Assessment of Carotid Artery Wall Shear Stress and Plaque Vulnerability Using 4D Flow MRI in Patients Undergoing Carotid Endarterectomy

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Abstract

Vulnerable atherosclerotic plaques in the carotid arteries can lead to ischemic stroke even when the artery is not very narrow. It is believed that WSS helps lead to the accumulation and deterioration of plaques. Now, the latest technology in 4D Flow MRI enables doctors to measure the flow of blood non-invasively and map WSS in the carotid artery. This study examines if there is a connection between different carotid artery WSS patterns and the vulnerability of plaque, as seen on CEA specimens. Preoperative 4D Flow MRI was done on patients before their CEA surgery to examine three-dimensional blood flow and determine WSS measures. Examination of removed plaques after surgery showed signs of vulnerability, such as thin fibrous caps, lipid-rich necrotic cores, and black spots from bleeding. Researchers examined the relationship between WSS patterns and histopathological features. It was found that plaques located in areas of weak and constantly varying WSS tended to show signs of being vulnerable. This evidence backs the idea that changes in blood flow can lead to unstable plaques. Regions with only one direction of WSS had more firm and steady plaque characteristics. 4D Flow MRI allows for better assessment and measurement of carotid artery function, which reveals information regarding plaque behavior aside from the narrowing. It is evident from the data that magnetic resonance imaging with 4D Flow is especially useful in risk assessment and decision-making for stroke patients. Including hemodynamic data in assessing the carotid artery may help develop personalized treatment plans for people with cerebrovascular.

Keywords

Carotid Artery Wall Shear Stress (CAWSS), Plaque Vulnerability (PV), 4D Flow MRI, Carotid Endarterectomy (CE)

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The word carotid artery wall shear stress means the specific force that is exerted by blood on the wall of a carotid artery because of blood flow. There are many important factors that are dependent upon carotid artery wall shear stress. For instance, plaque formation is dependent upon Carotid Artery Wall Shear Stress. Endothelial function and atherosclerosis development are also influenced by Carotid Artery Wall Shear Stress. If we understand carotid artery wall shear stress, we can identify the possible risk of stroke in patients[1]. We can also monitor the progression of the disease in real time along with decisions about the type and time of treatment. The word plaque Vulnerability means the risk of atherosclerosis plaque rupture, which may also lead to thrombosis, embolism, and stroke as well. There are some important factors which may contribute to plaque formation in the carotid artery. These factors are plaque composition, inflammation in the Carotid Artery, high lipid content, and others. Here we are going to discuss the relationship between carotid artery wall shear stress and plaque Vulnerability. If there is low wall shear stress, it will lead to instability of plaque along the formation and progression of plaque[2]. In case of high wall shear stress, there is a risk of plaque erosion or Plaque rupture. Recent studies have shown that wall shear stress can affect endothelial function, which can promote inflammation and plaque formation in the carotid artery. The word carotid endarterectomy refers to a specific surgical procedure in which there is removal of plaque from the carotid arteries. It is done to prevent a stroke or improve blood flow in the brain or to reduce the risk of cerebral embolism. For this surgery, there is the use of 4D MRI, which has important benefits[3]. The first and foremost benefit of 4D MRI for carotid endarterectomy is that it is useful for pre-surgical planning. It can help visualize the anatomy of the carotid artery along with understanding the main characteristics of plaque. This kind of pre-surgical planning also includes assessing blood flow and hemodynamics related to the carotid artery. Not only for pre-surgical planning, this 4D MRI can also be used for post-surgical evaluation[4]. After this surgery, we can use this 4D MRI for monitoring changes in blood flow because of the surgery. After surgery, if there are some complications, these complications can also be detected easily by 4D MRI. If we discuss about important benefits of 4D MRI for carotid endarterectomy, we may come to know that it is a noninvasive imaging that can provide detailed information. It has having potential for improvement in surgery to enhance the chances of positive outcomes[5]. If we discuss important steps of removal of plaque from the carotid artery, we may come to know that the first surgical step is incision. It includes making a particular incision in the area of neck to get access to the carotid artery for surgery. The second step of this surgery includes artery exposure, in which the carotid artery is exposed, and there is identification of an area of plaque in that artery[6]. The next step after artery exposure is the removal of plaque through various instruments. After that, there is the main step of artery repair in which the artery incision is closed. This 4D Flow MRI is beneficial in this surgery in various ways. For example, it can be used in imaging protocols in which the main step is patient preparation. For example, removal of metal objects from patient's body before surgery. This 4D Flow MRI can also be used to visualize blood flow in carotid artery, so we can monitor these aspects before and after surgery. This 4D Flow MRI can also be used for quantitative analysis because it can assess the velocity of blood flow, wall Shear Stress, and other such factors. There are some important advantages and disadvantages of 4D Flow MRI for carotid endarterectomy[7]. As we have mentioned earlier that this 4D Flow MRI is useful for imaging, providing detailed information, visualization of blood flow, anatomy of the carotid artery, and many others. Recent studies have shown that there is improvement in patient care because of this 4D Flow MRI because which has helped in informing about treatment decisions. Some limitations are related to 4D Flow MRI for carotid endarterectomy. The first and foremost limitation is that there is limited availability of 4D Flow MRI[8]. Some specific institutes offer such 4D Flow MRI for carotid endarterectomy. In this way, this facility is not easily accessible to patients of all categories in our society. Secondly, the image quality in 4D Flow MRI needs to be improved to prevent noise and artifacts in carotid endarterectomy. There is an important aspect of data analysis in 4D Flow MRI, and the whole procedure of diagnosis and treatment is dependent upon accurate data analysis[9]. For such accurate data analysis, there is a need for a team of experts for the use of 4D Flow MRI for carotid endarterectomy. There are also some other options of imaging modalities which can be opted for in carotid endarterectomy because this 4D Flow MRI can be proven very costly to be used in carotid endarterectomy. There is also an important aspect of contradictions that act as a main limitation of the use of 4D Flow MRI for carotid endarterectomy. There is a stringent need for some important considerations for the use of 4D Flow MRI for carotid endarterectomy. The first important consideration is that there is a need to balance the benefits and limitations of 4D Flow MRI for getting useful outcomes. Secondly, we need to provide institutional resources so that we can ensure availability of such imaging technology in all types of healthcare and diagnostic enters. As we know that 4D Flow MRI can also be used to assess carotid artery wall shear stress by various steps. The first step of analysis is segmentation, in which there is a need to define carotid artery boundaries. Then there is velocity mapping, in which we have to calculate velocity vectors. After velocity calculation, there is a calculation of wall shear stress. After this step, there is a need to calculate the magnitude and direction of wall shear stress as well.

