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TOPICAL REVIEW

Next Generation Cognition-Aware Hearing Aid Devices With Microwave Sensors: Opportunities and Challenges

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ABSTRACT The strong association between hearing loss and cognitive decline has developed into a major health challenge that calls for early detection, diagnosis and prevention. Hearing loss usually results in severe health implications that include loss of mobility, communication problems and cognitive decline. This study provides an overview of the effects of hearing loss on cognition and progressive neurological disorders with a discussion on the future scope of microwave portable technologies in care homes arrangement. Moreover, the efficacy of hearing aids in reversing cognitive decline and dementia has been investigated. The interconnection between hearing loss, cognitive load and neurodegeneration is also explored. Furthermore, this study looks into the prospects of using portable microwave sensors for the detection and monitoring of cognitive load. For early detection of dementia, this study proposes the integration of microwave sensors with hearing aid devices. Implications and design challenges of portable antenna systems for neurodegeneration detection have also been considered. Future improvement areas regarding robust analysis and diagnosis, system accuracy and security, user-centricity and device privacy for a broader clinical implementation are also discussed.

INDEX TERMS Age-related hearing loss, cognitive load, dementia, mild cognitive impairment, microwave sensors, neurodegeneration, non-invasive, portable.

I. INTRODUCTION

More than 5% of the world's population suffers from hearing loss which is around 360 million people across the globe [1]. Hearing loss affects roughly 11 million people in the UK, making it the second most prevalent disability [2]. Hearing loss increases sharply with age, and affects more than 40% of adults over the age of 50 in the UK, growing to more than 70% over the age of 70 [3]. Around 75% of the old population in care homes is disproportionately affected by some form of hearing loss. Healthy ageing is linked to neurological and microvascular changes, which often means the start of Age-Related Hearing Loss (ARHL) and cognitive decline at the same time [4]. It is important to address hearing loss immediately after diagnosis, to diminish the adverse impacts. There are several measures available for the rehabilitation of people with hearing loss which include the use of hearing aids, middle ear and cochlear implants. Hearing aids could benefit 6.7 million of the 8 million individuals in the UK, but only two million use them [5]. Unassisted hearing loss usually leads to severe health implications in older people which include social isolation, mobility loss and cognitive decline. In the case of unassisted hearing loss, people with minor hearing loss are twice as likely as those without hearing loss to suffer from cognitive decline. People with moderate hearing loss are three times more likely to suffer from dementia,

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while those with severe hearing loss are five times more likely.

Around six million people in the UK suffer from brain-related diseases each year. Major elements that lead to neurodegeneration include cognitive loading, dementia, Alzheimer's disease and stroke. People with dementia experience memory loss due to neurodegeneration affecting brain areas responsible for creating and retrieving memories. The gradual nature of dementia, starting with the mild early-stage symptoms of cognitive degeneration and the low diagnosis rate, makes it difficult to have an early diagnosis. Mild Cognitive Impairment (MCI) is the period between the cognitive decline of normal ageing and the serious decline of dementia [6]. MCI may increase the risk of dementia triggered by Alzheimer's disease or other neurodegenerative conditions [7]. MCI is triggered due to various underlying medical conditions that may include high blood pressure, diabetes and heart issues. These underlying conditions may result in abnormal blood flow to the brain, which in turn can affect the cerebral metabolism and result in an increase in cognitive load [8]. Delay in diagnosis usually results in progressive loss of brain neurons that causes cognitive decline in elderly patients. Early diagnosis of cognitive load and removal of underlying risks is important to slow down the risk of cognitive decline and dementia [9]. Some existing radiology technologies like Magnetic Resonance Imaging (MRI), Positron Emission Tomography (PET) and Computerized Tomography (CT) scans can detect this degeneration at advanced stages but require extensive medical supervision and are expensive. Radiofrequency and microwave sensors can be an effective substitute for these conventional medical technologies. Considerable research in biomedical applications for wearable sensors is done during the past few years. These are directed more towards Alzheimer's disease [10], [11], brain tumour [12], hemorrhagic stroke [13] and cancer [14] detection. There is not much work done on wearable healthcare applications for cognitive load detection and dementia. There is a research gap in terms of microwave portable sensors for cognitive load leading to dementia detection. These portable devices can be linked to hearing aid devices for the estimation of cognitive load inside the brain. This can help to avoid the progression of neurodegeneration at a preliminary stage. Early detection of cognitive decline will help to ease the burden on both medical and care home facilities. It is also important to investigate the link between hearing loss, cognitive load, and dementia. This is the prime motivation behind writing this literature review.

The rest of this paper is structured as follows: Section II discusses the causes, implications and challenges that arise from hearing loss. Section III gives an overview of hearing loss implications on neurological function and progressive diseases, with a focus on cognitive load and dementia. The interrelation between hearing loss, cognitive load and dementia is also discussed. The prospects of early cognitive load detection in reversing cognitive decline and the onset of dementia are investigated in Section IV. The role of hearing aids in reversing cognitive decline is discussed in Section V. Section VI explores the factors that lead to high cognitive load and symptoms associated with it. Section VII provides a brief overview of major neurodegenerative diseases along with the latest statistics. Section VIII explains the scope of wearable microwave sensor systems in the detection of neurodegeneration, with a focus on dementia, stroke and Alzheimer's disease. Challenges and limitations of wearable microwave sensor systems concerning robust diagnosis, system security, accuracy, user-centricity and device privacy for a broader clinical practice are discussed in Section IX. Future research directions along with considerations for improvement are discussed in Section X. The review concludes by discussing the future areas and potential of smart microwave portable technologies in hospitals and care homes arrangement.

II. EFFECTS OF HEARING LOSS ON BRAIN

Hearing loss or impairment usually occurs among the elderly, and affects Activities of Daily Living (ADLs) [15]. Hearing loss causes a shift in cognitive resources from memory to auditory processing, putting an undue strain on brain functions [16]. In severe situations, this leads to cognitive decline and dementia.

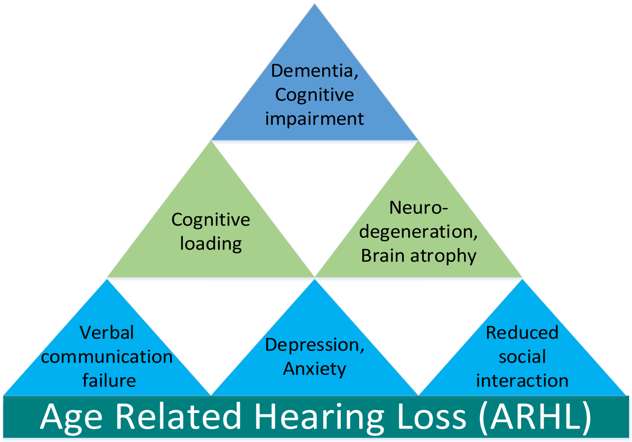

FIGURE 1. Association hierarchy of ARHL with dementia.

Hearing loss usually coincides with other conditions including social isolation, anxiety, falls, depression, decreased quality of life, and memory and communication problems. ARHL has been linked to a quicker rate of cognitive decline [17]. There are multiple theories associated with it, first one is related to cognitive load that happens as a result of untreated hearing loss. Hearing loss is more common in adults with dementia [15]. According to recent studies, dementia and Alzheimer's disease are more likely to occur in older adults with hearing loss [17], [18]. The brain gets overworked by constant strain to understand audio and speech. More concentration is directed towards information deciphering and the brain becomes less focused on retaining that information.

The second theory relates to social isolation and loneliness, untreated hearing loss causes a reduction in socializing [19]. Social isolation usually results in less stimulation of the brain. Brain cells, particularly those that hear and process sound, can decrease due to a lack of stimulation. This affects motor skills and leads to structural changes which cause the brain to shrink. Long-term auditory deprivation can affect cognitive performance by lowering communication quality, which can lead to social isolation, depression, and dementia [18]. Hearing loss is recurrently linked to cognitive deterioration in most studies. However, extensive research on the relationship between hearing impairment and MCI has only been undertaken in the last decade. Hearing impairment is linked to a higher risk of dementia and cognitive impairment [20].

Auditory deprivation results in social isolation that leads to depression and a decline in cognitive function. Long-term hearing loss shifts cognitive resources away from memory and toward auditory processing [16], putting an undue burden on higher cortical functions that eventually leads to cognitive decline. The complete hierarchy of ARHL with dementia is given in Fig.1. Hearing loss can alter the auditory pathway and affects the auditory brain, resulting in dementia and cognitive decline [16]. The other hypothesis is that neurodegenerative diseases attack the auditory brain, resulting in peripheral and central hearing loss [21]. These neurodegenerative pathologies include canonical dementias such as Lewy-body dementia, vascular dementia, Alzheimer's disease and frontotemporal dementia. Temporal, frontal, subcortical and parietal circuits that underpin auditory cognition are all compromised by these neurodegenerative pathologies [22]. The principal neurodegenerative causes of dementia in middle to later life are pathogenic protein distribution over large-scale cerebral networks and various forms of localized brain shrinkage. These are the key symptoms which can help to anticipate the hearing impairments which accompany these specific dementia conditions.

III. COGNITIVE DECLINE AND HEARING LOSS

Hearing loss causes degraded auditory signals, and auditory perceptual processing necessitates more cognitive resources/ This results in a cognitive shift away from other tasks and toward effortful listening [23]. This phenomenon finally leads to cognitive reserve depletion. The excessive cognitive load causes neurodegeneration with mild to severe brain changes [24]. Hearing impairment may be aggravated by this cognitive reserve depletion and this leads to degeneration in auditory perception [25]. Therefore, the attention required to understand and comprehend speech is vital for individuals with hearing loss.

