Detecting dopamine dysfunction with pharmacological MRI

Schrantee, A.G.M.

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Chapter 8

The age-dependent effects of a single-dose methylphenidate challenge on cerebral perfusion in patients with attention-deficit/hyperactivity disorder

Anouk Schrantee, Henk-Jan MM Mutsaerts, Cheima Bouziane, Hyke GH Tamminga, Marco A Bottelier, Liesbeth Reneman

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Abstract

Introduction: Methylphenidate (MPH) is a stimulant drug and an effective treatment for attention-deficit/hyperactivity disorder (ADHD) in both children and adults. Pre-clinical studies suggest that the response to stimulants is dependent on age, which may reflect the ontogeny of the dopamine (DA) system, which continues to develop throughout childhood and adolescence. Therefore, the aim of this study was to investigate the modulating effect of age on the cerebral blood flow (CBF) response to MPH in stimulant treatment-naive children and adults with ADHD.

Methods: Ninety-eight stimulant treatment-naive male pediatric (10-12 years) and adult (23-40 years) patients with ADHD were included in this study. The CBF response to an acute challenge with MPH (0.5 mg/kg) was measured using arterial spin labeling pharmacological magnetic resonance imaging, as a proxy for DA function. Region-of-interest (ROI) analyses were carried out for the striatum, thalamus and medial prefrontal cortex and in addition voxel-wise analyses were conducted.

Results: An acute challenge with MPH decreased CBF in both children and adults in cortical areas, although to a greater extent in adults. In contrast, ROI analyses showed that MPH decreased thalamic CBF only in children, but not adults.

Discussion: Our findings highlight the importance of taking the developmental perspective into account when studying the effects of stimulants in ADHD patients.
Pharmacological treatment of attention-deficit/hyperactivity disorder (ADHD) is increasing in children, but also in the adult population (McCarthy et al., 2012). Stimulants, such as methylphenidate (MPH), are the main pharmacological treatment in both children and adults. MPH is the most frequently prescribed stimulant and is particularly effective in reducing behavioral symptoms (MTA group, 1999), at least on the short term. Its therapeutic efficacy has largely been ascribed to its ability to prevent reuptake of catecholamines, such as dopamine (DA) and noradrenalin (NA), thereby enhancing DAergic and noradrenergic neurotransmission (Arnsten, 2011). Indeed, neuroimaging studies have suggested major DAergic alterations in the pathogenesis of ADHD and thereby lend further support for the efficacy of stimulants (Castellanos et al., 1996; Larisch et al., 2006; Spencer et al., 2013). Thus, assessment of the functioning of the DA system is key for studying the pathophysiology of ADHD across development.

The DA system develops throughout childhood, but is not fully mature until adulthood (Wahlstrom et al., 2010). Remodeling of pre- and postsynaptic receptors continues during development, resulting in differential functioning and output of the DA system at different developmental stages. For example, preclinical studies have observed a major shift in the ratio of excitatory D1/D5 and inhibitory D3/D2/D4 receptors (Chen et al., 2010). Also, previous studies have demonstrated anatomical developmental abnormalities in patients with ADHD (Shaw et al., 2009, 2014). In addition, both the structure and function of the DA system may be altered in children and adults with ADHD when compared to healthy controls (Weyandt et al., 2013).

Functional abnormalities in DAergic areas have originally been assessed using perfusion studies with position emission tomography (PET), single photon emission computed tomography (SPECT) but more recently also with magnetic resonance imaging (MRI). Using these techniques, not only baseline perfusion in DAergic brain areas can be studied, but also the response to stimulant medication such as MPH. Although early PET studies in children with ADHD suffered from methodological constraints such as small sample size, they consistently reported decreased perfusion in the striatum compared to controls, which was, in some studies, reversed by a single dose of MPH (Kim et al., 2001; Lee et al., 2005; Lou et al., 1989). In contrast, in adult ADHD patients both increases and decreases in CBF have been reported following MPH administration using PET and MRI (O’Gorman et al., 2008; Schweitzer et al., 2003). Thus, the current evidence suggests that the effects of MPH on CBF and DA function may be modified by age, although this has not been properly studied.

