4-10-2001

The measurement of regional cerebral blood flow during the complex cognitive task of meditation: a preliminary SPECT study

Andrew B. Newberg  
*University of Pennsylvania, andrew.newberg@uphs.upenn.edu*

Abass Alavi  
*University of Pennsylvania, ALAVI@OASIS.RAD.UPENN.EDU*

Michael J. Baime  
*University of Pennsylvania, baime@mail.med.upenn.edu*

Michael Pourdehnad  
*University of Pennsylvania*

Jill Santanna  
*University of Pennsylvania*

*See next page for additional authors*

---

**Recommended Citation**


---

Publisher URL: [http://dx.doi.org/10.1016/S0925-4927(01)00074-9](http://dx.doi.org/10.1016/S0925-4927(01)00074-9)

This paper is posted at ScholarlyCommons. [http://repository.upenn.edu/neuroethics_pubs/25](http://repository.upenn.edu/neuroethics_pubs/25)  
For more information, please contact repository@pobox.upenn.edu.
The measurement of regional cerebral blood flow during the complex cognitive task of meditation: a preliminary SPECT study

Abstract
This study measured changes in regional cerebral blood flow (rCBF) during the complex cognitive task of meditation using single photon emission computed tomography. Eight experienced Tibetan Buddhist meditators were injected at baseline with 7 mCi HMPAO and scanned 20 min later for 45 min. The subjects then meditated for 1 h at which time they were injected with 25 mCi HMPAO and scanned 20 min later for 30 min. Values were obtained for regions of interest in major brain structures and normalized to whole brain activity. The percentage change between meditation and baseline was compared. Correlations between structures were also determined. Significantly increased rCBF (P<0.05) was observed in the cingulate gyrus, inferior and orbital frontal cortex, dorsolateral prefrontal cortex (DLPFC), and thalamus. The change in rCBF in the left DLPFC correlated negatively (P<0.05) with that in the left superior parietal lobe. Increased frontal rCBF may reflect focused concentration and thalamic increases overall increased cortical activity during meditation. The correlation between the DLPFC and the superior parietal lobe may reflect an altered sense of space experienced during meditation. These results suggest a complex rCBF pattern during the task of meditation.

Keywords
frontal cortex, thalamus, single photon emission computed tomography

Comments

Author(s)
Andrew B. Newberg, Abass Alavi, Michael J. Baime, Michael Pourdehnad, Jill Santanna, and Eugene d'Aquili

This journal article is available at ScholarlyCommons: http://repository.upenn.edu/neuroethics_pubs/25

Andrew Newberg**, Abbas Alavi†, Michael Baime‡, Michael Pourdehnad*, Jill Santanna*, Eugene d’Aquili†

*Division of Nuclear Medicine, Department of Radiology, University of Pennsylvania Medical Center, Philadelphia, PA 19104, USA
†Department of Medicine, University of Pennsylvania Medical Center, Philadelphia, PA 19104, USA
‡Department of Biometrics and Epidemiology, University of Pennsylvania Medical Center, Philadelphia, PA 19104, USA
*Department of Psychiatry, University of Pennsylvania Medical Center, Philadelphia, PA 19104, USA

1. Introduction

Meditation, in general, is a complex neurocognitive task that is often associated with alterations in body physiology and psychological measures. Over the past 30 years, a number of studies have explored the physiological correlates of different types of meditation. It is important to note here that meditation refers to a large variety of practices that range from purely relaxation-based to those performed with the goal of attaining powerful spiritual experiences. This variation, in itself, makes the study of such practices difficult. However, we have tried to find similarities among these practices, and feel that enough prior studies have demonstrated changes associated with these practices that it seems worthwhile to continue to explore them. Several studies have shown that meditation and related practices are associated with changes in the brain’s electrical activity as observed on electroencephalography (EEG; Anand et al., 1961; Banquet, 1972; Corby et al., 1978; Benson et al., 1990). In particular, increased alpha-wave activity over the frontal regions of the brain has been observed during meditation and different EEG patterns may be associated with the relative strength of the experience. Other studies have measured different physiological changes associated with meditation including changes in autonomic nervous system activity such as those related to heart rate and blood pressure, and changes in cortisol levels (Jequier et al., 1992; Kesterson, 1988; Sudsuan et al., 1991).

Despite the availability of functional imaging techniques such as positron emission tomography (PET), single photon emission computed tomography (SPECT), and functional magnetic resonance imaging (fMRI), we are aware of only three reports utilizing neuroimaging techniques to study subjects practicing meditation. In these studies, neuroimaging was utilized to measure changes in cerebral function in subjects undergoing meditative relaxation techniques (Herzog et al., 1999; Lou et al., 1999; Lazar et al., 2000). Because there are many different types of meditation, it is important to evaluate and compare changes associated with different types of meditation to help elucidate the physiological mechanisms underlying the effects of meditation.

