Contrast Enhancement of the Normal Infundibular Recess Using Heavily T2-weighted 3D FLAIR

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Purpose: The purpose of the present study was to evaluate contrast enhancement of the infundibular recess in the normal state using heavily T2-weighted 3D fluid-attenuated inversion recovery (FLAIR) (HT2-FLAIR).

Methods: Twenty-six patients were retrospectively recruited. We subjectively assessed overall contrast enhancement of the infundibular recess between postcontrast, 4-hour (4-h) delayed postcontrast, and precontrast HT2-FLAIR images. We also objectively conducted chronological and spatial comparisons by measuring the signal intensity (SI) ratio (SIR). Chronological comparisons were performed by comparing SI of the infundibular recess/SI of the midbrain (SIRIR-MB). Spatial comparisons were conducted by comparing SI on postcontrast HT2-FLAIR/SI on precontrast HT2-FLAIR (SIRPost-Pre) of the infundibular recess with that of other cerebrospinal fluid (CSF) spaces, including the superior part of the third ventricle, lateral ventricles, fourth ventricle, and interpeduncular cistern.

Results: In the subjective analysis, all cases showed contrast enhancement of the infundibular recess on both postcontrast and 4-h delayed postcontrast HT2-FLAIR, and showed weaker contrast enhancement of the infundibular recess on 4-h delayed postcontrast HT2-FLAIR than on postcontrast HT2-FLAIR. In the objective analysis, SIRIR-MB was the highest on postcontrast images, followed by 4-h delayed postcontrast images. SIRPost-Pre was significantly higher in the infundibular recess than in the other CSF spaces.

Conclusion: The present results demonstrated that the infundibular recess was enhanced on HT2-FLAIR after an intravenous gadolinium injection. The infundibular recess may be a potential source of the leakage of intravenously administered gadolinium into the CSF.

Keywords: infundibular recess, three-dimensional fluid-attenuated inversion recovery, magnetic resonance imaging, contrast enhancement, gadolinium deposition

Introduction

The infundibular recess is a cerebrospinal fluid (CSF)-filled space of the third ventricle floor that extends into the pituitary stalk. This space is surrounded by the median eminence, one of the circumventricular organs (CVOs) characterized by permeable fenestrated capillaries lacking a blood-brain barrier (BBB). Therefore, substances move freely between the blood and CVOs. Fluorescence endoscopy visualized the median eminence after the intravenous administration of fluorescein sodium.1,2

Previous studies indicated that the median eminence was enhanced after the intravenous administration of gadolinium on T1-weighted (T1W) or fluid-attenuated inversion recovery (FLAIR) imaging.3–5 FLAIR is an MRI sequence with inversion recovery that suppresses the signal from water. FLAIR provides greater sensitivity for detecting subtle T1 shortening induced by contrast material than T1W imaging and has been applied to various intracranial lesions.6 Heavily T2-weighted (T2W) 3D FLAIR (HT2-FLAIR) is a variant of the 3D turbo spin echo (TSE) FLAIR sequence with variable flip-angle refocusing pulses.7 This sequence provides greater sensitivity to low concentrations of contrast material in a fluid than conventional 3D FLAIR and has been applied to
the inner ear and brain. A previous study demonstrated that
the anterior eye segment and various areas of the cranial
subarachnoid space were enhanced on HT2-FLAIR in
patients without eye disease or subarachnoid space disease.

However, to the best of our knowledge, the enhancement of
the normal infundibular recess on contrast-enhanced MRI has
not yet been demonstrated. In our clinical practice, we noted
that the infundibular recess was enhanced on HT2-FLAIR.
Although a few studies speculated that a relationship exists
between the infundibular recess and endocrine system, its
function remains unclear. Kanda et al. demonstrated gadolinium
deposition in the brain after its intravenous administration.
Although the exact mechanisms have not yet been elucidated in
detail, several hypotheses have been proposed, one of which is
the glymphatic system. The glymphatic system is a functional
waste clearance pathway for the central nervous system. This
system drives CSF into the interstitial space of the brain along
the perivascular space surrounding arteries and out along the
perivascular space around the veins. Therefore, an evaluation of
contrast enhancement of the infundibular recess may provide
novel insights into the transport of gadolinium into CSF and its
deposition in the brain. The purpose of the present study was to
evaluate contrast enhancement of the infundibular recess in the
normal state using HT2-FLAIR.