This assessment is useful because by studying carotid artery wall shear stress, we can get an idea about plaque Vulnerability in the Carotid Artery. In this way, we can evaluate stroke risk even before showing any symptoms of this disease in patients[10]. The relationship between WSS and plaque vulnerability in patients with carotid artery disease who undergo a CEA is evaluated using 4D Flow MRI imaging. Wall shear stress is essential since it influences the growth and advancement of atherosclerotic plaques. Vulnerable plaques are frequently found in locations where the arterial wall is exposed to low or rapidly alternating levels of WSS. 4D Flow MRI allows researchers to non-invasively measure and analyze the detailed three-dimensional motions of blood in the carotid artery for each patient. The patients considered for CEA underwent preoperative 4D Flow MRI to establish the spatial distribution of WSS and investigate associations between flow abnormalities and plaque features suggestive of vulnerability, confirmed by postoperative histopathological study of resected tissues. Low and oscillatory WSS was strongly linked to areas of vulnerable plaques with a predisposition to rupture, as indicated by the presence of lipid-laden necrotic material and a thin fibrous cap. This imaging method provides unique information about the biomechanical setting of atherosclerotic plaques, helping to improve the assessment of stroke danger and individualized treatment management. Including 4D Flow MRI in clinical practice allows doctors to detect patients with subtle signs of cardiovascular risk more accurately, which can lead to better prevention and planning for interventions.

Research Objective

The main objective of this research is to comprehend assessment of carotid artery wall shear stress and plaque Vulnerability Using 4D Flow MRI in those patients who are undergoing carotid endarterectomy. These studies have effectively explained that 4D Flow MRI can be useful for various purposes during carotid endarterectomy.