Hearing loss, according to the cognitive load hypothesis, results in degraded auditory signals. Increased cognitive resources required for auditory perceptual processing, and diversion from other cognitive tasks to effortful listening, finally lead to cognitive reserve depletion [26], as shown in Fig. 2. According to this proposition, the ageing brain suffers from a neurodegenerative process that causes both cognitive impairment and hearing loss. Another study established that hearing loss leads to cognitive deterioration which is either permanent or reversible with rehabilitation [18]. Hearing loss increases cognitive strain in patients with cognitive impairment, according to this study. Impaired perception may lead to deterioration in cognition and social seclusion, both of which can contribute to cognitive decline. When a person has difficulty remembering things, learning new things, concentrating, or making decisions that influence their daily lives, they are said to be suffering from cognitive decline [27]. Cognitive decline levels usually increase from mild to severe. Changes in cognitive functions start after a mild cognitive decline, but it does not affect the everyday activities of the person suffering from it. Severe cognitive decline can lead to a loss of ability to talk, write, and comprehend things which result in dependence on others for daily activities, thus creating an inability to live independently [28].

Cognitive load is the amount of load being faced by the human cognitive system while going through a specific task. It represents the strain on cognitive resources such as working memory, brain processing, and visual and verbal information processing units. In cognitive psychology, the amount of working memory resources being utilized is referred to as cognitive load [29].

Several underlying factors which can be responsible for an increase in cognitive load include hearing loss, hypertension, hyperlipidemia, and cardiovascular and cerebrovascular disease [30], as illustrated in Fig. 3. Persistent high blood pressure levels result in arterial muscle hyperplasia and arterial stiffness which eventually leads to vascular remodelling and inflammation in cerebral blood vessels [31].

Other factors that contribute to the increase in cognitive load are chronic hypertension and hyperlipidemia. Hypertension affects small cerebral arteries which can lead to stroke and brain haemorrhage. Hypertension disturbs the mechanisms that regulate cerebral blood flow, in addition to changing the anatomy of cerebral blood vessels [32]. These alterations make it harder for brain metabolites like beta-amyloid and tau-tangles to be cleared, rather than allow them to build up. These anatomical and functional abnormalities caused by hypertension increase cognitive load. This culminates in cerebrovascular dysfunction, making the brain more susceptible to degenerative pathologies like dementia and Alzheimer's disease [33]. Cognitive decline or MCI is a harbinger of severe neurological conditions such as Alzheimer's disease, dementia and stroke [34]. MCI is an intermediate stage between the possible cognitive decline of normal ageing and the more severe decline of dementia. MCI can increase the vulnerability to dementia caused by Alzheimer's disease or other neurodegenerative conditions [35]. Capturing the early signs of cognitive decline may help to delay the acute dementia development at later stages.

IV. DEMENTIA AND HEARING LOSS

Around 50 million people worldwide suffer from dementia, a figure that is expected to rise to 152 million by 2050 [36].

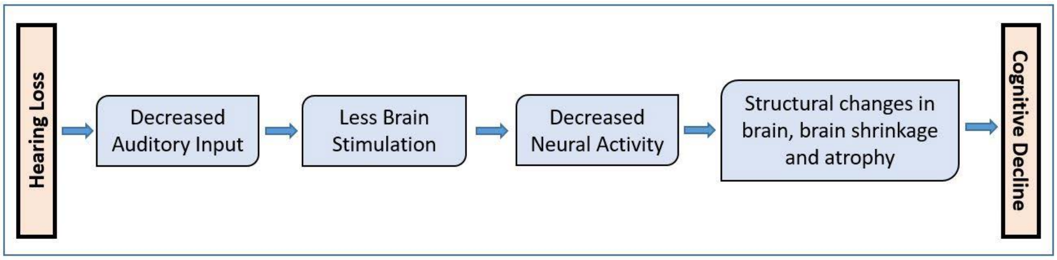

FIGURE 2. Effects of hearing loss on cognitive function.

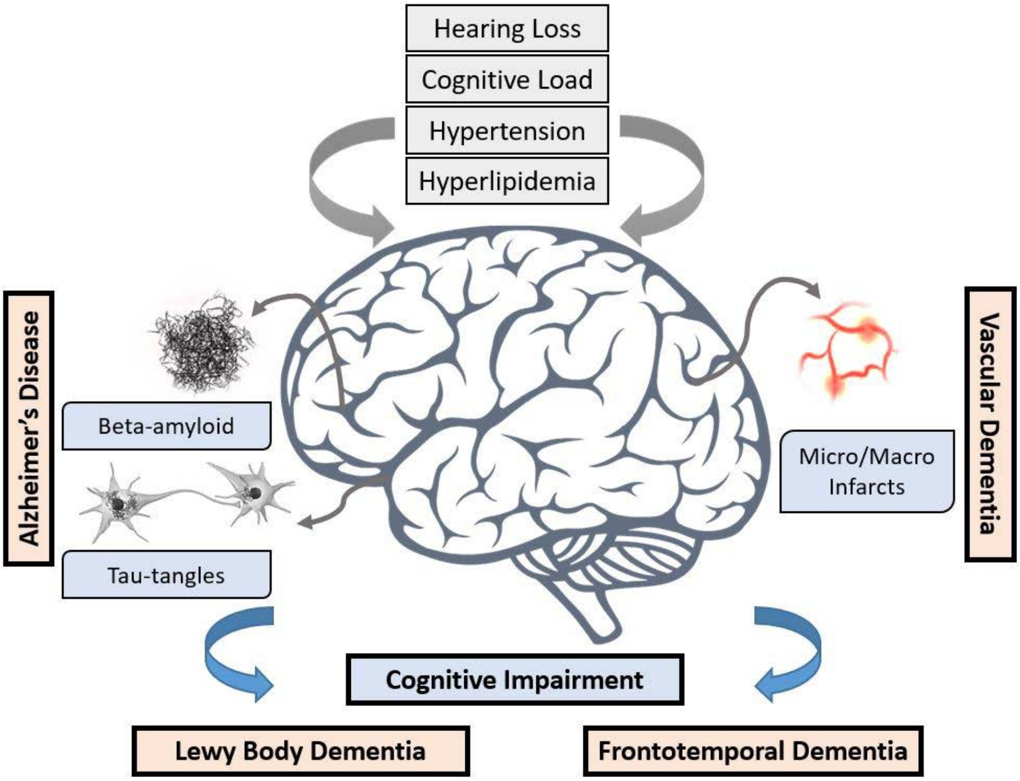

FIGURE 3. Progression from hearing loss to cognitive impairment.

Furthermore, hearing loss affects over 465 million individuals, including one-third of those over the age of 65. According to the World Health Organization, untreated hearing loss costs the world economy \$750 billion per year, while the current annual cost of dementia is around \$1 trillion, with estimates that this could double by 2030 [37].

Hearing loss in middle age is supposed to contribute to 9% of dementia occurrences, and the latest statistics suggest that dementia affects 47 million people worldwide [38]. ARHL is usually caused by cochlear damage, while dementia occurs as a result of cortical degeneration with an initial deterioration in the multimodal cortex [39]. There are multiple studies which relate peripheral auditory decline to major cortical changes associated with dementia [24].

Recent studies have linked severe dementia to intensive hearing loss. This means that hearing loss has a linear relationship with dementia and that the risk of dementia increases multiple times with incremental severity of hearing loss [22]. Cognitive processing gradually slows down with age [40], and at the age of 70, one-fifth of the population is estimated to have a considerable degree of cognitive loss [41].

According to this study, ARHL impacts severely on the brain and is assumed to be a primary reason for cognitive decline in older adults. ARHL has a negative influence on cognitive performance and raises the risk of dementia by adding more damage to existing brain impairments such as tau-tangles [17], amyloid-beta, brain atrophies [42] and microvascular infarct [24]. Vascular brain anomalies, macro and microvascular infarction, aggravated as a result of ARHL, usually lead to vascular dementia and Alzheimer's in most cases. Some studies have suggested a strong correlation between hearing loss and stroke [43], [44]. Central white matter pathways degradation and lower cortical volumes in the primary auditory cortex are also linked to peripheral hearing loss [45]. Cochlear losses may result in cortical reorganization and degeneration of stria vascularis [46].

Hearing impairment may result in rapid brain shrinkage and decreased primary auditory cortex volumes in elderly adults, and ARHL is commonly associated with reduced brain volume [47]. Grey matter volume reduction in the auditory cortex is suggested to be a probable cause of peripheral hearing loss in the elderly [42], [48]. Hearing ability and grey matter volume had a significant linear relationship [49], and individual differences in hearing capacity predicted the amount of neuronal activation in temporal gyri, comprising of auditory cortex, brainstem, and thalamus.

Central auditory processing is the ability of the brain to understand sounds received by the cochlea [3]. As a result, it is vulnerable to neurodegeneration, and data suggests that central auditory processing is impaired early in Alzheimer's disease and MCI [50]. Central auditory impairment is measured by dichotic listening activities and can be a precursor to Alzheimer's disease [51].

V. DO HEARING AIDS HELP IN REVERSING COGNITIVE DECLINE?

Hearing aids or a cochlear implant can help with social and emotional functioning, communication, and cognitive performance, as well as improve the overall quality of life [52]. Detecting the severity of hearing impairment is critical to slow down the disease progression. Routine hearing care can be provided to the general public to protect cognitive function and reduce the public health costs associated with MCI and dementia [53]. Hearing examinations can be used clinically to assess the risk of MCI/dementia, and hearing aids can be used to delay dementia in older people with hearing impairment [54].