Materials and Methods

Patients
This retrospective study was approved by the Institutional
Review Board of our institution. We obtained written informed
consent for the procedures and opt-out consent for the use of
retrospective clinical data from all patients/from parents or
legal guardian of patient less than 18 years. We reviewed the
imaging records of 27 consecutive patients with suspected
dolymphatic hydrops between March 2017 and July 2020.
Patients were enrolled according to the following inclusion
criteria: 1) MR cisternography (MRC) was available, 2) HT2-
FLAIR images with and without gadolinium-based contrast
material were available. Patients were excluded if image quality
was insufficient to interpret the images, the infundibular
recess was not included in the FOV, or the infundibular recess
and surrounding tissues (median eminence and pituitary stalk)
showed clinical and/or radiological abnormalities.

MRI
MRI was performed on all patients using the 3 Tesla MR
imaging unit (MAGNETOM Skyra, Siemens, Erlangen,
Germany) with a 32-channel head coil. Twenty-seven
patients underwent axial HT2-FLAIR and axial heavily
T2W MRC of the inner ear (Fig. 1), according to a protocol
proposed by Naganawa et al. for the evaluation of endolym-
phatic hydrops. MRC was performed for an anatomical
reference of total lymph fluid. We fused an MRC image
and each HT2-FLAIR image into one blended image to
accurately localize contrast enhancing areas.

HT2-FLAIR was conducted using the following para-
meters: TR 9000 ms, TE 542 ms, inversion time 2250 ms,
a frequency-selective fat suppression prepulse, variable flip-
angle echo train with an average flip angle of 120° followed
by a 90° restore pulse, echo train length 519, matrix size 384
× 384, FOV 166 × 196 mm, axial slices 104, 0.5 × 0.5 mm in-
plane resolution at a slice thickness of 1.0 mm, bandwidth
434 Hz/pixel, an acceleration factor 2 using the generalized autocalibrating partially parallel acquisitions (GRAPPA) parallel imaging technique, number of excitations 2, and acquisition time 7.17 min. Postcontrast HT2-FLAIR images were obtained approximately 0.5 to 5 min after an intravenous injection of gadolinium-HP-DO3A (Gadoteridol) at a single dose of 0.2 mL/kg (0.1 mmol/kg).

MRC was acquired with the following parameters: TR 4400 ms, TE 542 ms, a frequency-selective fat suppression prepulse, variable flip-angle echo train with an average flip angle of 120° followed by a 90° restore pulse, echo train length 519, matrix size 384 × 384, FOV 166 × 196 mm, axial slices 104, 0.5 × 0.5 mm in-plane resolution at a slice thickness of 1.0 mm, bandwidth 434 Hz/pixel, an acceleration factor 2 using the GRAPPA parallel imaging technique, number of excitations 1.8, and acquisition time 3.15 min.

**Imaging analysis**

**Subjective analysis**

We visually assessed overall contrast enhancement of the infundibular recess. The presence of contrast enhancement was defined as a higher signal intensity (SI) on postcontrast or 4-hour (4-h) delayed postcontrast HT2-FLAIR than on precontrast HT2-FLAIR. We also compared SI between postcontrast and 4-h delayed postcontrast HT2-FLAIR. Overall contrast enhancement of the median eminence was evaluated using the same approach and was compared with that of the infundibular recess. All images were independently reviewed in a random order by two board-certified radiologists (I.O and E.K) who were blinded to clinical information and sequence parameters. Discrepancies between the two radiologists were resolved by consensus.