Therefore, to further enhance our understanding of the functioning of the DA system in response to MPH, we set up the current study in which we directly investigated the modulating effect of age on the CBF response to MPH in stimulant treatment-naive boys and men with ADHD. We used arterial spin labeling (ASL) based pharmacological MRI (phMRI) with a MPH challenge to assess changes in cerebral perfusion. PhMRI is based on the principle that neurotransmitter-specific drug challenges evoke changes in neurovascular coupling that result in hemodynamic changes (Jenkins, 2012). Non-invasive phMRI measurements have been shown to be well-correlated with PET and SPECT studies of DA function (Chen et al., 1997; Jenkins et al., 2004). Based on previous studies, we hypothesized that a single oral dose of MPH would increase CBF in the striatum, thalamus and prefrontal cortex (PFC) in children, whereas in
adults we expected a decrease in perfusion, as a result of the functional ontogeny of the DA receptors (Chen et al., 2010).

**METHODS**

**Participants**

Participants were stimulant-treatment naive boys and men with ADHD; 50 aged between 10 and 12 years and 49 aged between 23 and 40 years. The children were recruited from clinical programs at the Child and Adolescent Psychiatry Center Triversum (Alkmaar) and from the department of (Child and Adolescent) Psychiatry of the Bascule/AMC (Amsterdam). The adults were recruited from the clinical programs at the PsyQ mental health facility (The Hague) and from the department of Psychiatry of the AMC (Amsterdam). Patients were diagnosed based on the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV, 4th edition) and the diagnosis was subsequently confirmed with a structured interview: Diagnostic Interview Schedule for Children (National Institute of Mental Health Diagnostic Interview Schedule for Children Version IV (NIMH-DISC-IV, authorized Dutch Translation) in children and Diagnostic Interview for ADHD (DIVA) for adults (Kooij, 2012). Participants were excluded when diagnosed with a co-morbid axis I psychiatric disorder requiring pharmacological treatment at study entry; IQ < 80 (estimated with two subscales of the Wechsler Intelligence Scale for children-Revised (WISC-R); prenatal use of MPH by the mother; clinical treatment with drugs influencing the DA system (for adults before 23 years of age), such as stimulants, neuroleptics, antipsychotics, and D_{2}/D_{3} agonists; MRI contraindications; or MPH contraindications. ADHD symptoms severity was assessed in children using the DBD-RS (Pelham et al., 1992) and in adults using the ADHD-SR (Kooij et al., 2008).

### Table 1. Demographics and patient characteristics

<table>
<thead>
<tr>
<th></th>
<th>Children (N=40)</th>
<th>Adults (N=48)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean age (y)</td>
<td>11.5 (0.8)</td>
<td>28.6 (4.6)</td>
</tr>
<tr>
<td>Estimated IQ</td>
<td>104.0 (18.3)</td>
<td>107.9 (7.6)</td>
</tr>
<tr>
<td>ADHD symptom severity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DBD-RS Inattention</td>
<td>22.3 (3.2)</td>
<td></td>
</tr>
<tr>
<td>DBD-RS Hyperactivity</td>
<td>15.9 (5.7)</td>
<td></td>
</tr>
<tr>
<td>ADHD-SR</td>
<td></td>
<td>30.5 (9.6)</td>
</tr>
<tr>
<td>Co-morbidity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depressive episode(s) in the past</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Anxiety disorder in the past</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>ODD/CD</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

*a For children: WISC, for adults: NART  
*b For adults: MINI Plus 5.0  
*c For children: NIHM DISC-IV
Procedure
The current study reports data from the baseline MRI assessment of a 16-week double blind, randomized, placebo-controlled trial: the ePOD study (Bottelier et al., 2014). After the screening procedure, but before randomization and onset of treatment, participants underwent two MRI scans, one before and one 90 minutes after administration of 0.5 mg/kg MPH (with a maximum dose of 20 mg for children and 40 mg for adults), at peak plasma levels (Swanson and Volkow, 2003).

Pharmacological MRI
Data were acquired using a 3.0T Philips Achieva MR Scanner (Philips Medical Systems, Best, The Netherlands). A pseudo continuous arterial spin labeling (pCASL) sequence with a gradient-echo echo-planar imaging readout was used with the following parameters: TR/TE = 4000/14 ms; post-label delay = 1525 ms; label duration = 1650 ms; FOV = 240x240x119 mm; 75 dynamics; voxel size 3x3x7 mm, no background suppression, scan time = 10 minutes. In addition, a high resolution anatomical 3D T1-weighted scan was obtained.