In this study, we present the r-lumbar HMPAO (hexamethyl propyleneamine oxime) SPECT data from eight practitioners of a form of Tibetan Buddhist meditation, performed specifically for spiritual, non-health-related, purposes. In this form of meditation, practitioners initially focus their attention on a visualized image and maintain that focus with increasing intensity. The “peak” experience of their meditation is described as a sense of absorption into the visualized image associated with clarity of thought and a sense of space and time. We selected practitioners of this type of meditation because of their ability to reproduce the meditative experience despite being in the laboratory setting. The SPECT imaging technique used in this study measures regional cerebral blood flow (rCBF), which correlates closely with cerebral activity. Thus, this technique allowed for a comparison between the rCBF at baseline and during meditation.

We would like to emphasize that SPECT imaging and the methodology described below were chosen over other imaging techniques for several important practical reasons. Functional magnetic resonance imaging, while having improved resolution over SPECT and the ability of immediate anatomic correlation, was not be very difficult to utilize for the study of meditation because of the noise from the machine. In fact, we attempted the use of fMRI with our initial subject in order to determine feasibility, but the subject found it extremely difficult to carry out the meditation practices. While PET imaging also provides better resolution than SPECT, our goal was to make the environment as distraction free as possible to maximize the chances of having as strong a meditative experience as possible. In order to achieve this goal, and because of our large research and clinical service, these scans were all performed after hours when fluorodeoxyglucose was no longer available. Thus, while PET and fMRI offer certain technical advantages, SPECT appeared to provide the best option for this initial study of meditation.

With regards to specific areas of the brain that might be involved during meditation, we...
elaborated several hypotheses that would be the focus of this study. (1) Several investigators, including our group, have postulated increased activity in the frontal lobes, and in particular the prefrontal cortex, during meditation. This notion is based, in part, on the above-mentioned EEG studies on meditation as well as previous studies which have found increased frontal activity during attention-focusing tasks (Mizuki, 1983; Frith et al., 1991; Farro et al., 1991). (2) Meditation is also associated with attenuation in the subjective experience of space and time. We have postulated that there should be decreased activity in the superior parietal lobe since studies have shown this area to be involved with visual-spatial and temporal processing as well as body orientation (Lynch, 1983; Joseph, 1990). Furthermore, studies of spatial attention have demonstrated increased activity in the frontal lobes with relative decreases in the association areas. Thus, there should be a correlation between relative increases in the frontal lobes and relative decreases in the superior parietal lobes (Frith et al., 1991). (3) Meditation subjects often describe decreased sensory awareness and decreased motor activity, and we therefore predicted a decrease in the activity in the sensorimotor area. (4) There may be changes in the midbrain related to autonomic changes associated with meditation (Jenning et al., 1992; Sud男友 et al., 1991). (5) We expected relatively little change in the cerebellum, the superior frontal cortex, and the occipital lobes since no studies had implicated these areas as involved in meditation.

We also considered the possibility that there may be baseline differences in rCBF between subjects who practice meditation and those without such experience. In order to test this hypothesis, baseline rCBF in the meditation subjects was compared to that in a group of control subjects who were recruited for other, unrelated studies.

2. Methods

2.1. Subjects and imaging acquisition

Eight subjects with no history or clinical evidence of medical, neuropsychological, or drug abuse that would potentially alter CBF were recruited to participate in this study. Four were women and four were men with ages ranging from 38 to 52 years with a mean age of 45 years. Each subject described himself or herself as a practicing Tibetan Buddhist meditator with more than 15 years of experience, usually including several three-month retreats and a yearly one-month retreat. They have meditated approximately 1 hr per day, and at least five days a week. On the day of the study, after obtaining informed consent (approved by the Human Institutional Review Board with the study protocol), a room was set up in the hospital to function as a meditation room. Subjects were allowed to use incense throughout the baseline and meditation scans. Approximately 20 min prior to the baseline scan, an intravenous canula (IV) was placed in one arm. The subjects reported minimal discomfort from the IV that resolved prior to initiating the remainder of the study. Subjects were instructed to rest in the room with their eyes closed and ears unoccluded for 5–10 min at which time they were injected through the IV with 7 mCi of 15O-Tc-HMPAO (Amersham International, Arlington Heights, IL) prepared as specified by the manufacturer. Thirty minutes following the injection, the subject was scanned for 45 min in a Picker–Prism (Picker Inc., Cleveland, OH) triple-headed rotating gamma camera using high-resolution fanbeam collimators. Projection images were obtained at three-degree angle intervals on a 128 x 128 matrix (pixel size 3.56 X 3.56 mm) over 360° by rotating each head 120°. These SPECT images were reconstructed in the transaxial, coronal, and sagittal planes using filtered backprojection, followed by a Weiner post filter and 1st order Chang attenuation correction. The reconstructed slice thickness was 4 mm with a spatial resolution of 8-10 mm.