**Objective analysis**

An objective analysis was conducted by measuring the signal intensity ratio (SIR) in predefined ROIs followed by chronological and spatial comparisons on the workstation (Synapse VINCENT version 5.2; Fujifilm, Tokyo, Japan). SIR was calculated as follows: $\text{SIR}_{\text{IR-MB}} = \text{SI of the infundibular recess (SI}_{\text{IR}})/\text{SI of the midbrain (SI}_{\text{MB}})$ and $\text{SIR}_{\text{Post-Pre}} = \text{SI on postcontrast HT2-FLAIR (SI}_{\text{Post}})/\text{SI on precontrast HT2-FLAIR (SI}_{\text{Pre}})$. SI was the mean SI of the infundibular recess. SIIR was the mean SI of the midbrain. SIRIR was the mean SI of the infundibular recess or other CSF spaces on postcontrast HT2-FLAIR.

Chronological comparisons were performed by comparing SIRIR-MB between each time point. We decided to manually place a freehand ROI on the infundibular recess and an ovoid ROI on the midbrain at the level of the median eminence on MRC, and then copied the ROI to each image on HT2-FLAIR. The size of the ROI on the infundibular recess ranged between 2.6 and 8.6 mm² (mean 4.9 mm²), while that on the midbrain was 20 mm². After measuring SIIR and SIMB, we calculated SIRIR-MB to compare between each time point.

Spatial comparisons were conducted by comparing SIRPost-Pre of the infundibular recess with that of other CSF spaces, including the superior part of the third ventricle (ovoid ROI size 3 mm²), lateral ventricles (ovoid ROI size 1.5 mm² on each side), fourth ventricle (ovoid ROI size 3 mm²), and prepontine cistern (ovoid ROI size 3 mm²). Each ROI was placed in the same manner as described above. SI of the lateral ventricles was calculated as the mean of the right and left sides. Measurements of the CNR were performed by a single observer (I.O).

**Statistical analysis**

Chronological comparisons of SIRIR-MB were performed using the Friedman test followed by the Holm correction for multiple comparisons. We compared SIRPost-Pre of the infundibular recess with that of other CSF spaces using the Kruskal-Wallis test followed by the Steel test for multiple comparisons to a control. Two-tailed $P$ values less than 0.05 were considered to be significant. All statistical calculations were conducted with JMP 14.0.0 software (SAS Institute, Cary, NC, USA) and the statistical computing language R (Version 3.4.3; The R Foundation, https://www.r-project.org).

**Results**

**Patients**

Twenty-seven patients underwent MRC and HT2-FLAIR with and without gadolinium-based contrast material. Twenty-six out of the 27 patients with available images satisfied the inclusion criteria. One patient was excluded because the infundibular recess and surrounding tissues were compressed due to bilateral chronic subdural hematomas. The patient cohort included 11 males and 15 females, with an average age of 53 years (range from 17 to 80 years).

**Subjective analysis**

All cases showed contrast enhancement of the infundibular recess on both postcontrast and 4-h delayed postcontrast HT2-FLAIR (Fig. 2). All patients showed weaker contrast enhancement of the infundibular recess on 4-h delayed postcontrast HT2-FLAIR than on postcontrast HT2-FLAIR. Among 26 patients, 14 showed contrast enhancement of the median eminence on postcontrast HT2-FLAIR (Fig. 3), whereas the remaining 12 did not on postcontrast or 4-h delayed postcontrast HT2-FLAIR. Furthermore, contrast enhancement of the median eminence decreased on 4-h delayed postcontrast HT2-FLAIR in all 14 patients (weaker enhancement; n = 8, no enhancement; n = 6). Contrast enhancement of the median eminence was weaker than that of the infundibular recess on both postcontrast (n = 14) and 4-h delayed postcontrast (n = 8) HT2-FLAIR.

