Feasibility**. The feasibility of building the *pBAe* has technical and economic aspects. Technically, several tools (see Section 2) assist in the automation of atlas creation, at least for the cerebral cortex and subcortical nuclei. However, there is not yet a solution for automatic and accurate segmentation, modeling, parcellation, and labeling of the cerebrovasculature and cranial nerves; though there are various methods for automated cerebral vessel segmentation based on skeletonization, thresholding, mathematical morphology, deformable models [34], expectation maximization [35], statistical model analysis with curve evolution [36], atlas [37] and AI [38]. They are mostly for segmenting TOF MRA scans and are not able to handle smaller vessels, e.g., such as collaterals.

The cost of atlas creation depends both on its content and processing. More frequent scanning improves the temporal resolution of the atlas at the expense of its increased cost. Processing-wise, creating a detailed and accurate brain atlas that is fully parcellated and completely labeled by applying a traditional approach is a long-term and tedious process. Even for the given automatically segmented models, checking, labeling, and validating multiple models, each with thousands of components, is very time-consuming. For instance, the atlas [6] employed here for illustration contains about 3,000 3D objects, including 630 cranial nerve segments and 1,500 vessels (1,300 for the intracranial and 200 for extracranial cerebrovasculature). The difficulty in the automated labeling of vessels results not only from their large number but also from their high variability, as the cerebral arteries and especially the cerebral venous system are highly variable with numerous variants [39]. An illustration of the development of a 3D interactive brain atlas of cerebral arterial variants is featured in [40].

Therefore, one of the main goals of future work shall be to develop rapid and robust AI technology for the automatic conversion of subject-specific scans to 3D segmented and annotated cerebral models embedded in a personal *pBAe*. An example of a rapid and robust AI-based method is *BRAVE-NET* [41] - a multiscale 3D convolutional neural network for fully automated TOF MRA arterial brain vessel segmentation (though it is still unable to perform automated vessel labeling). The *BRAVE-NET* deep learning architecture integrates the 3D Unet with multiscaling for better spatial information integration and deep supervision for improving model convergence. It is robustly validated on high-quality labeled data of 264 patients with cerebrovascular disease. *BRAVE-NET* is of high performance, and for clinically used data dimensions, the segmentations can be obtained within minutes on a standard CPU system (e.g., 2 min on AMD Ryzen 7 1700X), and the same data on a standard GPU (NVIDIA Titan Xp) system take 40 sec. **Atlas content extension**. The atlas content proposed in Section 2 is quite basic. The smaller the atlas content, the easier and cheaper the *pBAe* development is. Moreover, its brain function is realized through annotations, so functionally, such a basic atlas is not fully personalized. On the other hand, extending this content and building advanced versions of the *pBAe* increases its potential at the expense of cost.

Individual structure- and function-based brain parcellations facilitate understanding anatomical and functional variations among individuals. Brain function can be noninvasively measured by applying different techniques, such as functional MRI. In

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DOI: 10.1007/978-3-032-29924-6_12

particular, resting-state functional MRI (rsfMRI) helps reveal the brain's functional organization [42]. Moreover, the integration of various modalities could provide a more comprehensive depiction of brain function and structural organization [43-44].

Brain connections (the connectome) play a central role in understanding brain function, cognition, behavior, and neurologic disorders. Individual differences in intelligence, memory, and personality characteristics can be linked to variations in brain connectivity. So far, the human connectome has only been created at the macroscale by providing anatomical and functional connectivity [45-46]. An example of a 3D interactive atlas of anatomical connectivity with parcellated and labeled white matter tracts is presented in [47]. The *MIDB Precision Brain Atlas,* developed by employing functional mapping, is a basic and clinical research resource with functional neural networks from over 9,950 individuals containing more than 53,00 network maps [48].

The extension of the *pBAe* with the spinal cord and spinal nerves is also vital, as they are part of the nervous system. Note that the prevalence of back pain resulting from various causes (such as musculoskeletal, nerve-related, lifestyle, and stress-related) increases with age, and low back pain is the leading cause of disability worldwide [49].