The available treatments include hearing aids, middle ear and cochlear implants that can delay the onset of cognitive decline. Recent studies have confirmed that hearing aids are beneficial in the early stages of ARHL, and hearing aids can be helpful in the rehabilitation of higher cortical functions [55], [56]. The use of hearing aids helps to reverse central auditory system ageing [4]. Statistical survey analysis proved that hearing aids can be an effective tool to slow down the conversion from MCI to dementia [57]. But the role of hearing aids in vacating high-level processing resources and improving cognitive function is not fully explored. Considerable improvements are observed in cognition with hearing aid usage and the results returning to baseline where the hearing aid is not involved in human subjects.

VI. COGNITIVE LOAD, DIAGNOSIS AND REPERCUSSIONS

Listening effort to comprehend speech results in higher utilization of cognitive resources for hearing impaired individuals. The depletion of cognitive reserve causes an undue cognitive strain on neurological functions [58].

There are various other factors contributing to cognitive load. Major causes include age-related hearing loss, cardiovascular disease, depression, and hypertension [59]. These underlying causes eventually lead to disruption of blood flow to the brain and affect cerebral metabolism. Cognitive load, if left untreated, may progress to dementia in later stages [60].

Preliminary cognitive load symptoms can be associated with a change in blood glucose pattern for the brain, which is directly linked to changes in blood flow pattern [61]. This could appear before any noticeable neuron loss and reduction in grey matter volume. Changes in blood perfusion levels, as well as the target location within the brain, can help in the differentiation between different kinds of dementia [62]. Recent studies have discovered a positive linear association between cognitive load and blood pressure [12]. An increase in blood pressure can lead to a high cognitive load [13]. As a result, different blood pressure levels can be used to assess the amount of cognitive load. Increased systolic blood pressure is easy to detect and is more likely to have an impact on the human body. Because blood pressure and metabolic rate are related in a positive linear way [63], the metabolic rate is also a major indicator to gauge the cognitive loading state.

VII. NEURODEGENERATION: ETIOLOGIES AND CHALLENGES

Neurons are the basic building blocks of the human nervous system and constitute a major part of the brain. Neurons do not reproduce or regenerate themselves, and cannot be replaced by the body in case of damage due to neurodegenerative diseases [64]. Neurodegenerative diseases are often incurable and result in progressive degeneration, which cannot be reversed but can be slowed down if diagnosed at an early stage [65]. Major degenerative diseases include Dementia, Parkinson's, Huntington's, Alzheimer's and motor neuron disease. Ageing is a common risk factor in all of these, and increasing life expectancy worldwide is resulting in the sharp growth of neurodegenerative diseases [66]. Factors like age-related hearing loss, hypertension, and microvascular and cardiovascular anomalies increase the likelihood of cognitive decline and neurodegeneration.

Alzheimer's disease is the most common type of neurodegeneration and the sixth largest cause of death in the United States, with 5.5 million people aged 65 and older living with Alzheimer's disease [67]. Around 50 million people worldwide suffer from dementia which is estimated to increase to 152 million by 2050 [68]. The distribution of major neurodegenerative diseases according to recent statistics is provided in Fig. 4. The annual cost of dementia is almost $1 trillion, according to the World Health Organization (WHO), with estimates that this could double by 2030 [69]. An increase in the ageing population is leading to a considerable financial and socioeconomic burden on both individuals and caregivers.

Beta-amyloid and tau-tangles are two toxic proteins that cause cellular brain damage in Alzheimer's disease [73]. Beta-amyloid plaques form between neurons and disrupt the neurotransmitter receptors, making it difficult for the cell to operate and relay messages to neighbouring neurons [74]. Beta-amyloid also interferes with other proteins

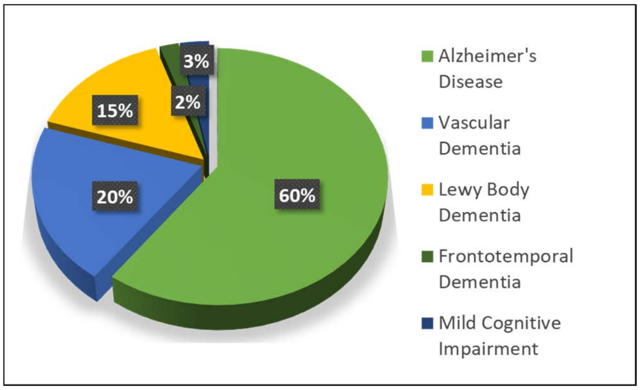

FIGURE 4. Distribution of major neurodegenerative diseases, based on statistics from [36], [67], [70], [71], [72].

in the hippocampus that is a crucial component of the brain for memory [75]. As the neuron's function is reduced, fewer neurotransmitters are produced, and communication between neurons decreases. Tau tangles are twisted protein strands found inside neurons that cause cell death by preventing cells from receiving essential nutrients [76]. The damage induced by beta-amyloid plaques and tau tangles eventually kills brain cells. The effects of these plaques and tangles are most noticeable during the middle stage of dementia.

Vascular dementia is the second most common form of dementia after Alzheimer's disease and is also one of the leading causes of death today [77]. Around 17 percent of people above 65 years of age with dementia have vascular dementia [78]. Vascular dementia typically starts with a decreased blood flow to the brain due to clots or vascular blockage in various segments of the brain [79]. This leads to vascular impairment, infarcts, white matter lesions and brain atrophy in some cases. Initial pathological changes occur in the white matter of the brain which is followed by micro and macro-infarcts [80]. In some cases, this leads to brain atrophy due to cerebrovascular impairment and long-term reduced blood flow in the brain. The damage caused by the infarction is mostly irreversible, however, a timely diagnosis can help avoid future cerebrovascular incidents.

VIII. PORTABLE MICROWAVE SENSORS FOR COGNITIVE LOAD AND NEURODEGENERATION DETECTION

In today's health sector, expensive medical imaging applications like MRI, ultrasound, PET, and CT scan tests are extensively deployed. Medical practitioners often use these procedures to obtain images of internal organs to diagnose disorders. These traditional technologies require more time and high exposure to the radiations to generate the imaging report. Imaging results produced by these invasive methods vary in terms of operating method, radiation exposure time, resolution, and implementation cost, as shown in Table 1. Even though these procedures are widely deployed, they are not flexible and depend on ionizing radiations which may have adverse effects on exposure for a longer duration [81].

Microwave sensing and imaging systems have gained much attention in recent years as they provide a low-cost, flexible, compact, non-invasive, low-exposure and non-ionizing solution. Microwave sensing technology holds the potential to replace existing imaging equipment in the near future. Electromagnetic (EM) waves in the microwave frequency region are non-ionizing and can penetrate tissue, making them ideal for diagnostic applications [82]. Several techniques have been reported recently for the detection of tumours, brain stroke, Alzheimer's and breast cancer [11], [12], [14], [83]. However, high temporal resolution is required for functional neuroimaging to detect abrupt variations in cerebral hemodynamics [82]. Microwave sensing techniques operate based on differences in dielectric permittivity and electrical conductivity between unhealthy and healthy regions of the human body. Electromagnetic (EM) waves are transmitted towards the intended area and reflected signals are received back to the sensors for diagnosis and analysis of any potential disease in that area of the body. The received signals are scattered and reflected with varying intensity depending on the difference in electrical properties of that body area. In the case of multiple antenna sensors, an antenna array can be used to send radiofrequency pulses to the target area of the human brain. Microwave signals are reflected through backscattering, received by the array and then analyzed using relevant software to detect if there is an active degeneration. The antenna sensors should be able to transmit signals over a wide range of frequencies to obtain high resolution and accurate images in such microwave imaging systems using the Ultra-wideband (UWB). Recent research on the detection of neurodegeneration through microwave sensors is summarized in Table 2.

A. COGNITIVE LOAD

Cognitive load detection is crucial to avoid the progression of neurodegenerations like stroke, carotid artery disease, Parkinson's disease and dementia. Various parameters can be utilized to assess cognitive load states. These include heart rate, blood pressure, skin conductance [84], [85], pupillometry [86] and thermal imaging [87]. However, the most accurate monitoring of the cognitive load can be achieved from the brain using sensors like Positron Emission Tomography (PET), Electroencephalogram (EEG) and head-mounted devices. PET scan produces detailed three-dimensional images to determine blood flow, oxygen levels, and metabolic variations. PET scanner detects the radiations returned by injected radiotracer inside the body [88]. It provides a detailed overview of metabolic changes appearing at the cellular level in tissue or an organ and is thus considered superior to CT scans and MRI [89]. EEG techniques use electrodes on the scalp to record the electrical response of the brain. Ionic motions in and around neurons generate these electrical signals during the activation and deactivation of neurons involved in cognitive tasks. The varying voltages in these electrical signals are measured by the EEG [90].

TABLE 1. Comparison of conventional medical imaging technologies.