Nine control subjects, recruited as a group of healthy controls for other activation studies, had undergone a baseline SPECT imaging scan similar to those described above. The baseline scans of the control subjects were then compared to the baseline scans of the meditators to assess baseline changes in the meditation subjects.

Following this 'baseline' scan, the subject returned to the room for meditation. They were also allowed to utilize several meditation books initially, although they had their eyes closed (their ears were also unoccluded) during approximately the final 30 min of the meditation, including during the time of the second injection of HMPAO. Outside noise was kept to a minimum and the door of the room was closed during the meditation. The subject meditated for approximately 1 hr, which time the subject provided a 'signal', observable to the investigators, that was incorporated as part of the meditation practice (because of the use of this signal that marked when the subjects were about to begin the most intense part of the meditation, we felt that concurrent measurement using electroencephalography to determine if subjects were asleep was not necessary). Several minutes after this signal, the subject was injected with 25 mCi of 15O-Tc-HMPAO followed by the IV from outside the meditation room (in order not to disturb the subject) while he/she continued to meditate for approximately another 10–15 min, maintaining the same intensity of meditation. The medication session was ended, and 30 min after this injection the subject was then scanned ('meditation' scan) for 30 min using the same imaging parameters as for the baseline study.

2.2. Image analysis and statistics

Several different statistical approaches were used in order to answer the questions raised by our hypotheses.

2.2.1. Region of interest analysis

The images of the baseline and meditation scans were reconstructed and resliced, using an oblique reformatting program, according to the anterior–posterior commissure line so that the final two sets were at comparable anatomical sites for the analysis. A previously validated template methodology consisting of regions of interest (ROI) corresponding to the major cortical and subcortical structures was placed over the baseline scan (Restino et al., 1993). For the purposes of this study, we examined the rCBF as measured in only a selected number of ROIs, which was hypothesis driven. The ROIs examined were the inferior frontal, superior frontal, dorsolateral pre-frontal, orbital frontal, dorsal medial cortex, inferior temporal, superior parietal, inferior parietal, occipital, and sensorimotor areas, as well as the caudate, thalamus, midbrain, cerebellum, and cingulate gyri. Each ROI (which is small and therefore represents a 'punch biopsy' of any given area) had its placement adjusted manually in order to achieve the best fit according to the atlas. The ROIs were then copied directly onto the meditation scan. This was possible because the images were already resliced into the same planes as described above. The count values for the meditation scans were obtained by determining the number of counts in each ROI on the meditation scan and subtracting the number of counts in the same ROI on the baseline scan which were decay corrected to the midpoint of the two scans. Counts per pixel in each ROI were obtained for both the baseline and meditation scans and normalized to the whole brain activity. This provides an rCBF ratio for each ROI compared to the whole brain. A percentage change was calculated using the equation:

\[
\text{% Change} = \frac{1}{2} \times (\text{Meditation} - \text{Baseline}) \times 100.
\]

A laterality index (LI) was also calculated to determine the relative activity of homologous regions in the left and right hemisphere using the following equation:

\[
\text{LI} = \frac{(\text{Right} - \text{Left})}{(1/2 \times (\text{Right} + \text{Left}))} \times 100.
\]

A mixed model analysis was used to compare baseline and meditation (CBF using data from both the left and right brain hemispheres. The mixed model was necessary to adjust for the correlation between multiple observations collected on each subject (SAS Institute, Inc.). These results are presented in Table 1 and discussed in
2.2.3. Correlations between brain structures

Pearson correlations were generated to assess the association between changes in CBF values in different regions. Significance tests for the correlations were limited to the structures of the posterior superior parietal lobes, dorsolateral prefrontal cortex, thalamus, midbrain, and sensorimotor cortex since these were the areas that would most likely interact with each other during the task of meditation. Because of the small sample size, all results were confirmed using Spearman correlations. The results of both methods were similar, so only Pearson correlations will be presented.

2.2.4. Baseline changes in meditators compared to controls

Using a two-tailed Student's t-test, the rCBF values at baseline for the meditators were compared to those of a group of healthy control subjects, involved in other SPECT studies, who underwent a similar baseline imaging protocol.

3. Results

The results of the mixed model analysis for this study are shown in Table 1 (see also Fig. 1).