Modalities other than MRI can also be applied in the construction of a personalized atlas, such as cognitive tests, electroencephalography (EEG) to record the spontaneous electrical activity of the brain, and computed tomography (CT) enabling bone imaging. For instance, a cognitive test *Mini-Mental State Examination* (MMSE), a widely utilized tool for assessing cognitive function [50], can be employed to measure brain health [51]. EEG can also be used clinically to evaluate brain health [51]. CT is suitable for skull and spine imaging, and it facilitates, e.g., the detection and quantification of skull malformations (such as plagiocephaly, trigonocephaly, macrocephaly, and microcephaly). Having the skull and spine models included in the *pBAe*, makes them potentially useful in head and spine injuries as a pre-injury reference. An example of a 3D interactive and stereotactic skull atlas is described in [52-53].

Impact. The impact of the *pBAe* concept can be tremendous at various levels, including individual, social, scientific, and technological for AI.

Individual human brains vary immensely in morphology, connectivity, function, and organization. For an individual, the *pBAe* is potentially beneficial in health prevention, prediction, diagnosis, disorder monitoring, prognosis, and treatment progression. In health, as the *pBAe* provides annotated scans (Figure 5) as well as structures and cortical areas (Figure 3), function description (Figure 4), and quantification (Figures 6 and 7), the atlas owner can educate him/herself about own brain's structure, function, and disorders. The brain health status can be monitored by MR imaging being a common method of brain health measurement by structural volumetric estimates, particularly those of total brain volume, total grey matter volume, grey matter volume of specific regions (such as the hippocampus and ventricular system), and the presence and volume of white matter hyperintensities [51]; additionally, cognitive tests and EEG also measure brain health [51]. Such knowledge shall motivate the atlas owner to pursue a suitable lifestyle and adopt a healthful diet to keep the brain (and the body) healthy.

Knowing brain health measurement facilitates prevention and enables prediction. For instance, the identification and quantification of white matter hyperintensities are useful in stroke occurrence assessment as they are associated with an increased risk of

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DOI: 10.1007/978-3-032-29924-6_12

stroke [54] and its recurrence [55]. Similarly, the closeness of cranial nerves to unruptured aneurysms may predict neuropathy caused by nerve compression. Ischemic stroke is a leading cause of morbidity and mortality worldwide [56]. There are many methods for diagnosis and treatment of stroke, and under certain conditions, the standard 4.5-hour treatment window for intravenous thrombolysis can be extended [57]. Collaterals and vascular variants are vital as collateral circulation plays a crucial role in sustaining blood flow to the ischemic regions. Good collateral circulation has demonstrated protective effects toward a favorable functional outcome and a lower risk of stroke recurrence [58], whereas poor collaterals are associated with larger ischemic infarcts and worse clinical outcomes as well as higher occurrence of hemorrhagic transformations [59]. The circle of Willis, the primary collateral circulation, has many variants and less than 50% of patients have a complete, symmetrical, and well-developed circle (see Figure 7); these variants may considerably affect collateral blood flow, and they have been demonstrated to impact outcomes in ischemic stroke [59]. From the individual standpoint, knowledge about own collaterals is important, particularly in the case of poor collaterals, since regular exercise improves collateral circulation [60]. A potential application of a functionally parcellated *pBAe* in stroke is the decision-making in thrombolytic treatment. The risk of performing a thrombolytic procedure is the occurrence of hemorrhagic transformation, which may be fatal, so several conditions shall be checked [57]. For the atlas-assisted decision-making, brain atlases of anatomy and blood supply territories have been applied providing the complete list of anatomic structures and blood supply territories with their volumes and percentage of contributions to the infarct (i.e., damaged tissue) and penumbra (i.e., tissue at risk of progressing to infarction that is still potentially salvageable) [61-62]. The personalized functional brain atlas would enhance this decision-making by considering the trade-off between the risk of treatment versus the loss of functions in the penumbra region if not being treated. Note that this decision process could include the patient’s (or his or her family's) own preferences.