Features \ Imaging Technologies	Computed Tomography (CT) Scan	Magnetic Resonance Imaging (MRI)	Ultrasound
Principle of operation	Multiple X-rays from various angles to generate 3D cross-sectional imaging	Powerful magnetic fields and radiofrequency pulses are utilized for imaging	High-frequency sound waves to examine soft tissues such as muscles and internal organs
Applications and benefits	Detection of solid tumours, Superior bone tissue contrast compared to MRI	Detection of brain abnormalities and diagnosing soft-tissue injuries, More detailed imaging compared to CT Scan and Ultrasound	Real-time 2D imaging, Fast and sedation is not required for patients
Operation and maintenance cost	Less expensive than MRI	More expensive than CT scan and Ultrasound	Cheaper than CT scan and MRI
Scan time	5 to 10 minutes, depending on the area under scan	15 minutes to 2 hours, depending on the area being examined	15 to 45 minutes, depending on the area under scan
Radiation exposure	High radiation, Chest CT is equivalent to 100 chest X-rays	No ionizing radiation	No ionizing radiation
Effects on the human body	Ionizing radiation, Sedation or anaesthesia is required in some cases	Sedation or anesthesia is required in some cases, Requires patient to remain still for half-hour or more	Sedation or anesthesia is not required
Degree of invasiveness	Low	Low (But noisy and may cause claustrophobia, due to the enclosed space of the imaging machine)	Low
Disadvantages	Harmful for unborn babies Potential reaction to the use of dyes	More expensive than a CT scan, Slow image acquisition Expensive device	Lower image quality than CT scan, with effectiveness highly dependent on technician skills, Poor tissue contrast

Near-Infrared Spectroscopy (NIRS) and MRI can be utilized for cerebral blood flow measurement but both technologies are expensive and require extensive medical supervision. Functional Magnetic Resonance Imaging (fMRI) measures brain activity and neurovascular coupling through the detection of blood flow variations [91]. Similarly, the dielectric contrast between grey matter and blood can be utilized for microwave functional neuroimaging. Limited work is available in the literature for the detection of cognitive loading through microwave sensors. A UWB impulse radar is presented in [82] to detect blood volume in the cerebral cortex. Reflection from phantom liquid was detected and the attenuation was determined across a range of frequencies in the UWB band. Other than the head-mounted devices, chest-mounted and wrist-worn devices are also presented in the literature.

Several solutions have been presented recently for cognitive load monitoring using physiological parameters like galvanic skin response, heart rate, skin temperature and heart rate variation. Physiological sensors for measuring these indicators are low-cost, non-intrusive and readily available. Various studies have presented a linear relationship between galvanic skin response and cognitive load as the cognitive load increases with an increase in skin response [84]. Cardiac measurements including heart rate and heart rate variations are also utilized in some studies for estimation of cognitive load. Cognitive stress is measured remotely using a digital camera [92] and physiological parameters like breathing rate, heart rate, and heart rate variation are correlated with the sensors data to obtain an accuracy of more than 85%. Cognitive load was determined in driving conditions using heart rate variability [93]. It was established that the combination of skin conductance and heart rate measurements can result in a more accurate prediction of cognitive load.

Eye-tracking technology is another non-intrusive way of cognitive load estimation through monitoring of eye features and movement. Different estimation metrics presented in the literature are based on eye fixations, involuntary eye movements, frequent blinking and eye pupil oscillations. Longer eye fixations have been associated with a high cognitive load state in a few studies [94]. However, some studies indicated the opposite by correlating longer eye fixation with low cognitive stress [95]. Other than eye fixation, rapid eye movement is linked to high visual load and thus associated with higher cognitive load [96]. A high cognitive load state is also linked to more frequent eye blinking [97]. Cognitive load is also considered to have a persistent influence on eye pupil oscillations and pupil diameter [98].

Neuroimaging techniques can provide accurate detection of cognitive load but the technology is relatively expensive and not readily available to patients. Detection of cognitive load through neuro-imaging and Electroencephalography (EEG) is investigated in recent studies [99], [100]. Near-infrared spectroscopy (NIRS) and EEG were combined to estimate the reaction and information processing time in intense cognitive load conditions [101]. The results were recorded through analysis of hemodynamics from the prefrontal, parietal and occipital lobe areas of the brain.

B. DEMENTIA

Despite improvement in lifestyle and reductions in risk factors such as cardiovascular anomalies, hypertension and hyperlipidemia, the cerebrovascular disease remains a threat, especially among the elderly. Factors such as protein deposits and reduced blood flow can result in degeneration of cortex and hippocampus atrophy [102], [103]. This could lead to mild or severe stage Dementia. This results in shrinkage of the hippocampus, enlargement of the brain's fluid-filled spaces and reduction in brain size. Dementia is an umbrella term to represent several diseases that affect memory, cognition, judgment and communication. Fig. 5 represents the dementia disease variations along with the major symptoms that lead to dementia.

The brain with dementia cannot receive its normal amount of blood and oxygen [104]. This reduces blood flow to the brain and damage brain cells [105]. Numerous underlying factors lead to dementia. These include high blood pressure, hyperlipidemia, diabetes, cardiovascular disease and stroke. Degeneration starts in the white matter of the brain which leads to brain atrophy and infarcts. The degeneration from infarction is irrevocable, but the progression of the disease can be restricted with an early diagnosis.

Timely diagnosis and detection of dementia are critical to avoid brain damage. Brain imaging is an essential tool in the diagnosis and determines the future treatment options available to the patient. Currently, CT-Scan, MRI and carotid ultrasound are being used for brain imaging and vascular dementia diagnosis [106], [107]. But these technologies are expensive, require extensive medical supervision and are not easily accessible, which causes substantial delays in diagnosis and results in irreversible damage.

Radio Frequency and microwave technologies can provide rapid sensing and diagnosis through compact, low-cost, non-invasive and wearable sensors. Major physiological changes can be captured at the preliminary stage using the reflection coefficient and dielectric variations. These wearable microwave sensors can detect the grey and white matter lesions, micro bleed, and micro and macro infarcts which leads to brain atrophy in the case of vascular, Lewy-body and frontotemporal dementias.

Dementia diagnosis requires cognitive assessment along with brain neuroimaging. Brain neuroimaging can detect structural degeneration including focal atrophy, tumour, bleeding and infarcts [108]. PET scans and functional neuroimaging are the most common methods for diagnosis of structural degeneration in vascular, Lewy-body and frontotemporal dementia. Due to the invasive and complex nature of these traditional scanning technologies, microwave sensing can be an inexpensive alternative.

An eight-element square monopole antenna with metasurface superstrate is presented in [109]. A blood mimicking target is identified in hemorrhagic stroke conditions and the system was designed to operate in the 0.5 GHz to 2 GHz band. A flexible, wideband, low-profile 8-element antenna array is proposed in [83] with an embedded Electromagnetic Band Gap (EBG) and metamaterial unit cells reflector. Antennas were designed on a multilayer low-cost, transparent, low loss and robust polymer Poly-Di-Methyl-Siloxane (PDMS) substrate that was optimized to operate in contact with the human head. The system comprised of a 4×4 radiating patch and a 10-unit EBG cell array around the feeding network that effectively suppressed the surface waves and improved the antenna impedance bandwidth. This antenna system was experimentally verified and tested on a three-dimensional (3D) head phantom with real human head properties. Accurate detection of infarction and bleeding was made using a confocal imaging algorithm.

A wearable device with integrated flexible microwave antennas was proposed to detect the progression of brain atrophy and lateral ventricle enlargement [11]. The device had an operating frequency range of 800 MHz to 2.5 GHz and was designed with a thin flexible Polyethylene Terephthalate (PET) substrate. Brain atrophy and lateral ventricle enlargement were detected and correlated using reflection and transmission coefficients. The device was tested on a realistic human head model with skin, skull, blood, and grey and white matter. Brain atrophy was simulated through a uniform reduction in the size of white and grey matter. The gaps were filled with cerebrospinal fluid. The wearable device was able to detect different levels of brain atrophy and lateral ventricle enlargement in both reflection and transmission modes. Similarly, changes in microwave reflection patterns can be utilized to diagnose lesions, atrophies and infarcts inside the frontal/temporal, white/grey matter of the brain, using wearable microwave devices.

C. ALZHEIMER'S DISEASE

Alzheimer's disease is the most common neurodegenerative disease and is also the sixth leading cause of death in the United States [110]. Alzheimer's disease is the most common cause of dementia in the United Kingdom. In the UK, Alzheimer's disease affects around 591,480 people out of estimated 954,000 dementia patients [111]. These figures are expected to increase to 1.5 million by 2040. Alzheimer's disease is a progressive neurodegenerative disorder that causes brain shrinkage, and atrophies and eventually results in neuron death [112].

MRI and PET scans are the primary monitoring techniques in use today, for Alzheimer's disease progression. Cerebrospinal fluid (CSF) testing is also performed in some cases to obtain evidence of Alzheimer's disease [108]. There is not much work done on wearable healthcare applications for cognitive load detection and dementia. However, considerable research exists in wearable healthcare applications for brain stroke and Alzheimer's detection. Six ultra-wideband monopole bidirectional antenna elements arranged symmetrically inside a wearable hat is presented in [11] to detect brain atrophy. Changes in brain volume and cerebrospinal fluid were captured using variation in reflection coefficient measurements. The design was simulated and experimentally verified using a real lamb brain inside a human head phantom.

Similarly, a six-element stepped monopole wideband antenna was designed to detect beta-amyloid plaques and tau tangles in the brain, for the diagnosis of Alzheimer's disease [10]. In addition to Alzheimer's disease detection, the dielectric properties of human brain tissue were investigated and an imaging algorithm was presented to reconstruct images of tangles and plaques. Relative permittivity and conductivity were measured for brain tissues affected by Alzheimer's disease and the results were compared with healthy brain tissues [113]. Tissues with a considerable amount of beta-amyloid plaques and tau tangles were collected from both grey matter and white matter of the frontal cortex. Results indicated an increase in conductivity and decrease in dielectric permittivity due to the presence of plaques and tangles, compared to the results from healthy brain tissues. Conductivity increased significantly with an increase in frequency from 100 MHz to 3 GHz, for both grey matter and white matter. The outcomes of this study can be beneficial in the detection of other neuropathologies and neurodegeneration.