LITERATURE REVIEW

The main observation of the researchers in recent years has convinced us that there is an increase in cases of plaque formation. So, ongoing research is needed to understand the causes of this plaque formation. With time, we came to know that there is a relationship between carotid artery wall shear stress and plaque Vulnerability. In other words, we can say that the stress of blood flow on blood vessels has an important impact on plaque formation in these blood vessels. The study of Plaque Vulnerability is important because we know that plaque formation can cause disastrous results[11]. For example, Plaque formation can result in stroke, blood clotting, embolism, and other such aspects. After a long term of research, we came to the point that carotid endarterectomy can be proven effective for the treatment of plaque formation. Carotid Endarterectomy is a type of surgical procedure in which plaque is removed from the carotid artery to prevent a brain stroke[12]. There are different types of MRI, which are used for visual imaging and image analysis in the case of carotid artery disease. As mentioned earlier, there is a need to understand the structure of the artery and the composition of plaque for the removal of plaque effectively. For these purposes, 4D Flow MRI is used nowadays[13]. We can define 4D Flow MRI as a modern kind of magnetic resonance imaging technique which is used for detailed information of blood vessels in the aspect of blood flow. If we discuss about key components of 4D Flow MRI, we can say that there are three important components of this imaging technique. The first and foremost component is time solved imaging, in which there is capturing of blood flow dynamics are captured from time to time to understand carotid artery wall shear stress. The second most important component is three-dimensional imaging, in which we visualize blood flow in the carotid artery in 3D space[14]. The last component is velocity encoding, in which we have to make calculations related to blood flow capacity. The working of this 4D Flow MRI consisted of a few important steps. The first step in the working of 4D Flow MRI is data acquisition. In this step, we use MRI scanners that capture data on blood flow from carotid arteries. In the second step of working on 4D Flow MRI, there is image processing, which is based on the calculation of velocity[15]. The third step of working is visualization, which is the main extract of 4D Flow MRI for carotid endarterectomy. The main applications of 4D Flow MRI are versatile. This kind of imaging technique can be used for the diagnosis of cardiovascular diseases at a very early stage. It is because we know that cardiovascular diseases are related to blood flow in the cardiac arteries[16]. So, if we assess changes in blood flow in cardiac arteries, we can also predict the risk of cardiovascular diseases in advance. This imaging technique is widely used for surgical planning because it helps in making decisions related to surgery. It is also widely used for research purposes to study important aspects of blood flow dynamics. As mentioned earlier that there are some important steps for plaque formation in the carotid artery. The first key step is endothelial dysfunction, which means that there is damage to the inner lining of the carotid artery. After it, there is lipid accumulation. If lipid content is high in the blood, there will be penetration of these lipids into the inner wall of the carotid artery[17]. After the accumulation of lipids, there will be an immediate immune response, and such an immune response will cause inflammation at that site. The next step can be explained in terms of foam cell formation, which is due to the ingestion of lipids by macrophages. In this way, plaque growth will increase at the particular site. Some important risk factors may contribute to plaque formation in the carotid artery[18]. These risk factors are high cholesterol, high blood pressure, diabetes, smoking, and others. 4D Flow MRI is useful in this way that it can diagnose plaque formation at any step with high accuracy. There are some important ways in which 4D Flow MRI is used for pre-surgical planning for Carotid Endarterectomy. The first important way is the aspect of identification of high-risk patients. As we know that some contributing factors cause Plaque formation, so there is a need to diagnose these risk factors. Those patients who have such risk factors may be termed as high-risk patients. 4D Flow MRI will help in the identification of these patients who are at high risk of stroke[19]. Different surgical techniques are used in carotid endarterectomy, but the decision about these surgical techniques can be made with the help of 4D Flow MRI. To close in a nutshell, we can say that 4D Flow MRI helps in determining the surgical approach for carotid endarterectomy as well. Surgical strategy can also be optimized with the help of 4D Flow MRI because it will help in planning the most effective strategy. Not only for pre-surgical planning, but 4D Flow MRI is also important for post-surgical planning for Carotid Endarterectomy[20].

