Perfusion Imaging in Acute Traumatic Brain Injury

David B. Douglas, MD[a,b], Ruchir Chaudhari, MD[a], Jason M. Zhao, MD, PhD[b], James Gullo, MD[b], Jared Kirkland, MD[b], Pamela K. Douglas, PhD[c], Ely Wolin, MD[b], James Walroth, MD[b], Max Wintermark, MD, MBA[a,*]

KEYWORDS

• Concussion • Traumatic brain injury • TBI • Perfusion

KEY POINTS

- Noncontrast computed tomography (CT) scan is the most appropriate initial neuroimaging study for a moderate to severe closed head injury.
- Perfusion CT has a higher sensitivity for detecting cerebral contusions than noncontrast CT examinations.
- Future research in perfusion imaging may improve the diagnosis, prognosis, and management of acute traumatic brain injury.

INTRODUCTION

Traumatic brain injury (TBI) is a major health care issue affecting 1.7 million people, hospitalizing 275,000 people and resulting in 52,000 deaths annually in the United States, and the incidence of emergency room visits related to TBI is increasing.[1–3] It is estimated that 3.2 million people are living with long-term disability from TBI.[4] The most common causes of TBI include motor vehicle accidents, falls, sports-related injury, and assault in the civilian population,[1–3] and explosion-related injury in the military.[5] Neuroimaging plays a key role in the diagnosis, treatment, and prognosis of TBI.

The American College of Radiology has provided appropriateness criteria to help referring physicians make the most appropriate decisions on imaging examinations. As an example, for a moderate or severe acute closed head injury (Glasgow Coma Scale <13), the most appropriate initial neuroimaging study is a noncontrast computed tomography (CT) scan.[6] A noncontrast CT scan can diagnose injuries, such as an epidural hematoma, that

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[a] Department of Neuroradiology, Stanford University Medical Center, 300 Pasteur Drive, Room S047, Stanford, CA 94305-5105, USA; [b] Department of Radiology, David Grant Medical Center, 101 Bodin Circle, Travis Air Force Base, CA 94535, USA; [c] Institute for Simulation and Training, University of Central Florida, 3100 Technology Parkway, Orlando, FL 32826, USA

* Corresponding author. Department of Neuroradiology, Stanford University Medical Center, 300 Pasteur Drive, Room S047, Stanford, CA 94305-5105.

E-mail address: mwinterm@stanford.edu

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require emergent neurosurgical intervention. However, there are limitations associated with noncontrast CT scans. For example, early CT scans have been found to underestimate the size of parenchymal contusions.[7] For this reason, short-interval follow-up CT scans may be beneficial. In addition, early conventional noncontrast CT imaging does not show secondary ischemic changes related to cerebral edema and intracranial hypertension, which are responsible for nearly half of TBI-related deaths after admission.[8]

In recent years, neuroimaging has advanced beyond structural imaging to functional tissue characterization including cerebral perfusion. Perfusion is physiologically defined as the flow of blood per unit volume of tissue. The term tissue emphasizes that this specifically means capillary blood flow. Perfusion imaging is commonly used in clinical practice in the setting of stroke because it has the ability to distinguish normally perfused cerebral parenchyma from ischemic penumbra from infarcted tissue.[9–12] Recently, perfusion neuroimaging techniques have been explored in TBI to determine and characterize potential perfusion neuroimaging biomarkers to aid in diagnosis, treatment, and prognosis. Following TBI, it is thought that alterations in the cerebrovascular parameters may lead to secondary injuries.[13] The ability to improve clinical outcomes following TBI may rely on the ability to detect potentially salvageable tissue known as traumatic penumbra and secondary ischemic events.[14–16] This article reviews perfusion imaging techniques in TBI, including bolus perfusion CT (PCT), bolus perfusion MR imaging, arterial spin labeling (ASL) perfusion MR imaging, and stable xenon PCT. This article concludes with a discussion of future research techniques.

PERFUSION IMAGING IN COMPUTED TOMOGRAPHY

Introduction

The underlying basis for PCT is conservation of flow. In order to measure flow, a nondiffusible tracer (ie, an agent that remains in the vasculature) is administered intravenously. Bolus perfusion imaging is performed on a multidetector CT scanner in the axial plane typically with a 4 mL/s contrast injection rate.

With regard to image processing, the PCT images are used to create time-enhancement curves registered to each pixel in the data set. From the time-enhancement curves, processing software can generate key parameters, including regional cerebral blood volume (rCBV), mean transit time (MTT), and regional cerebral blood flow (rCBF), which have been validated to stable xenon CT (Xe-CT).[17]

The cerebral blood volume (CBV) map is calculated from the area under the time-enhancement curves and represents the blood volume within the arterioles and venules of a given parenchymal tissue volume with units of milliliters of blood per 100 g of brain tissue. The MTT represents the average time that it takes for blood to flow from the arterial input through the brain tissue and to the venous drainage, and has units of seconds. MTT is calculated by a mathematical process called deconvolution.[18–20] The MTT requires a reference arterial input function (AIF), which commonly uses a region of interest drawn around the anterior cerebral artery. Time to peak is the time from the arrival of contrast into the AIF to the peak of the time-enhancement curve for each voxel. The time of maximum concentration (T_{max}) is calculated from the time to peak, with $T_{max} = 0$ for normal perfused tissue without delay.[21] In addition, cerebral blood flow (CBF) is the volume of blood flowing through a given volume of brain tissue over a certain time period and has units of milliliters of blood per 100 g of brain tissue per minute (**Fig. 1**).

The central volume principle describes the relationship between a compartment volume, blood flow through the compartment, and the mean transit time through the compartment.[12] According to the central volume principle, the MTT is equal to the rCBV divided by the rCBF.[22] The cerebral parenchyma viability is completely dependent on CBF. Alterations in CBF can influence electrical and metabolic neuronal activity. Cerebral autoregulation plays a role in ensuring that there is adequate CBF despite alterations in systemic pressure.

Bolus Computed Tomography Perfusion Imaging Applied to Acute Traumatic Brain Injury

Wintermark and colleagues[23] explored PCT on admission CT scans and found perfusion abnormalities associated with juxtadural collections, cerebral edema, and intracranial hypertension. In the Wintermark and colleagues[23] study, which included 48 patients who had cerebral contusions diagnosed on delayed follow-up imaging, 19 of the 48 contusions were seen on the initial noncontrast CT images (sensitivity of 39.6%) and 42 of the 48 were seen on the PCT images (sensitivity of 87.5%). The 42 perfusion abnormalities were noted to occur in the same location as the contusion on delayed CT. The difference in the sensitivity of noncontrast CT and PCT was statistically significant ($P<.001$). The specificity of