ASL post-processing was performed with the "ExploreASL" toolbox, an in-house developed toolbox based on SPM (Statistical Parametric Mapping, Wellcome Trust Centre for Neuroimaging, London, UK) (Mutsaerts et al., 2016). First, the T1 images were registered to the MNI template and segmented into gray matter (GM) and white matter (WM) probability maps. Then, for the ASL time series, motion estimation was used to assess large motion artifacts and discard any motion spikes frames, where the spike exclusion threshold was the mean + 3 standard deviations (SD). Participants were removed from the analysis if the mean frame-wise displacement vector was > 2 mm. With the cleaned dataset, accurate motion estimation was run. Subsequently, the ASL perfusion-weighted images were registered to the GM tissue probability maps of each subject using 6 parameter rigid body registration. After this, label and control images were pair-wise subtracted (ΔM), corrected for slice gradients and averaged. CBF was calculated according to Alsop et al. (2014) using the mean of the control images as M0 image. Following quantification, voxel-based outlier rejection was applied (mean +/- 3 SD) and CBF images were averaged. The GM tissue probability maps were then spatially normalized using the Diffeomorphic Anatomical Registration analysis using Exponentiated Lie algebra (DARTEL) algorithm (Ashburner, 2007), and the transformation fields were applied to the CBF maps as well.

Statistical analysis
Regional changes in the striatum, thalamus and medial PFC (mPFC) were assessed with a region of interest (ROI) analysis. From the CBF maps, the median CBF was extracted for these ROIs within a subject-specific GM mask. Subsequently, the effect of MPH on ROI values was analyzed in SPSS using a mixed model with head motion as a time-variant covariate. Additionally, explorative voxel-wise changes in CBF were determined non-parametrically using the Randomise toolbox in the Functional Magnetic Resonance Imaging of the Brain (FMRIB) Software Library (FSL 4.0, Oxford, UK; http://www.fmrib.ox.ac.uk/fsl) was used (Winkler et al., 2014). CBF maps were smoothed within the GM mask with a 7 mm FWHM Gaussian kernel for the voxel-based analysis. Permutation inference was used to assess the acute effects of MPH on CBF, thresholded at family-wise error (FWE) corrected p < 0.05 using threshold free cluster
enhancement (TFCE) (Smith and Nichols, 2009). An independent t-test was used to assess baseline CBF differences between children and adults. To assess the effect of MPH in each group, and the interaction effect of MPH and age group, we conducted a paired samples t-test and a 2-way mixed effect analysis of variance, respectively. As head motion has been identified as a confounder, particularly in ADHD patient groups, log-transformed head mean motion was added to the model as a nuisance regressor.

RESULTS

Table 1 summarizes the patient characteristics. From the initial sample of 50 children, six children were excluded because of excessive motion. In addition, one child was excluded because we could not obtain the second phMRI scan after MPH administration (due to technical difficulties) and 3 children were excluded because the ASL scan was obtained with a different protocol. In addition, from the initial sample of 49 adults, one adult was excluded because of undisclosed prior treatment with stimulants. Thus, 40 children and 48 adults were included in the analysis. Mean motion differed between children and adults (t=5.42, p<0.01) at baseline. In children, motion was significantly reduced after the MPH challenge (t=3.93, p<0.01), whereas in adults this effect was not statistically significant (t=1.72, p=0.09). As expected, baseline CBF was higher in children than in adults (Figure 1) in both cortical and subcortical areas, and similar to values that have been reported in the literature for the respective age groups (Biagi et al., 2007). Our ROI analyses demonstrate that in children acute MPH significantly decreased CBF in the thalamus (F=8.12 p<0.01) and the mPFC (F=5.55 p=0.02), whereas in adults MPH only decreased CBF in the mPFC (F=11.58 p<0.01). In addition, we found a significant age x MPH challenge interaction in the thalamus (F=8.07 p<0.01), indicating that in this brain region the effects of MPH on CBF differ between children and adults. Our voxel-wise analyses demonstrated a reduction in CBF in cortical areas following MPH administration in children and adults. In the adults mostly cortical regions showed a response, whereas in children mainly the subcortical areas, such as the thalamus, were affected. Although the global maps (Figure 3c) indicated that the effect of MPH on CBF differed between children and adults, on the voxel-based analysis we did not identify any clusters that showed a significant interaction between age group and MPH administration.