This 4D Flow MRI is used for the evaluation of surgical Success to understand the effectiveness of the procedure of carotid endarterectomy. As we know that it is an important imaging technique, so this technique will visualize the condition of the carotid artery after surgery and will tell us about the Success of that surgery. It will also be useful for monitoring blood flow after surgery. As we know that plaque formation affects blood flow in the carotid artery, so after surgery, this blood flow will be improved. The proper monitoring of this blood flow can be done by using 4D Flow MRI. In some cases, it has been seen that there is a risk of possible complications after surgery in carotid endarterectomy, but these complications can also be easily detected by using 4D Flow MRI. 4D Flow MRI is not directly used during surgery in carotid endarterectomy because of some limitations. The first important limitation is that there are accessibility Issues in case of intraoperative imaging by using 4D Flow MRI. Secondly, it has also been seen that using such imaging techniques during surgery in carotid endarterectomy can disrupt workflow. If these challenges are resolved with the help of improvement, 4D Flow MRI can be used during surgery in carotid endarterectomy shortly subsequently.

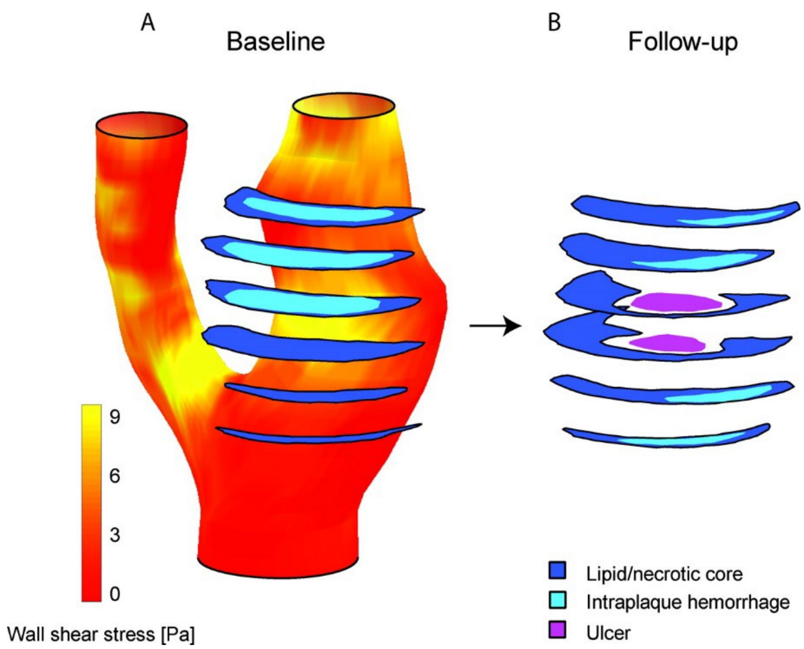

Figure 1: Efficient Identification of Stroke Risk

ASSESSMENT THE IMPLICATIONS OF CAROTID ARTERY WALL SHEAR STRESS AND PLAQUE VULNERABILITY

In patients undergoing carotid endarterectomy, using 4D Flow MRI to assess wall shear stress and plaque vulnerability has important clinical, diagnostic, and research implications.

Efficient Identification of Stroke Risk

Rather than concentrating only on luminal stenosis, it looks at the forces present in artery walls to better understand stroke risk (Figure 1). Iden Ensuring WSS zones are low and fluctuate helps doctors more precisely predict which patients are most likely to have cerebrovascular problems and offers the chance for safer and more effective treatments. Many people die every year from strokes and many more end up disabled. It is important to identify people at risk quickly to avoid, improve and manage healthcare issues. Stroke risk is related to factors that can be modified as well as those that cannot and using both old and modern screening methods together allows for quick diagnosis. Usually, medical professionals start traditional stroke risk identification by assessing existing risk factors.