**Objective analysis**

Figure 4 shows chronological changes in SIRIR-MB. SIRIR-MB was significantly higher on postcontrast HT2-FLAIR.
Fig. 2 Chronological changes in contrast enhancement in the infundibular recess. The infundibular recess shows hyperintensity on MRC (a, arrow). On HT2-FLAIR, in comparisons with a precontrast image (b), a postcontrast image (c, arrow) shows stronger enhancement of the infundibular recess. A 4-h delayed postcontrast image (d, arrow) demonstrates decreased contrast enhancement of the infundibular recess. We fused an MRC image and each HT2-FLAIR image into one blended image (e, f, and g), on which contrast enhancement on postcontrast HT2-FLAIR (f) corresponds to the hyperintensity of the infundibular recess on MRC. 4-h, 4-hour; HT2-FLAIR, heavily T2-weighted 3D fluid-attenuated inversion recovery; MRC, MR cisternography.

Fig. 3 Contrast enhancement of the median eminence. The infundibular recess (a, arrow) is surrounded by the median eminence (a, arrowheads) on MRC. On HT2-FLAIR, in comparisons with a precontrast image (b), a postcontrast image (c, arrow) shows stronger contrast enhancement of the infundibular recess. The median eminence shows weaker contrast enhancement than the infundibular recess (c, arrowheads). A 4-h delayed postcontrast image (d) shows decreases in contrast enhancement of the infundibular recess and median eminence. 4-h, 4-hour; HT2-FLAIR, heavily T2-weighted 3D fluid-attenuated inversion recovery; MRC, MR cisternography.
than that on precontrast (1.30 ± 0.63; 
$P < 0.0001$) and 4-h delayed postcontrast (4.55 ± 2.72; 
$P < 0.0001$) HT2-FLAIR. SIRIR-MB was significantly higher
on 4-h delayed postcontrast HT2-FLAIR than on precontrast
HT2-FLAIR ($P < 0.0001$). Figure 5 shows spatial compar-
sions of SIRPost-Pre. The infundibular recess showed signifi-
cantly higher SIRPost-Pre (7.46 ± 2.41) than the other CSF
spaces (the superior part of the third ventricle 1.04 ± 0.56; 
$P < 0.0001$; the lateral ventricles 1.16 ± 0.80; $P < 0.0001$; the
fourth ventricle 0.96 ± 0.30; $P < 0.0001$; and the pre-
pontine cistern 1.24 ± 0.61; $P < 0.0001$).

Discussion

The present results demonstrated that the normal infundibu-
lar recess was enhanced on HT2-FLAIR. Enhancement of
the infundibular recess was stronger on postcontrast
HT2-FLAIR than on 4-h delayed postcontrast HT2-FLAIR.
Furthermore, the infundibular recess was more strongly
enhanced than other CSF spaces.

Currently, it remains unclear why the infundibular recess
showed contrast enhancement. One possible explanation is the
leakage of contrast material into CSF from the median emi-
nence. The median eminence is a CVO that is located at the
interface between the ventral hypothalamus and infundibular
recess. CVOs are midline structures located around the third
and fourth ventricles. Although the functions and morpholo-
gies of CVOs vary, they have several common features: 1) a
fenestrated capillary lacking BBB and surrounded by large
perivascular spaces, 2) specialized neuroglial cells (tanicytes
and pituicytes), and 3) an interface between the brain, blood,
and CSF. These organs play a critical role as a transducer of
information between the brain, blood, and CSF.

There are seven major CVOs that include the median
eminence, neurohypophysis, pineal gland, subcommisssural
organ, organum vasculosum laminae terminalis (OVLT),
subfornical organ, and area postrema. CVOs may be classi-
ﬁed as secretory (the median eminence, neurohypophysis,
pineal gland, and subcommissural organ) and sensory
(OVLT, the subfornical organ, and area postrema). Secretory CVOs allow the discharge of substances into the
blood or ventricles, while sensory CVOs receive a wide
range of chemical signals from the blood and then pass
information to other brain regions.