D. BRAIN STROKE

Stroke is the fourth leading cause of death in the UK with more than 100,000 cases every year [120]. Age is an important factor for stroke and it is most likely to occur after the age of 55, but younger people including children also seem to be affected according to the latest statistics [121], [122]. A stroke occurs as a result of disruption in blood flow to the brain and can result in lifelong disabilities and death in extreme cases. In addition to the timely diagnosis and treatment, risk factors need to be managed for the prevention of stroke. High blood cholesterol and lipids result in plaque buildup inside arteries and can contribute to the thickening of arteries. This decreases the amount of blood flow to the brain, which can lead to Ischemic stroke [123]. Chronic high blood pressure damages the blood vessels and arteries which supply blood to the brain. Blood spills out in the brain due to damage to blood vessels and results in Hemorrhagic stroke [124].

A stroke is a medical emergency and an early diagnosis is crucial for prompt treatment [125]. Brain imaging is essential to localize the bleeding and clots. Traditional imaging technologies like CT Scan, MRI, Computed Tomographic Angiography (CTA), Magnetic Resonance Angiography (MRA) and carotid ultrasound can detect the damage to brain cells, bleeding and blood flow inside the arteries [126]. Although these technologies are extensively recommended for an accurate diagnosis of stroke, the invasiveness, high cost, low availability, long scan time, and expensive operation and maintenance make these procedures less viable for stroke patients.

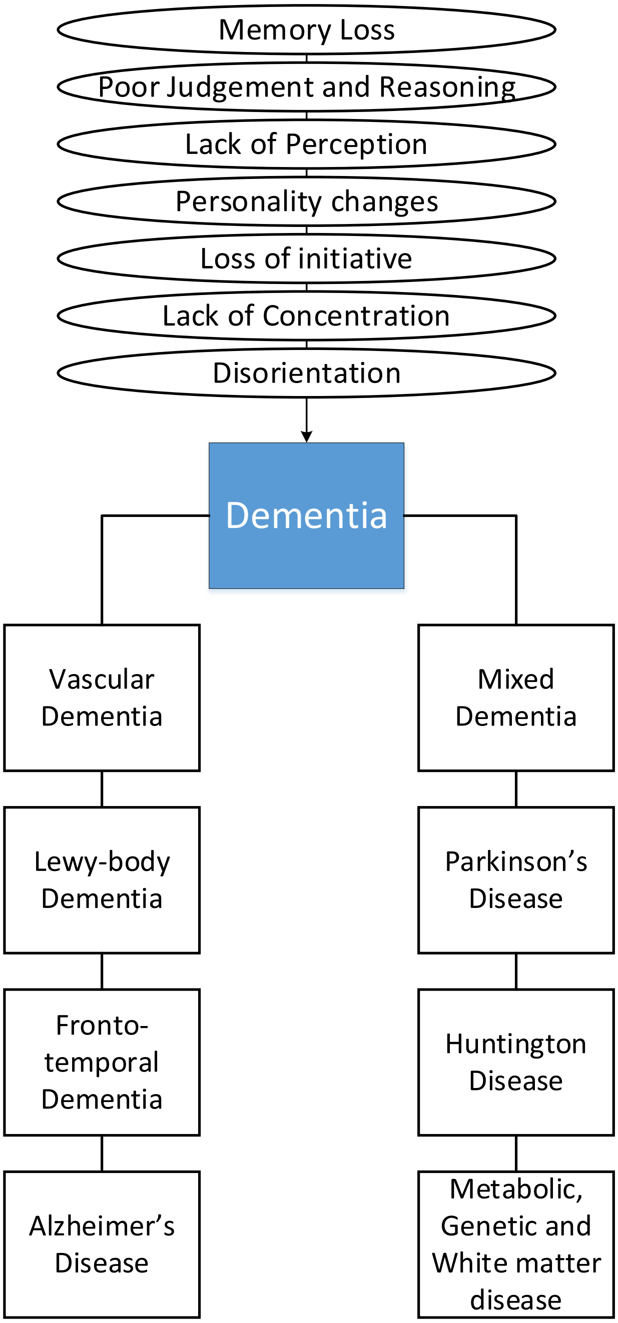

FIGURE 5. **Dementia variations and major symptoms.**

In recent years, microwave sensing and imaging applications have been proposed and developed for sensing and imaging brain stroke and tumours. A Vivaldi antenna for stroke detection is proposed in [127], which was designed to operate between 1 GHz and 4 GHz. Multiple elements array of Vivaldi antennas were designed and interconnected using

TABLE 2. Comparison of microwave-based imaging solutions for neurodegeneration.

Sr. No.	Case Study	Health Area	RF and Microwave Technology	Operating Frequency	Key Findings
1	Razzicchia et al, 2021 [109]	Hemorrhagic stroke detection	8-element Printed square monopole antenna, enhanced by a metasurface superstrate	Operable in 0.5-2 GHz band	Possibility to detect target without using a bulky immersion liquid. MTS superstrate loading enhances the reflection coefficient and signals difference due to the presence of the target. A blood mimicking target is identified, and results are improved by MTS superstrate loading.
2	Alqadami et al, 2019 [83]	Hemorrhagic stroke detection	4 x 4 antenna array with symmetric U-slots, enhanced by mushroom-like 10- unit EBG around the feeding network to reduce surface waves	The operational frequency range of 1-2 GHz	Imaging results validated the capability of using the designed array system for the detection of bleeding in the brain using a confocal image algorithm. The designed system is flexible, low-profile, wideband, and unidirectional with Electromagnetic Band Gap (EBG) and metamaterial (MTM) unit cells reflector.
3	Bashri et al, 2018 [114]	Hemorrhagic stroke, brain injury	An antenna array of 12 wideband monopole antennas are used for the detection of brain injury and blood clots inside the brain. The reflection and transmission coefficient of antennas are collected for healthy and unhealthy brains. Use of low-power microcontroller with RF switches to control them via Bluetooth connection	The operational frequency range of 0.5-4 GHz	Blood clots are successfully detected by applying the confocal delay-and-sum imaging technique. Low cost, compact and lightweight RF switching system for wearable head imaging applications. Non-invasive and remote monitoring and imaging with this wearable device is possible using Bluetooth connectivity.
4	Bashri et al, 2017 [115]	Hemorrhagic stroke detection	8-element wearable flexible antenna array for stroke detection	The operational frequency range of 1.3-3.5 GHz	Capable of detecting stroke with flexible and lightweight antenna structure. Good reflection coefficient results over the designed ultra-wideband frequency range. Mutual coupling between adjacent antenna elements is less than -20 dB and SAR is within an acceptable range, 1.7 W/kg per 10g of tissue mass.
5	Alqadami et al, 2020 [13]	Brain stroke	16-element antenna array integrated with a flexible room temperature vulcanizing silicone cap	The operational frequency range of 0.6-2.5 GHz	Capability to detect and reconstruct 2D images of bleeding inside the brain. Enhanced antenna-skin matching with a flexible matching layer inside the cap. Challenges of size, rigidity and complex structures of existing systems are addressed.
6	Alqadami et al, 2021 [116]	Brain stroke	24-element planar antenna array, configured in two elliptical rings. Dielectric properties and favourable mechanical flexibility are enhanced by a flexible electromagnetic cap of customized polymer-ceramic composite Flexible matching layer on antenna array apertures, for enhanced impedance matching with skin	The operational frequency range of 0.9-2.5 GHz	Detection capability is experimentally verified on 3D head phantom with different stroke and imaging scenarios. 3D and 2D images using the beamforming and polar sensitivity encoding (PSE) image processing algorithms verifies the system's suitability for onsite brain imaging
7	Amor Smida, 2020 [117]	Brain stroke	Five different antenna designs are presented for brain stroke detection. SAR modelling and bioheat transfer analysis of the proposed system	The operational frequency range of 2.5 GHz	Simulated results confirmed the feasibility of stroke detection with the proposed antenna system and present high viability for portable, low-cost, and rapid stroke detection applications.
8	Saied et al, 2019 [11]	Alzheimer's disease	Six monopole bidirectional antenna elements are arranged symmetrically inside a wearable hat. Simulated and experimentally verified to detect brain atrophy, using a real lamb brain inside the human head phantom	Specific Absorption Rate between 0.0115~0.135 W/Kg and Operable in 0.8 to 3 GHz band	Capable of detecting various levels of brain atrophy and lateral ventricle enlargement. Results are verified by replacement of the brain's outer layer with Cerebral Spinal Fluid (CSF) and insertion of a cavity in the sample model
9	Saied et al, 2020 [10]	Alzheimer's disease	Six ultra wideband antennas are designed and optimized around the head phantom. Dielectric properties are analyzed first for the grey and white matter, to recreate various stages of Alzheimer's disease including Mild Cognitive Impairment	Dielectric measurements were obtained from grey and white matter regions of brain tissues with severe Alzheimer's disease pathology, within the frequency of 200 MHz to 3 GHz	Capable of Non-invasive monitoring and a novel wearable tool for medical diagnostic devices. Simulations and experimental results confirm that the designed system can detect different levels of brain atrophy and lateral ventricle enlargement in both the reflection and transmission modes. A promising tool for monitoring patients with Alzheimer's disease
10	Rezaeieh et al, 2015 [12]	Brain tumour Detection	3D slot-rotated antenna for microwave head-imaging stem for detection of brain tumour. Parasitic patches are connected to slot area for enhancement of operational bandwidth	The operational frequency range of 1.4-3.5 GHz	Able to detect tumour target, results are verified on tumour target with 1 cm radius inside the artificial phantom. Compact size, wide operational bandwidth, unidirectional radiation.
11	Vasquez et al, 2020 [118]	Brain stroke	24-element helmet-shaped antenna array is presented for brain stroke imaging, with low complexity monopole antennas enclosed in graphite-silicon material	The operational frequency of 1GHz	Detected stroke target placed inside the liquid phantom, the system is validated through its digital twin which shows simulated data consistency with measured data. Full 3D brain imaging for detection of stroke target.
12	Sohani et al, 2020 [119]	Haemorrhagic stroke detection	Two antennas are embedded in an appropriate cavity, antennas are designed to rotate around the head and measure transmission and reflection data for capturing the stroke target.	The operational frequency range of 1-2 GHz	A haemorrhagic stroke target is detected using an anthropomorphic human head model, operable at very low input power. A portable device that is rotatable around the head for complete imaging of the brain. For imaging, the rotation subtraction artefact removal method is used in simulation and measurements.

microwave coaxial switches. This Vivaldi antenna array system could only be used for immobile diagnosis and was not portable. A flexible eight-element monopole antenna array is presented in [115], operable at frequencies between 1.3 GHz and 3.5 GHz. Antennas were arranged in an elliptical configuration on a thin flexible Polyethylene Terephthalate (PET) substrate, which makes them suitable for wearable applications. A flexible electromagnetic cap with an integrated 16-element antenna array is presented in [13]. It was designed with an operational frequency range of 0.6 to 2.5 GHz. This design was compact, light-weight and antenna elements were placed in a flexible multilayer wearable cap. An imaging algorithm was developed to process the collected data, and detection capability was verified using stroke-like targets in a realistic head phantom.