Examples are hypertension, diabetes mellitus, atrial fibrillation, hyperlipidemia, smoking, obesity and having a family member who had a stroke. To calculate stroke risk, many doctors apply the Framingham Stroke Risk Profile and use the CHA_2DS_2-VASc score. They review information about a person's age, sex, blood pressure, diabetes and cardiac health and use this to guess their chances of having a stroke. Still, these can give reliable results, except when used on people with no symptoms. Linking biomarkers and imaging tools has made it easier to identify diseases. To capture these problems, the physician uses MRI at a high resolution, performs a carotid ultrasound and does CT angiography. High levels of hs-CRP, Lp-PLA2 and D-dimer in the blood can signal both intense inflammation and increased risk of blood clots, providing extra information for managing the patient's five-year risk. Currently, AI and machine learning techniques are being used to predict a person's likelihood of having a stroke [21]. AI is able to discover hidden risks in health data that regular methods are unlikely to spot. For example, using deep learning, technology can pinpoint atrial fibrillation on a heart monitor and allow doctors to prevent potential complications by applying anticoagulant therapy. Strategies in public health are vital for discovering who is at risk for stroke. Screening in the local community helps to detect and control hypertension, diabetes and dyslipidemia among people who are likely to suffer from these diseases. With mobile health apps and telemedicine, individuals can keep an eye on their blood pressure and sugar levels in real time and easily inform their doctors if they notice anything concerning. Generally, genetic testing and learning about one's family medical history help uncover potential predispositions.

Dynamic changes in certain clotting factors or lipid levels in the body may lead to more careful monitoring by healthcare professionals. All in all, recognizing the risk for stroke should involve checking for symptoms in combination with advanced solutions. Using AI with analytics, imaging and biomarkers in everyday care may bring about a stroke prevention revolution. Identifying strokes at an early stage allows quick steps to be taken and greatly reduces the problems caused by stroke. To ensure the best results, these approaches should include teaching patients, reaching out to communities and providing equal access to healthcare services.

Figure 2: Treatment Plan Personalization

Treatment Plan Personalization

Improvements in the clinical assessment of patients can be achieved with the help of WSS data (Figure 2). Individuals with delicate plaques and moderate stenosis should be given priority for surgery or special medical treatment. Stable plaques with good blood flow may protect patients from unnecessary procedures, avoiding complications and too much cost. Nowadays, medical teams look to personalize treatments based on a person's genetics, habits, any accompanying diseases and what is important to them. With diseases such as cancer, heart problems and brain or blood diseases such as stroke and diabetes, personalized care helps patients, reduces the risk of adverse effects and encourages active participation in treatment. Usually, these approaches are designed for all patients using guidelines that come from research on large groups of people. Though the guidelines are useful, they do not always take into account that everyone's body reacts differently to disease, medication and treatments. By personalizing therapy, that gap can be closed by meeting the needs of each patient individually. Genomic medicine helps personalize treatment. Lab tests and developments in pharmacogenomics have proven that genetic makeup can alter a person's response to medicines. Tumor biology can be used to determine how to best treat cancer; for example, HER2 inhibitors may be chosen for patients with breast cancer and EGFR inhibitors may be recommended for lung cancer [22]. Similarly, using genetics in cardiology, it is possible to inform treatment with the drug clopidogrel by checking for certain DNA changes in CYP2C19. Treatment options are also shaped by factors such as a person's age, gender, how their organs work, dissimilar diseases and any social factors affecting their life.

Take diabetes management: A young adult might use pump therapy or a continuous glucose monitor, while an elderly patient should be managed with simpler regimes to avoid too much medicine and possible low blood sugar. Doctors are using AI and machine learning to offer patients personalized treatment. They study a wide range of clinical data to detect certain patterns and suggest the most suitable treatments. Through clinical decision support, AI can determine when a patient needs a different dose, para suggest new courses of action and track if treatments are taken according to plan.

Figure 3: Improvement in Surgical Decision-Making

Improvement in Surgical Decision-Making

Using preoperative 4D Flow MRI data, surgeons can better analyze how blood flows in the area of a lesion (Figure 3). As a result, decisions around intervention timing and extent may be improved, possibly leading to safer and more effective outcome for the patient. With the adoption of more advanced tools and guidelines, together with patient-centered care, the way surgeons choose a course of action has advanced.

Before, surgeons used experience and their judgment to plan a procedure, but now they use various tools to make the process safer and more successful. Advances in technology now allow us to use medical imaging and various tools to diagnose diseases. The use of high-resolution MRI, CT scans and images during surgery helps surgeons evaluate the condition and select the correct approach for surgery. They help reduce the risks involved in surgeries that are complicated or done with minimal intervention. AI and machine learning are very important in predicting results of different surgeries. These technologies review information about the patient, including their age, medical history, test and lab findings and CT scans, to make these predictions. It provides better guidance for personal choices, especially on issues where the outcomes are uncertain. Bringing together various experts in MDT gatherings has improved decision-making in healthcare. Many experts such as surgeons, anesthetists, radiologists and oncologists, join forces to assess the cases of their patients and prepare a better treatment plan for each individual.