The median eminence is characterized by permeable fene-
strated capillaries lacking BBB. As a result, substances move
freely between the blood and extracellular space within the
median eminence. A series of tracers (Trypan blue, Evans
blue, ferritin, and horseradish peroxidase) administered intra-
venously escape from the portal capillaries into the perivas-
cular space and readily reach the intercellular space within
the median eminence.14 The vascular permeability of CVOs
is size-selective; low-molecular-weight substances are
more permeable than high-molecular-weight substances.15
Secretory CVOs may be more permeable than sensory
CVOs.16 The median eminence contains specialized ependyl-
mal cells called tanicytes, which line the floor of the third
ventricle and form a bridge between the portal capillary
system and the third ventricle. The dorsal wall of the median eminence bordering the floor of the infundibular recess is lined by β2 tanycytes. Tight junctions between β2 tanycytes at the ventricular pole restrict the passage of substances between CSF and the extracellular space within the median eminence.

However, previous studies reported the transport of substances from the median eminence to CSF in the third ventricle. Caraty et al. demonstrated that gonadotropin-releasing hormone (GnRH) was not uniformly distributed throughout the third ventricle and was more concentrated in the infundibular recess. They hypothesized that the median eminence may be a major, if not the only, source of GnRH entering CSF. Other studies revealed that peptide hormones, including leptin and ghrelin, were transported after their peripheral administration from the blood to the CSF via tanycytes in the median eminence. Therefore, tight junctions between β2 tanycytes may be leaky. Since the infundibular recess is devoid of multiciliated ependymal cells, CSF flow may be reduced at this level, which may contribute to the accumulation of gadolinium within the infundibular recess.

Gadolinium deposition in the brain after its intravenous administration was initially reported by Kanda et al. in 2014. The risk of gadolinium accumulation has been extensively debated. Although the exact mechanisms by which gadolinium is deposited in the brain remain unknown, several hypotheses have been proposed. Recent studies indicated that the glymphatic system may be one of the transport pathways of gadolinium into the brain parenchyma. Iliff et al. used contrast-enhanced MRI and revealed that gadolinium-based contrast agents administered intrathecally passed through the paravascular pathways to enter the live rat brain. In humans, contrast-enhanced MR studies also demonstrated that gadolinium entered the brain parenchyma after its intrathecal administration. Previous studies reported that intravenously administered gadolinium was distributed into perivascular spaces as well as CSF spaces around various tissues, including the peripheral part of the cranial nerves and the cortical veins. The perivascular space, comprising the glymphatic system, plays the role of a transport conduit of CSF and solutes in the brain. The constellation of these MRI findings suggests the involvement of the glymphatic system in the transportation and deposition of gadolinium in the brain. Large perivascular spaces surrounding the median eminence might act as conduits for the transport of gadolinium.

The present results revealed the weaker enhancement of the median eminence than that of the infundibular recess on HT2-FLAIR in some cases. Contrast-enhanced MRI studies showed that CVOs, including the median eminence, were enhanced using T1W imaging or FLAIR. Azuma et al. reported that among CVOs on postcontrast 3D T2-FLAIR, marked enhancement of the median eminence was most frequently observed; they did not describe contrast...
enhancement of the infundibular recess. Although the imaging parameters employed for 3D FLAIR in the present study were not equivalent or comparable to those in Azuma’s study, contrast enhancement of the median eminence and infundibular recess may not be differentiated on 3D T2-FLAIR, possibly because of lower in-plane resolution (0.9 × 0.9 mm) than with HT2-FLAIR (0.5 × 0.5 mm).