A 3D electromagnetic head imaging system with 24 elements planar antenna array is presented in [116] for stroke diagnosis. The designed array was arranged in two separate elliptical rings inside a compact flexible cap. A flexible layer was added to the front apertures of the antenna array to enhance impedance matching with the skin. Results were experimentally verified on realistic 3D head phantom using the beamforming and polar sensitivity encoding imaging algorithms. A portable 16-element antenna array is proposed in [128] for head imaging and stroke diagnosis. The antennas were designed on a 4mm room-temperature-vulcanizing (RTV) silicon substrate, operable on 0.45 to 3.6 GHz frequency band. Due to the meander-line structure, antenna elements were compact as compared to [13] and [116]. The generated images from testing on an artificial head phantom confirmed the viability of the system for stroke detection and diagnosis.

IX. PRACTICAL IMPLICATIONS OF PORTABLE MICROWAVE SENSORS

In contrast to traditional technologies, microwave systems are considered safe for the human body and can be employed in medical applications. Microwave sensors can provide non-invasive, low-radiation imaging that employs the external scattering field to measure the target. The most critical factor in microwave detection is precision. The antenna sensor system is responsible for transmitting and receiving signals in microwave imaging systems, hence its performance has a direct impact on the imaging effect. It is critical to create an antenna that is miniaturized for microwave imaging systems and may include features such as ultra-wide bandwidth, high gain, and good directivity. This requires design optimization to ensure that the antenna receives accurate data, keeping into consideration the suitability of design material for biomedical applications. Some of these design aspects are discussed below:

A. EASE OF USE AND USER-CENTRICITY

Portable gadgets have recently gained much attention due to their wide range of applications in sports, navigation, military, medical and space industry. A major bottleneck in the optimization of electronic components for portable applications is antenna design. These antennas must either be built into the human body, like wearables or incorporated within the clothing. They must be low-cost, low-profile, portable, resilient, reliable and low-power, or else they will be ineffective for these applications. The portable sensors should be immune to de-tuning and performance degradation caused by surrounding components when mounted on the body. The shadowing, scattering, fading and mismatching effects resulting from the human body and surrounding environment must be considered for wearable antennas [129].

Designing antennas for wearable applications can be challenging as the radiation efficiency is degraded considerably due to the higher dielectric constant of the body. There are various factors which need to be considered for user-centric design: the non-uniform structure of the human body, different blood concentrations and the composition of biological matter for each individual. The antenna performs differently for each human body depending upon the structure of internal organs, body mass, fat and muscle index [130]. For an efficient user-centric wearable device, some modelling constraints need to be considered. These include biological composition, body structure and varying electrical parameters of body matter. Another important factor that makes these portable devices more user-centric and conformable is the flexibility of antennas. The choice of non-rigid antennas for portable applications depends on the type of materials, substrate, processing technique and target application. The demand for flexible printed antennas has increased in recent years, specifically for biomedical applications [131], [132]. Flexible antennas are already being implemented in monitoring applications for neural interfaces, gait analysis, organ functions, vital signs and drug delivery systems [133]–[135]. The choice of substrate material is based on the dielectric properties and resistance to mechanical deformation like twisting, wrapping and bending of antennas [136].

B. DEVICE ACCURACY AND PRIVACY

Designing antenna sensors for portable applications is challenging as it requires careful consideration of antenna size, structure complexity and material of the dielectric substrate. Using free space antennas in radar-based systems can result in a severe mismatch between high permittivity skin and air with relatively lower permittivity [128]. To overcome this issue, additional air-skin medium and complicated calibration techniques are required to increase the matching between antenna elements and skin. Higher matching improves the penetration and detection capability for the localization of targets, particularly in the central part of the head. Effective matching requires a smooth transition of electromagnetic waves, for near-body applications. To compensate for the losses due to the high dielectric permittivity of the human body, successive layers of materials with increasing permittivity can be utilized for progressive adaption of electromagnetic waves between the air-tissue mediums. Two flat dielectric graded-index lenses were designed to increase the matching between free space and tissues, for external hyperthermia [137]. This enhanced matching resulted in an effective propagation of electromagnetic waves within lossy and nonhomogeneous media.

Other parameters that need to consider for the design of microwave antenna sensors include reflection coefficient, peak gain, efficiency, Total Active Reflection Coefficient (TARC), Specific Absorption Rate (SAR), radiation pattern, impedance bandwidth and antenna polarization diversity.

Privacy and data safety risk mitigation in the sensing technology is of prime importance, as the imaging data gathered for analysis is vulnerable to privacy risks. Hence, the safety of patient data is mandatory and can be ensured by keeping the information in safe data storage systems. However, clear guidelines will be required for the safe operation of wearable devices and mitigation of data privacy concerns in domestic and care home setup.

C. ROBUST DIAGNOSIS

A low scan period and timely imaging results are critical for a robust diagnosis of neurodegeneration. Microwave sensors for biomedical applications are designed to use low frequencies for higher penetration. UWB antenna systems provide high capacity, high penetration and multipath robustness. Robust diagnosis is ensured by fine time resolution for accurate delay estimate. UWB antenna systems are inexpensive and utilize low transmission power with multi-access. For robust diagnosis through on-body microwave sensors, factors such as dispersion from human tissues across the frequency band need to be considered. Antennas with non-dispersive characteristics are required for optimal performance with radiation. This minimizes the path losses incurred through the UWB band.

D. ANTENNA MINIATURIZATION AT LOW FREQUENCIES

Designing antennas for portable applications is challenging as it involves antenna miniaturization to make it compatible with the wearable device. Antenna miniaturization helps to reduce the physical dimensions of the system while keeping the antenna functionality intact. For the miniaturization of antennas targeted at the elderly population, several design factors are required to be incorporated. These include ease-of-use, non-intrusive, adaptability and portability. But there are various challenges involved in the miniaturization of antennas operating at lower frequencies. The antenna can be made smaller by increasing the frequency and decreasing the wavelength. But the wearable body sensors applications targeted at the brain require antenna sensors that operate at lower frequencies. Portable antennas for wearable applications must be robust against the bending and twisting effects in real-time applications [138].

E. MUTUAL COUPLING ISSUE BETWEEN ANTENNA ELEMENTS

To effectively scan the target areas of the body, the portable sensor system should contain multiple elements for extended coverage. Designing an antenna array on a thick and lossy substrate is critical, as it results in high mutual coupling between the elements. Mutual coupling can be dominant in two ways for these systems, either through surface waves or via free-space waves. Any of the unwanted couplings can dominate the other while designing an antenna array system and is dependent on the substrate width, ground plane, antenna type and the number of modes excited by the system. In printed patch antennas, the surface waves can be more dominant if the substrate thickness is according to this condition [139];

$$\text{Substrate thickness} \geq \frac{0.3\lambda o}{2\pi\sqrt{\varepsilon_r}} \tag{1}$$

where λo is the free space wavelength and ε_r is the relative permittivity of the substrate. Surface waves can result in a mutual coupling that causes degradation in antenna radiations. Surface wave propagation can be suppressed by modification in patch design, substrate and ground plane structure. Change in substrate material composition alters the relative permeability and permittivity which leads to variation in radiation parameters of the antenna [140].

Placement of antenna elements close to each other results in mutual coupling between them, which affects the overall gain and efficiency. Several techniques can be implemented to keep the spacing to an optimum level, these include the introduction of Defected Ground Structure (DGS), Electromagnetic Band Gap (EBG) [141], parasitic elements and the use of metamaterials to enhance isolation between elements, as shown in Fig. 6. Effects of the human body on portable Multiple Input Multiple Output (MIMO) antenna parameters like Envelope Correlation Coefficient (ECC), Mean Effective Gain (MEG) and channel capacity are to be considered in the design. For MIMO antenna systems, the required isolation between antenna elements is required to be more than 15 dB, the Envelope Correlation Coefficient (ECC) to be less than 0.05 and diversity gain to be less than 10 dB [138].

1) DEFECTED GROUND STRUCTURE (DGS)

DGS is implemented to miniaturize the design with an enhancement of bandwidth and gain. The fabrication process is relatively easier compared to other gain and bandwidth enhancement techniques. DGS structure can be realized by the addition of slots or defects on the ground plane. These etched defects in the ground plane change the effective inductance and capacitance of the microstrip line by adding slot resistance, inductance and capacitance [142]. Depending upon the shape, size and dimensions of the defect, the current distribution is affected in the ground plane which excites controlled propagation of EM waves through the substrate layer. DGS can be adopted to address several parameters of MIMO systems which includes low gain, cross-polarization and narrow bandwidth [143]. A defected structure can effectively reduce surface waves and decrease cross-polarization levels by confining surface waves within the dielectric that causes coupling between antenna radiating elements [144], [145].