Figure 1. Baseline differences in CBF (mL/100g/min) a) Brain regions displaying significant higher CBF in children than adults (p<0.05, FWE corrected). Coordinates are in MNI standard space (radiological convention) b) Significantly higher mean GM CBF in children than adults (mean ± SEM) *p<0.05
Age-dependent acute effects MPH on cerebral perfusion in ADHD

**Figure 2.** ROI analysis. Effect of an acute challenge on the striatum, thalamus and medial PFC. * paired t-test P<0.05 # age x challenge interaction effect P<0.05

**Figure 3.** Whole brain analysis. Effect of acute challenge with 0.5 mg/kg MPH on CBF (mL/100g/min) in a) children b) adults (p<0.05, FWE corrected) c) differences between reductions in CBF in adults and children (non-significant); red = more reduction in CBF in adults than children, green = more reduction in CBF in children than adults. Displayed in radiological convention; coordinates provided in MNI standard space.
In this study we investigated the modulating effect of age on CBF response to a DA challenge in stimulant treatment-naive children and adults with ADHD. Whole brain analyses showed more widespread reductions in perfusion in the cortex in adults than children, whereas in ROI analyses we found significant reductions in thalamic CBF in children only. A significant age x MPH challenge interaction in the thalamus on our ROI analyses provided further evidence that the effects of MPH in the human brain differ particularly in this brain region.

Age-dependent effects of MPH on CBF

To our knowledge, this is the first study to directly compare the effect of a single dose of MPH on CBF between stimulant treatment-naive children and adults with ADHD. Interestingly, in this study the only area in which we find significant differences in the CBF response between children and adults was the thalamus (i.e. reduction in children, no change in adults). Activating inhibitory D2 receptors could induce lower CBF, but the thalamus is not rich D2 receptors, but rather contains more vasodilatory DA D3 receptors on the microvasculature (Choi et al., 2006). Activating those receptors would result in increased CBF rather than decreased CBF (Choi et al., 2006). Therefore, it is more likely that the large changes found in the thalamus are due to downstream inhibitory effects from the D2-rich striatum, as the thalamus is the main output structure of striatal circuitry. Furthermore, the thalamus is also rich in noradrenergic transporters, a secondary target of stimulants, which provides an alternative explanation for the thalamic CBF difference.

Although we do not find statistically significant differences between children and adults in the cortex, the extent of activation appeared to be larger in adults. In the cortex, the MPH challenge reduced CBF in frontal and parietal areas in children with ADHD. This is in contrast with previous clinical studies that report increased CBF after MPH administration in subcortical and cortical areas, although this was after prolonged treatment rather than a single dose of MPH (as used here) (Kim et al., 2001; Lee et al., 2005; Lou et al., 1989; Teicher et al., 2000). In adults, the MPH-induced CBF reductions in sensory-motor areas, rostral anterior cingulate cortex, temporal cortex and lateral frontal areas are in line with previous studies in ADHD patients. For example, a study in adults with ADHD demonstrated that 3 weeks of MPH treatment resulted in decreased rCBF, as measured by PET, in the striatum and precentral gyri, but increased CBF in the cerebellum, compared to the off-medication condition (Schweitzer et al., 2003). An ASL study, demonstrated higher CBF in adult ADHD patients in the caudate nucleus as well as frontal and parietal areas when compared to controls, which normalized when on medication (O’Gorman et al., 2008). However, these studies are difficult to compare with this study because of prior stimulant exposure and length of MPH treatment in the study.

In contrast, studies administering MPH to healthy volunteers report more mixed results. In a small group of adult healthy volunteers, an intravenous challenge with 0.25 mg/kg MPH decreased absolute CBF, but increased relative CBF measured with H2[15O] PET in the anterior cingulate, supplementary motor areas and temporal poles, as well as decreased relative CBF in the superior temporal gyri, right medial frontal gyrus, and right inferior parietal cortex (Udo de Haes et al., 2007). In an ASL-based study, decreased CBF was reported following 30 mg oral MPH in lateral frontal, rostral cingulate and sensorimotor areas, amygdala, parahippocampal gyrus and in multiple regions of the occipital and temporal cortices (Marquand et al., 2012). However,
they also report increased CBF, particularly in the striatum and thalamus in adult healthy volunteers. The discrepancy with our study might be explained by the difference in populations, i.e. healthy volunteers vs. ADHD patients. It has been shown previously that DA release to a stimulant challenge is altered in adult ADHD patients compared to healthy controls (Cherkasova et al., 2014; Volkow et al., 2007). Recent studies have suggested that neurobiologically, ADHD is characterized by reduced tonic firing of the DA system and subsequent augmented phasic DA release, which can be normalized by means of stimulant treatment (Badgaiyan et al., 2015). This might seem counterintuitive as MPH blocks the reuptake of DA through the pre-synaptic transporter, thereby increasing extracellular DA levels. Yet, this is specifically thought to increase tonic levels of DA, causing increased stimulation of presynaptic autoreceptors and reduce phasic DA release, which in turn results in lower CBF. Thus, the reductions in CBF we find here are in line with findings on the disturbance of the DA system in ADHD subjects and could therefore explain the discrepancy with studies in healthy volunteers.