Personalized medicine [63] will benefit from the personalized brain atlas. Diagnostically, the process of *pBAe* construction and actualization acts as a sort of a screening mechanism. The scans could reveal, e.g., any non-symptomatic lesions or congenital malformations. In addition, 3D models could facilitate the detection of vascular and cranial nerve variations. As the *pBAe* is constructed as a time series, it monitors, quantifies, and documents the changes over time, such as brain atrophy and ventricular enlargement.

Therapeutically, in the case of head injury or brain intervention, the *pBAe* serves as a reference storing the brain state prior to intervention. Moreover, the knowledge of vascular and cranial nerve variations can impact surgical approaches.

Individual parcellation may enable precise targeting of therapeutic regions, for instance, in deep brain stimulation (DBS). A standard atlas employed in DBS procedures is anatomic, and our electronic brain atlases have been embedded in the surgical workstations of major companies, such as Medtronic, Brainlab, and Elekta [64-65]. Probabilistic functional atlases derived from neuroelectrophysiology [66-68] and multimodal anatomic-functional-vascular atlas [69] can further enhance DBS procedures. An additional improvement of DBS is potentially feasible via individual surgical targets derived from white matter connectivity such as [70-71] and embedded in the *pBAe*.

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Scientifically, the *pBAe* can contribute to “population neuroscience”. Assuming that even slightly more than 1% of the world’s population were to possess the *pBAe*, and that each owner agreed to make his/her anonymized copy available for research, this would result in a huge, distributed database of approximately 100 million complete human brains. Such a massive and heterogeneous database would enable, among many others, the studies of brain organization, function, and diverse features in the entire brain and its numerous regions along with their variability in health and disease across various populations in terms of age, gender, ethnicity, lifestyle, education, job, living place, and nutrition; examine trends like temporal (development and aging) and geographic; and test various hypotheses (e.g., regarding behavior, cognition, personality, memory, emotion, language, and nature of creativity). These efforts would drive new discoveries leading to improved public health and the betterment of humankind. A better understanding of the brain’s architecture, networks, functions, algorithms, and representations employed will expedite the development of more advanced neuro-related technologies, including AI, neuroprosthetics, and brain-computer interfaces.

A successful global deployment of such an enormous initiative requires the automated, rapid, and accurate conversion of brain scans to 3D parcellated and annotated cerebral models. AI appears to be the most promising technology capable of executing this task. Robust and rapid solutions, such as *BRAVE-NET* [41], able not only to segment but also to parcellate and annotate segmented 3D models, would facilitate the development of detailed personalized brain atlases such as [6] in minutes and not in years. Therefore, constructing increasingly advanced versions of the *pBAe* in progressively shorter timeframes along with the growing penetration of Earth's population will necessitate continual advances in AI capabilities. And reciprocally, the analysis of this immense neurodatabase, which would be continuously growing in the number of brains as well as the quality and complexity of brain models, would result in new brain discoveries and insights inspiring the growth of AI.

Hence the *pBAe*, considered a process and a global initiative of continuously increasing both atlas complexity and its population penetration, will influence AI advancements and, at the same time, be influenced by them. Therefore, the symbiosis between the *pBAe* initiative and AI can create a ‘‘virtuous circle’’ advancing both fields. Several authors have already addressed the convergence and complementarity of AI and neuroscience [72-75]. For instance, the role of neuroscience in advancing AI research along with the applications of AI for the advancement of neuroscience, has been discussed by a Nobel Prize winner (for his work on AI) Hassabis et al. [75].

Finally, future work on the *pBAe* advancement, besides involving AI, shall also integrate ongoing efforts on brain modeling and handling at the nanoscale [76-79].

Acknowledgments. This publication is supported by the European Union’s Horizon 2020 research and innovation programme under grant agreement Sano No. 857533. This publication is supported by Sano project carried out within the International Research Agendas programme of the Foundation for Polish Science, co-financed by the European Union under the European Regional Development Fund. The publication was created within the project of the Ministry of Science and Higher Education “Support for the activity of Centers of Excellence established in Poland under Horizon 2020” on the basis of the contract number MEiN/2023/DIR/3796.

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DOI: 10.1007/978-3-032-29924-6_12

Disclosure of Interests. The author has no competing interests to declare that are relevant to the content of this article.

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