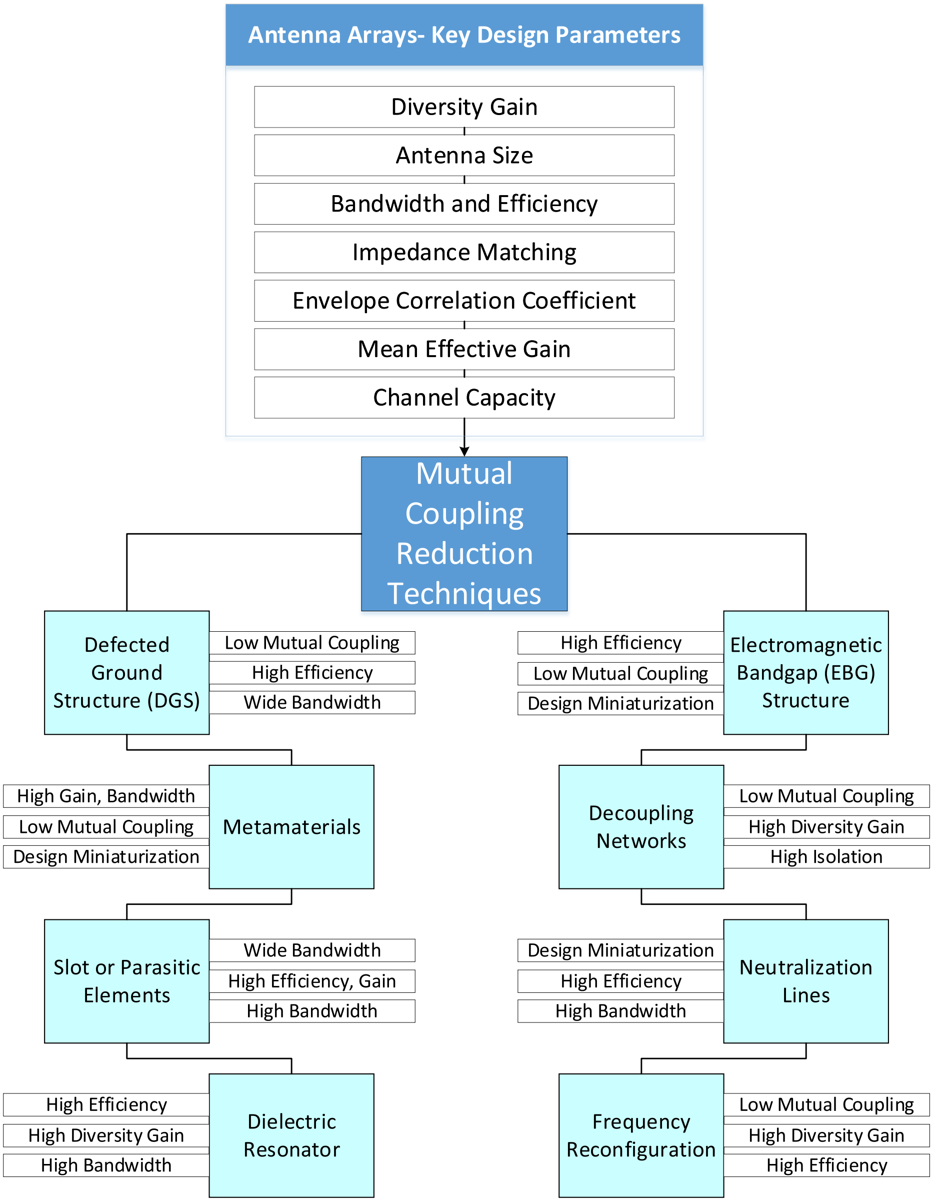

FIGURE 6. Key design parameters of antenna arrays and mutual coupling reduction techniques.

The surface wave reduction results in less diffraction from the substrate which leads to a reduction in back radiation [146]. DGS can provide low mutual coupling, maximum efficiency and wide bandwidth to the antenna design.

2) ELECTROMAGNETIC BANDGAP (EBG) STRUCTURE

Electromagnetic Band Gap (EBG) structures are periodic structures that could allow or prevent the propagation of electromagnetic (EM) waves in some frequency bands over certain incident angles and polarization states [147]. These frequencies are called partial band-gap. EBG structure is a periodic arrangement of metallic or dielectric material. The periodicity of the EBG structure can generate individual resonance of elements that produce multiple band gaps [148]. At a specific frequency band, EBG does not allow the propagation of EM waves in all directions and incident angles and this frequency band is called a global or complete bandgap [149]. EBG structure is useful to suppress surface waves, which results in more efficient antennas with reduced coupling. EBG structures can effectively increase operation bandwidth, directivity, and front-to-back ratio and reduce side-lobe levels. EBG structures provide miniaturization, low mutual coupling and high efficiency.

3) METAMATERIALS

Metamaterials are artificial periodic or aperiodic structures that can demonstrate uncommon and exotic electromagnetic properties like negative permittivity and permeability [150]. Properties of metamaterials are determined by the periodic arrangement of scattering structures that are much smaller than the wavelength of EM waves. These small structured metamaterials can vary in size, orientation, and geometry and are generally fabricated from plastic and metal [151]. Antennas designed with metamaterials have significantly high radiation power. Antenna systems with embedded metamaterials can manipulate EM waves in a different way than conventional materials. Integration of metamaterials in antennas can provide high flexibility and design novelty. Metamaterials can offer miniaturization, high gain, low mutual coupling and high bandwidth.

4) DECOUPLING NETWORKS

The decoupling antenna system is realized by adding transmission lines or discrete components. In a decoupling network, admittance is transformed to imaginary value by the addition of discrete components [152], [153], coupled resonators [154], eigenmode decomposition [155], and artificial structure [156] or dummy load. Decoupling networks can minimize the effects of mutual coupling in antenna arrays at either single or dual-frequency. Dual-frequency decoupling can be achieved by using a network of series or parallel resonant components [157]. Decoupling networks provide high diversity gain, low mutual coupling and high isolation.

5) SLOT OR PARASITIC ELEMENTS

In this technique, slots or parasitic elements are added to the ground plane or radiation path that enhance the impedance bandwidth of the antenna system. For patch antennas, the current distribution is not uniform and areas with low current density can be removed as it has no significant effect on the return loss. Implementation of slots can increase the bandwidth and dimensions of the antenna and could suppress low current density areas [158]. Slot antennas can provide high gain, wide bandwidth and high efficiency. Parasitic elements can increase the gain and bandwidth of the patch antenna. Surface wave losses can also be reduced using parasitic patches, which results in mutual coupling reduction for patch arrays [159].

6) NEUTRALIZATION LINES

Neutralization lines are employed to propagate EM waves from one antenna to the other through the lumped element or metallic slit. This creates an opposite coupling to decrease the mutual coupling at specific frequencies between the antennas. This technique reduces the overall antenna size, improves bandwidth and reduces mutual coupling between antenna elements. Thin printed neutralization lines have been used to increase the isolation between two monopoles [160]. A thin neutralization line is etched near the antenna feeding line to link the monopoles. By varying the length of the neutralization line, isolation and impedance bandwidth was controlled.

Pair of crossed neutralization lines were used to mitigate mutual coupling for a dual-band antenna with two symmetric antenna elements [161]. Isolation between antenna elements was enhanced through crossed neutralization lines, driven branch, vias and parasitic ground. Pair of ground plane neutralization lines were utilized to reduce mutual coupling between four antenna elements placed orthogonal to each other [162]. A partial ground plane with rectangular slots and twin neutralization lines helped to operate the MIMO antenna system on multiple frequency bands with enhanced isolation.

7) DIELECTRIC RESONATOR

Dielectric resonator antennas (DRA) are designed using ceramic blocks that are integrated into the ground plane or metal surface [163], [164]. DRA can transform guided signals into unguided RF waves for propagation through water, air or vacuum. DRA has a much wider impedance bandwidth as compared to the microstrip antenna. This is due to the radiation of DRA through the complete DRA surface except for the grounded part, compared to the microstrip radiation via two narrow radiation slots. Different techniques can be used to excite dielectric resonators which include probe, aperture and microstrip line and these can be either singlepoint, multiple-point or sequential rotation.

DRAs are designed in a circular, cylindrical [165], hemispherical [166], conical, triangular [167], trapezoidal [168] and rectangular [169] with cylindrical being the most common due to higher efficiency and lower loss compared to metal-only antennas. The size of DRA depends on the resonant frequency and dielectric constant of the materials. DRA provide high gain, low loss, high radiation efficiency and high isolation.

8) FREQUENCY RECONFIGURATION

Frequency reconfiguration is used to switch the frequency of operation to the desired range. This reconfiguration is realized by using varactor diodes, P-I-N diodes or Micro- Electro-Mechanical-Systems (MEMS) switches [170]. Reconfigurable antennas are designed to change the radiation parameters of an antenna which include frequency, radiation pattern, polarization or a combination of these parameters [171]. This antenna reconfiguration is realized by changing the feed location of the antenna or switching ground or radiating path that changes the corresponding resonating length. The controller circuit can be either microcontroller, Arduino or FPGA [172].

The two types of reconfigurable antennas are mechanical and electronically reconfigurable antennas. Electronic reconfiguration is achieved by switching the path of surface current on the ground or radiating element of an antenna. One or more switches can be used to switch paths that can be either P-I-N diodes, varactor diodes or MEMS switches [173], [174]. Schottky diode is used for high-speed switching and varactor diodes provide fine-tuning of frequency within the required band [175]. Mechanical reconfiguration is achieved by conductive fluid antennas, dielectric fluid antennas, gearing and origami-based antennas [172]. Reconfigurable antenna systems are capable of providing high diversity gain, low mutual coupling and high efficiency.