Surprisingly, we did not find any changes in striatal CBF in either children or adults, despite the striatum being the area with the highest DAT expression. However, when reviewing the literature, the effects of MPH on the striatum are inconsistent, with both increases in CBF and metabolism, as well as decreases and no change having been reported. This has been attributed to the state of the individual’s DA system at baseline resulting in a variable response of the striatum (Ernst et al., 1994; Volkow et al., 1997), or could be a consequence of prior stimulant treatment, which was not taken into account in these previous studies. An additional explanation for the discrepant findings is that particularly the downstream areas, such as the thalamus and frontal cortex, displayed changes in metabolism or perfusion following DA changes in the striatum (Udo de Haes et al., 2007).

*Neurobiological correlates of age-dependent CBF response to MPH*

We observed age-dependent effects of MPH administration on CBF. Adults showed a more widespread area of decreased perfusion in the cortex than children, whereas subcortically we found significant reductions in thalamic CBF in children only. These findings suggest an age-dependency in the CBF response to MPH, which could reflect different maturational stages of the DA system in children and adults. A preclinical phMRI study has previously demonstrated that MPH reduced subcortical and posterior cingulate rCBV in young rats, whereas it increased rCBV in the striatum and frontal cortex in adult rats (Chen et al., 2010). This was linked to a higher \( \frac{D_1}{D_2} \) ratio in adult vs young rats, as it has been shown that post-synaptic activation of \( D_1 \) receptors results in increased excitatory neurotransmission, which increases metabolic demand and subsequently increases CBF, whereas post-synaptic activation of the inhibitory \( D_2 \) receptors results in decreased CBF (Choi et al., 2006). The different patterns of activation between children and adults may also be explained in part by the ratio of \( D_1 \) and \( D_2 \) receptors and DAT expression in the developing brain. However, as little is known about the development of DA receptors in humans, most evidence comes from preclinical studies. In humans and non-human primates, \( D_1 \) and \( D_2 \) receptor expression appears to peak in childhood and to slowly decline thereafter. In contrast, studies in rodents typically show peak receptor expression in peri-adolescence (Wahlstrom et al., 2010). Functionally, adolescent rats express a pattern of \( D_1 \) hypo-activation in response to a \( D_1 \) agonist. This suggests a dominant response of the \( D_2 \) receptor in adolescence with a concomitant decrease in CBF (Chen et al., 2010).
Clinical relevance
This is the first study examining perfusion changes in patients with ADHD in a developmental context. We show that, in accordance with preclinical data from separate studies in children and adults, MPH affects the developing brain differently from the adult brain. Nevertheless, current treatment guidelines are based on weight and the assessment of symptom improvement and side-effects, ignoring age as an important determinant of the neurobiological response to stimulants. The adolescent brain is a rapidly developing system with high levels of plasticity. As such, it may be particularly vulnerable to drugs that interfere with these processes or modify the specific transmitter systems involved. Therefore, future long-term studies will have to show what the consequences of stimulant treatment during development are, and how they affect the course and outcome of ADHD.

Methodological considerations
Although we can explain the subcortical and cortical effects of MPH on CBF partially through the ontogeny of the DA system, other neurotransmitter systems may also contribute to this response. For example, the noradrenalin transporter is more important for clearing DA in (pre)frontal areas relative to DAT and, using phMRI, we cannot distinguish between these neurotransmitter systems. In addition, it is important to realize that both DA and noradrenalin have vasoconstrictive properties and we cannot exclude that our results can partially be explained by direct effects of these neurotransmitters on the microvasculature.

Here we show lower baseline CBF in children than in adults, comparable to reference values from healthy volunteers in literature (Biagi et al., 2007). However, a well-controlled experimental study has recently demonstrated that small changes in baseline CBF do not alter the absolute response to a neuronal stimulus and there therefore absolute CBF better reflects neuronal activity than relative CBF (Whittaker et al., 2015). This makes us confident that the presently observed changes in CBF after acute MPH administration are not solely due to different baseline CBF levels.

Conclusion
In sum, we here provide a direct comparison of the CBF response to MPH between children and adults in a large stimulant treatment-naive ADHD sample using ASL phMRI. The cortical response to MPH appears more widespread in adults than in children, whereas subcortical thalamic CBF was reduced following MPH in children, but not adults with ADHD. These findings confirm the age-dependent effects of MPH on CBF, possibly due to differences in the development of the DA system. Our findings thus highlight the importance of taking a developmental perspective into account for the treatment of ADHD.
REFERENCES


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