The present study demonstrated that the infundibular recess was enhanced relatively early (0.5 to 5 min) after the intravenous administration of gadolinium. On the other hand, in an MRI study on the heads of healthy male volunteers, the signal intensities of various CSF spaces (such as the subarachnoid space surrounding the optic nerve and Meckel’s cave) did not significantly differ between precontrast and 0.5-h postcontrast HT2-FLAIR. However, this finding does not necessarily suggest that intravenous gadolinium does not rapidly move into CSF spaces. Since that study only had a small sample size (n = 6), a larger sample size may yield a significant difference. Furthermore, Naganawa et al. reported that not only the OVLT but also the surrounding CSF spaces were enhanced on HT2-FLAIR 0.5 h after the administration of gadolinium. Therefore, contrast leakage from the OVLT was readily visualized after contrast agent administration.

Although the mechanisms underlying the early enhancement of the infundibular recess remain unknown, gadolinium leakage from the median eminence into the infundibular recess has been proposed. The present study showed that strong enhancement may occur at an early time point, nearly equivalent to that of the OVLT and the surrounding CSF spaces. Since the median eminence lacks a BBB, similar to the OVLT, intravenous gadolinium may rapidly move to the median eminence and then to the infundibular recess.

Another reason may be associated with CSF flow in the infundibular recess. As described earlier, since the infundibular recess is devoid of multiciliated ependymal cells, CSF flow may be reduced at this level, which may contribute to the accumulation of gadolinium. In addition, CSF flow may influence the sensitivity of 3D FLAIR to gadolinium; 3D FLAIR was sensitive to not only low concentrations of gadolinium but also to slow flow. If the infundibular recess contains slow-flowing CSF, HT2-FLAIR may improve the detection of gadolinium in the CSF. Therefore, early and prolonged enhancement of the infundibular recess may be associated with its CSF flow.

There were several limitations that need to be addressed. The present study was a retrospective evaluation of a limited number of patients. Furthermore, data were acquired at a few time points. In future studies, more time points need to be examined. Moreover, we assessed patients with cochleovestibular symptoms and did not include completely healthy subjects. However, we consider the results obtained to reflect the normal state of the infundibular recess because patients did not have neurological symptoms or MRI findings associated with the infundibular recess and surrounding tissues.

Conclusion

In conclusion, the present study demonstrated that the infundibular recess was enhanced on HT2-FLAIR after the intravenous gadolinium injection. Contrast enhancement of the infundibular recess was stronger than that of other CSF spaces and decreased 4 h after the administration of gadolinium. The infundibular recess is a potential source of the leakage of intravenously administered gadolinium into the CSF.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