F. ENSURE COST-EFFECTIVE, PORTABLE AND LOW-POWER SOLUTIONS

Wearable gadgets have recently gained much attention due to their wide range of applications in sports, navigation, military, medical and space industry. A major bottleneck in the optimization of electronic components for wearable applications is antenna design. These antennas must either be built into the human body, like wearables or incorporated within the clothing. They must be low-cost, low-profile, portable, resilient, reliable and low-power, else they will be ineffective for portable applications.

Radiofrequency systems are low cost with low power requirements and microwave imaging produces non-ionized radiations which makes them more effective than other medical imaging techniques [176]. Compared to the complex traditional medical equipment with high maintenance and implementation costs, microwave systems are portable and consist of a microwave source, receiver, antenna array and radiofrequency switch to shift between the antenna elements. For wearable microwave devices, integration of Vector Network Analyzer (VNA) and radiofrequency switches in the device can make it more portable, convenient and less obtrusive. Several design challenges are involved as the wearable antennas are subjected to the near-field effects of the body, channel interference and user acceptance problems [177]. To increase the battery life of the wearable microwave system, the energy efficiency of the device should be improved. RF transmission by the antenna sensors constitutes a major part of the overall energy consumption. This problem can be mitigated by decreasing the number of retransmissions and improving the link budget through increasing antenna diversity gain.

G. MITIGATION OF NEAR-BODY EFFECTS ON PORTABLE SENSOR SYSTEMS AND SPECIFIC ABSORPTION RATE (SAR)

Microwave systems designed for wearable applications usually operate within proximity to the human body. This not only has an impact on the performance of sensors but can also cause damage to human health through electromagnetic radiation. Longer exposure to electromagnetic radiation can result in adverse reactions in the central nervous system which can lead to cognitive impairment and pose a higher risk of brain tumours [178]. There are some beneficial effects of short-term exposure to microwave radiation, it can improve cognitive functions, short-term memory loss and attention disorder [179]. Moreover, the risk of Alzheimer's disease is around 30 percent lower in people who use a mobile phone regularly for more than 10 years compared to other individuals [180]. The radiation intensity is a major factor to consider while designing wearable antennas. SAR is a criterion for determining if an antenna is safe for the human body, and it refers to the ratio of radiation generated by the antenna to the amount of absorption. There are two standards in place, the IEEE standard allows maximum absorption of 1.6W/Kg for 1g and International Commission for Non-Ionizing Radiation Protection permits a maximum of 2W/Kg per 10g [181].

X. FUTURE RESEARCH

Microwave imaging and sensing techniques are promising alternatives to conventional imaging technologies. Portable microwave devices can provide a low-cost and robust detection for the majority of diseases through wearable applications. Integration of these portable devices with cloud databases will be beneficial for post-processing and diagnosis using cloud analytics. Ongoing future work, as part of the COG-MHEAR project [182], aims to develop and evaluate the use of emerging portable non-invasive sensing technologies [183] for the detection of cognitive load within a hearing aid device. This device could be used by people with hearing loss in smart care home settings to enhance their quality of life. Other aspects and research areas that can be explored in future are discussed below:

A. UNIFIED DEVICE FOR HEARING LOSS, COGNITIVE LOAD AND DEMENTIA MONITORING AND DETECTION

The possibility of an integrated device which can work in conjunction with the hearing aid module needs to be explored. Microwave portable non-invasive sensing technologies can be used in smart care home settings for the detection of cognitive load within a hearing aid device. This can be beneficial to capture the progression of neurodegeneration at a very early stage. Furthermore, these devices can be made easily available to smart care homes and regular monitoring can be ensured. This will lead to ease of burden on medical facilities and clinicians, as the initial diagnosis can be easily made without much clinical intervention.

B. CLINICIAN'S PARTICIPATION IN IMPROVEMENT OF DESIGNED SOLUTION

The involvement of clinicians in the design of microwave sensing systems can make the solution more practical and implementable in medical and care home setups. As the medical practitioners are more knowledgeable about the sensitivity of patients with medical devices, they can provide valuable inputs to make the devices user-friendly, safe and user-centric. Furthermore, they are in a better position to compare these portable sensing devices with conventional equipment to highlight the shortcomings and mitigate the challenges. Other than that, their feedback can help in the improvement of imaging techniques during the development phase.

C. PRIVACY AND SECURITY MANAGEMENT

Another challenge in widespread portable microwave sensors is to maintain the privacy of the patients. As these devices can be integrated with Wi-Fi to store the patient's data on the cloud as a medical record. The integrity and security of the data storage systems must be maintained to avoid any misuse and leakage of patient data. This requires viable solutions and data protection policies to be implemented in future for the maintenance of the data privacy rights of the patients involved. Homomorphic encryption can be used to maintain data privacy while performing data computations in the cloud [184]. It provides end-to-end dataflow privacy and enables secure storage of data in public clouds. This helps in data computations and Machine Learning (ML) predictions without accessing user data and decryption. Although it increases computational cost and packet size but helps to maintain the redundancy efficiency of distributed storage [185]. Federated learning is another privacy learning ML algorithm which enables computation and insights without moving patient data beyond the firewalls of their residing institution [186]. It enables multiple stakeholders to train collaboratively without the need to exchange or centralize the data sets. Federated learning can achieve adequate differential privacy and avoid sharing healthcare data and information leakage [187]. Blockchain is another emerging technology which can provide data privacy and security for patient data and clinical information. The blockchain model allows building a model through patients record on a distributed ledger where all members contribute to the consistency and integrity of the database [188]. A blockchain-based system can keep a record of not only original data but also holds information of all transformation applied to the data, that leads to quick and efficient detection of falsified figures [189].

D. MACHINE LEARNING BASED MICROWAVE SENSING AND IMAGING ALGORITHMS

In future, portable microwave devices can be linked to the cloud and the data obtained can be post-processed with cloud analytics and machine learning for better diagnostics and care services. The scattering parameters data received from the antenna sensors can be stored and compared with the output of conventional techniques to create suitable data for the machine intelligence system. This data can then be post-processed using suitable supervised machine learning algorithms like Nearest Neighbour (NN) [190], k-Nearest Neighbour (kNN) [191], and Support Vector Machine (SVM) [192] or Multi-Layer Perceptron (MLP) neural network [193], [194].

The selection of an imaging algorithm is crucial for accurate diagnosis and imaging of different neurodegenerative diseases. Imaging algorithms presented in the recent literature can generate a 2D image of the brain, but the exact location of a tumour or affected brain can be more accurately determined by 3D imaging. Therefore, future research on advanced 3D microwave imaging algorithms can improve the diagnosis. Microwave imaging can be enhanced by the adaptation of techniques like Machine Learning [195], [196], Artificial Intelligence and Big Data [197] to consolidate data from various use case, patients and their disease progression levels. This data can be used to compare the diagnosis of the target patient and accurately reconcile the results. Recent research has been focused on utilizing a deep learning network [198], PySpark-based reconstruction [199] and parallel delay multiply and sum image reconstruction algorithm [200], which performed more efficiently than the delay multiple and sum algorithm. The experimental results from these researches have shown that the Spark significantly accelerates the imaging reconstruction process without affecting the accuracy.

E. REALISTIC PHANTOMS DEVELOPMENT

Another challenge is to emulate the neurodegenerative diseases with realistic phantom models. This requires an initial dielectric measurement of the brain tissues, grey matter, white matter, blood pool and cerebrospinal fluid. Different layers can be used to realize the actual brain with the flexibility to control dielectric properties through slots, channels and pumps. Realistic phantoms can be designed using various techniques. Liquid phantoms are reported in [201] for the study of electromagnetic hyperthermia. This liquid phantom is composed of using a mixture of sodium chloride, sucrose and water. Liquid phantoms are the most flexible and commonly adopted models in biomedical microwave sensing. In another study, a gel-like time-durable phantom is presented to mimic skin, muscle, fat and blood [202]. This model is useful for the prediction of bio-effects at microwave and millimetre-wave frequencies. Polymer composition materials are used to fabricate stable and long-life head phantoms [203]. Polyepoxides (Epoxy), graphite, aluminium oxide, carbon and brass powders are used to fabricate the grey and white matter part of the brain. Blood mimicking material is used to represent stroke conditions and water-based material is utilized to emulate cerebrospinal fluid. Compared to liquid and gel-like phantoms, 3D printable solid phantoms can provide more realistic, stable and robust phantoms. The only drawback of these 3D-printed phantoms is the additive manufacturing and availability of materials [204]. These issues will certainly be resolved with the advancements in 3D printing technology as it will increasingly allow more materials to be processed in near future.

XI. CONCLUSION

Non-invasive portable sensors are being developed for conditions such as dementia and neurodegeneration detection. The integration of these sensors with a hearing aid device could lead to more effective procedures for the detection and treatment of more complex conditions arising in care settings. The current study presents an overview of the interrelation between hearing loss, cognitive load and dementia. Current research trends related to monitoring and detection of cognitive load are discussed, and the possibility of cognitive load detection through RF and microwave sensors is discussed in conjunction with hearing aid devices. Practical implications and challenges that can be faced in the realization of these devices are discussed, along with the possible viable solutions from existing literature. RF and microwave portable technology has the potential to revolutionize care homes and diagnostic radiology setups and to replace conventional diagnostic equipment with portable, low cost and non-invasive wearable devices. Integration with cloud computation and machine learning can further optimize the imaging analysis, diagnosis and prognosis through microwave sensors. Hence, this portable microwave technology holds immense potential if the discussed challenges and implications will be mitigated.

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