Also, it is now common for surgeons to involve patients fully in deciding how the surgery will take place. Patients are included in deciding on the risks, possible advantages and different treatments for their condition. Because of this, patients are more content, less likely to regret the choice they made and more likely to follow the instructions for their recovery. Professionals can use simulation software for surgery, 3D technology and virtual reality to practice techniques and design the best approach. With these tools, many surprises during surgery are decreased and operations become more accurate.

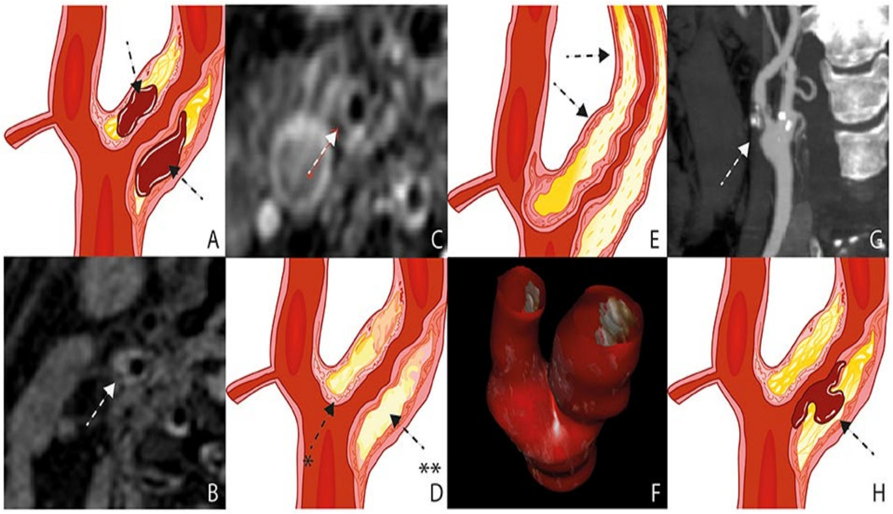

Figure 4: Characterizing Plaque in a Non-Invasive Way

Characterizing Plaque in a Non-Invasive Way

Images taken with 4D Flow MRI can show how blood flows and what the stress on blood vessels is, without any contrast agents or radiation (Figure 4). So, this technique is reliable and can help with repeatable tracking of plaques for therapy follow-up. It is vital to assess atherosclerotic plaque without surgery to have early knowledge about the disease, avoid serious problems and help patients unaware of any symptoms. If a plaque is weak and likely to break open, this increases the chance of stroke or heart attack. If plaques are found using non-invasive methods, patients remain safe and early interventions can be performed. Using advanced imaging tools has helped doctors characterize plaque in detail [23]. Carotid ultrasound with a Doppler technique is usually done to check the appearance and smoothness of plaques and the state of blood flow within the arteries. It can identify stable plaques that are often calcified from those soft plaques that might rupture and block a vessel. CTA pictures artery walls and calcified objects with great detail. CTA is able to detect plaque, identify narrowed areas in the arteries and spot any calcification which is considered a higher risk factor. Remarkably, coronary CTA is capable of measuring low-attenuation plaques and positive remodeling which are significant features of vulnerable plaques. MRI gives accurate images of the inner aspects of the arteries and so can easily identify important features such as lipid-rich cores, signs of internal bleeding and surfaces of the plaque's cap. Contrast can help doctors gain a clearer picture of neovascularization and inflammation with MRI. Metabolic activity in plaques can be spotted by using PET combined with CT or MRI. 18F-FDG may reveal parts of the body that are inflamed, a feature often found in unstable plaques.

Progress in the Study of Atherosclerosis

It supports scientific progress related to the mechanics of plaque and the effects of blood flow on its formation and breakdown. It encourages researchers to find medicines that impact WSS or stop plaques from forming.