1. Kubo S, Inui T, Yamazato K. Visualisation of the circumventricular organs by fluorescence endoscopy. J Neurol Neurosurg Psychiatry 2004; 75:180.
2. Longatti P, Basaldella L, Sammartino F, et al. Fluorescein-enhanced characterization of additional anatomical landmarks in cerebral ventricular endoscopy. Neurosurgery 2013; 72:855–860.
3. Horsburgh A, Massoud TF. The circumventricular organs of the brain: conspicuous on clinical 3T MRI and a review of functional anatomy. Surg Radiol Anat 2013; 35:343–349.
4. Tsutsumi S, Ono H, Yasumoto Y. The tuber cinereum as a circumventricular organ: an anatomical study using magnetic resonance imaging. Surg Radiol Anat 2017; 39:747–751.
5. Azuma M, Hirai T, Kadota Y, et al. Circumventricular organs of human brain visualized on post-contrast 3D fluid-attenuated inversion recovery imaging. Neuroradiology 2018; 60:583–590.
6. Naganawa S. The technical and clinical features of 3D-FLAIR in neuroimaging. Magn Reson Med Sci 2015; 14:93–106.
7. Naganawa S, Yamazaki M, Kawai H, et al. Visualization of endolymphatic hydrops in Ménière’s disease with single-dose intravenous gadolinium-based contrast media using heavily T2-weighted 3D-FLAIR. Magn Reson Med Sci 2010; 9:237–242.
8. Naganawa S, Yamazaki M, Kawai H, et al. Contrast enhancement of the anterior eye segment and subarachnoid space: detection in the normal state by heavily T2-weighted 3D FLAIR. Magn Reson Med Sci 2011; 10:193–199.
9. Caraty A, Skinner DC. Gonadotropin-releasing hormone in third ventricular cerebrospinal fluid: endogenous distribution and exogenous uptake. Endocrinology 2008; 149:5227–5234.
10. Robinson AG, Zimmerman EA. Cerebrospinal fluid and ependymal neurophysin. J Clin Invest 1973; 52:1260–1267.
11. Kanda T, Ishii K, Kawaguchi H, et al. High signal intensity in the dentate nucleus and globus pallidus on unenhanced T1-weighted MR images: relationship with increasing cumulative dose of a gadolinium-based contrast material. Radiology 2014; 270:834–841.
12. Iliff JJ, Wang M, Liao Y, et al. A paravascular pathway facilitates CSF flow through the brain parenchyma and the clearance of interstitial solutes, including amyloid β. Sci Transl Med 2012; 4:147ra111.
13. Naganawa S, Nakashima T. Visualization of endolymphatic hydrops with MR imaging in patients with Ménière’s disease and related pathologies: current status of its methods and clinical significance. Jpn J Radiol 2014; 32:191–204.
14. Rodríguez EM, Blázquez JL, Guerra M. The design of barriers in the hypothalamus allows the median eminence and the arcuate nucleus to enjoy private milieus: the former opens to the portal blood and the latter to the cerebrospinal fluid. Peptides 2010; 31:757–776.
15. Morita S, Furube E, Mannari T, et al. Heterogeneous vascular permeability and alternative diffusion barrier in sensory circumventricular organs of adult mouse brain. Cell Tissue Res 2016; 363:497–511.
16. Morita S, Miyata S. Different vascular permeability between the sensory and secretory circumventricular organs of adult mouse brain. Cell Tissue Res 2012; 349:589–603.
17. Ballard E, Dam J, Langlet F, et al. Hypothalamic tanycytes are an ERK-gated conduit for leptin into the brain. Cell Metab 2014; 19:293–301.
18. Collden G, Ballard E, Parkash J, et al. Neonatal overnutrition causes early alterations in the central response to peripheral ghrelin. Mol Metab 2015; 4:15–24.
19. Iliff JJ, Lee H, Yu M, et al. Brain-wide pathway for waste clearance captured by contrast-enhanced MRI. J Clin Invest 2013; 123:1299–1309.
20. Ringstad G, Vatnehol SAS, Eide PK. Glymphatic MRI in idiopathic normal pressure hydrocephalus. Brain 2017; 140:2691–2705.
21. Dyke JP, Xu HS, Verma A, et al. MRI characterization of early CNS transport kinetics post intrathecal gadolinium injection: Trends of subarachnoid and parenchymal distribution in healthy volunteers. Clin Imaging 2020; 68:1–6.
22. Naganawa S, Nakane T, Kawai H, et al. Gd-based contrast enhancement of the perivascular spaces in the Basal Ganglia. Magn Reson Med Sci 2017; 16:61–65.
23. Naganawa S, Taoka T, Kawai H, et al. Appearance of the organum vasculosum of the lamina terminalis on contrast-enhanced MR imaging. Magn Reson Med Sci 2018; 17:132–137.
24. Ohashi T, Naganawa S, Ogawa E, et al. Signal intensity of the cerebrospinal fluid after intravenous administration of gadolinium-based contrast agents: strong contrast enhancement around the vein of labbe. Magn Reson Med Sci 2019; 18:194–199.
25. Naganawa S, Suzuki K, Yamazaki M, et al. Serial scans in healthy volunteers following intravenous administration of gadoteridol: time course of contrast enhancement in various cranial fluid spaces. Magn Reson Med Sci 2014; 13:7–13.