Figure 5: Possibility of Incorporation into Everyday Clinical Care

Possibility of Incorporation into Everyday Clinical Care

With progress in the field, MRI with 4D Flow technology could soon be used more often, especially in patients with increased risk (Figure 5). To conclude, measuring carotid artery WSS and plaque vulnerability with 4D Flow MRI changes the way physicians' approach cerebrovascular disease. It improves accuracy in diagnosis, promotes personalized medicine, and encourages new advances in both treatment and study of the blood vessels. With technological progress, decreasing costs and news of improved results, advanced diagnostic tools and personal medicine can be used in everyday practice more frequently. Techniques such as carotid ultrasound, CT angiography and MRI are now becoming simpler to perform and more common, so patients with plaque in their blood vessels can be examined and cared for in outpatient clinics. Technology in health care can use AI to provide clinicians with advice on how to interpret information from EHRs related to stroke risk, planning for surgery and deciding on the best treatment methods. Clinical care relies on mobile health applications and wearable devices for tracking key health indicators and values, making them convenient for taking part in remote consultations [24]. Besides this, the standards are updated to take into account risk prediction factors and make greater use of imaging. Through education and training, clinicians are learning how to analyze and work with data used in precision medicine. It is important to note that as systems search for better outcomes at lower costs, using custom and predictive tools supports these aims. As AI and other technologies improve and gain policy support, they are easily used in ordinary care and make a big difference.

CONCLUSION

The assessment of carotid artery wall shear stress (WSS) and plaque vulnerability using 4D Flow MRI in patients undergoing carotid endarterectomy (CEA) represents a significant advancement in the understanding and management of atherosclerotic disease. This study has demonstrated that 4D Flow MRI, as a non-invasive imaging modality, offers unique insights into the complex hemodynamic environment within the carotid arteries, particularly in patients with high-grade stenosis. By quantifying multidirectional blood flow and WSS patterns, clinicians and researchers are now able to more accurately assess the biomechanical forces acting on the arterial walls and their association with plaque morphology and instability. The findings indicate that regions of low and oscillatory WSS are consistently linked with features of vulnerable plaques, such as thin fibrous caps, lipid-rich necrotic cores, and intraplaque hemorrhage. These characteristics are widely recognized as predictive of future cerebrovascular events, including ischemic strokes. Traditional imaging approaches, which primarily focus on the degree of luminal stenosis, often overlook the biological and biomechanical behavior of the plaque itself. Therefore, incorporating hemodynamic analysis through 4D Flow MRI can significantly enhance the ability to identify high-risk plaques even in lesions that may not appear severely stenotic on conventional angiographic imaging. Histopathological analysis of plaques removed during CEA has validated the correlation between disturbed flow dynamics and plaque vulnerability. This multi-modal approach strengthens the clinical relevance of WSS measurements, reinforcing the notion that local hemodynamic forces play a critical role in plaque destabilization. As such, the integration of 4D Flow MRI into routine clinical workflows has the potential to improve risk stratification for patients with carotid artery disease and guide surgical decision-making with a higher degree of precision. Moreover, this technique supports the concept of personalized medicine in vascular care. Patients with plaques exhibiting hemodynamic patterns associated with vulnerability may benefit from earlier surgical intervention or intensified medical therapy, even in the absence of severe stenosis. Conversely, patients with stable flow patterns and plaque morphology may be managed conservatively, thereby reducing unnecessary surgical procedures and associated risks.

Despite its promising potential, there are limitations to be addressed. The high cost, longer acquisition times, and the need for specialized software and expertise may limit the widespread adoption of 4D Flow MRI in standard clinical practice. Additionally, larger longitudinal studies are needed to validate its predictive power across diverse patient populations and to assess the impact of hemodynamic-guided interventions on long-term clinical outcomes. In conclusion, 4D Flow MRI emerges as a powerful diagnostic tool in evaluating carotid artery disease by bridging the gap between anatomical imaging and functional, biomechanical assessment. The demonstrated association between WSS and plaque vulnerability underscores the importance of flow dynamics in atherogenesis and stroke risk. As imaging technology continues to evolve, 4D Flow MRI holds promise for transforming the clinical assessment of vascular disease, enabling more accurate risk prediction, targeted interventions, and ultimately, improved patient outcomes in cerebrovascular care.

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