Table 1

<table>
<thead>
<tr>
<th>Part of the brain</th>
<th>F-value</th>
<th>Baseline mean</th>
<th>Meditation mean</th>
<th>Percent change</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior cingulate</td>
<td>0.0074</td>
<td>1.25</td>
<td>1.24</td>
<td>7.2</td>
<td>0.08</td>
</tr>
<tr>
<td>Cingulate body</td>
<td>0.0001</td>
<td>1.03</td>
<td>1.14</td>
<td>25.3</td>
<td>0.13</td>
</tr>
<tr>
<td>DLPFC</td>
<td>0.0001</td>
<td>1.21</td>
<td>1.45</td>
<td>10.7</td>
<td>0.08</td>
</tr>
<tr>
<td>Inferior frontal</td>
<td>0.0035</td>
<td>1.25</td>
<td>1.36</td>
<td>8.8</td>
<td>0.09</td>
</tr>
<tr>
<td>Midbrain</td>
<td>0.0166</td>
<td>1.16</td>
<td>1.29</td>
<td>11.2</td>
<td>0.14</td>
</tr>
<tr>
<td>Orbital frontal cortex</td>
<td>0.0015</td>
<td>0.97</td>
<td>1.22</td>
<td>23.8</td>
<td>0.24</td>
</tr>
<tr>
<td>Posterior cingulate</td>
<td>0.0014</td>
<td>1.19</td>
<td>1.29</td>
<td>8.4</td>
<td>0.09</td>
</tr>
<tr>
<td>Sensorimotor</td>
<td>0.0001</td>
<td>1.19</td>
<td>1.26</td>
<td>5.9</td>
<td>0.06</td>
</tr>
<tr>
<td>Thalamus</td>
<td>0.0014</td>
<td>1.40</td>
<td>1.60</td>
<td>14.3</td>
<td>0.21</td>
</tr>
<tr>
<td>Dorsolateral cortex</td>
<td>0.0014</td>
<td>1.36</td>
<td>1.31</td>
<td>4.0</td>
<td>0.06</td>
</tr>
<tr>
<td>Superior parietal</td>
<td>0.0171</td>
<td>1.18</td>
<td>1.12</td>
<td>3.9</td>
<td>0.11</td>
</tr>
<tr>
<td>Caudate</td>
<td>0.5743</td>
<td>1.29</td>
<td>1.32</td>
<td>2.3</td>
<td>0.13</td>
</tr>
<tr>
<td>Cerebellum</td>
<td>0.2324</td>
<td>1.23</td>
<td>1.23</td>
<td>1.6</td>
<td>0.04</td>
</tr>
<tr>
<td>Inferior temporal</td>
<td>0.2466</td>
<td>1.29</td>
<td>1.34</td>
<td>3.9</td>
<td>0.13</td>
</tr>
<tr>
<td>Superior frontal</td>
<td>0.7404</td>
<td>1.38</td>
<td>1.37</td>
<td>0.9</td>
<td>0.09</td>
</tr>
</tbody>
</table>

The results section. An analysis of the laterality indices for each homologous pair of ROIs in the baseline and meditation scan was performed using a two-tailed Student's t-test.

4. Discussion

Regarding our initial hypotheses, the first was that we expected to observe an increased level of activity in the frontal cortices, particularly the prefrontal areas. Several studies have examined the effects of the complex neurocognitive task of meditation on brain activity. Most of these studies involved electroencephalographic (EEG) measurements during meditation in comparison to baseline (Corby et al., 1978; Banquet, 1972). Proficient practitioners usually have been shown to have increased alpha and theta amplitudes, particularly over the frontal lobes, compared to baseline (Hirata, 1974). These changes were also associated with increased autonomic activation. One

Table 2

<p>| Location of significance (P &lt; 0.01) increase in regional cerebral blood flow during meditation |
|---------------------------------------------------------------|---------------------------------------------------------------|</p>
<table>
<thead>
<tr>
<th>Structure</th>
<th>Coordinates</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>z score</th>
</tr>
</thead>
<tbody>
<tr>
<td>R thalamus</td>
<td>4</td>
<td>-8</td>
<td>6</td>
<td>3.64</td>
<td></td>
</tr>
<tr>
<td>R thalamus</td>
<td>10</td>
<td>-24</td>
<td>2</td>
<td>3.97</td>
<td></td>
</tr>
</tbody>
</table>

Table 3

<p>| Location of significance (P &lt; 0.001) decrease in regional cerebral blood flow during meditation |
|---------------------------------------------------------------|---------------------------------------------------------------|</p>
<table>
<thead>
<tr>
<th>Structure</th>
<th>Coordinates</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>z score</th>
</tr>
</thead>
<tbody>
<tr>
<td>R superior parietal</td>
<td>13</td>
<td>-68</td>
<td>56</td>
<td>3.39</td>
<td></td>
</tr>
<tr>
<td>L superior parietal</td>
<td>-16</td>
<td>-58</td>
<td>20</td>
<td>3.39</td>
<td></td>
</tr>
<tr>
<td>R lateral temporal</td>
<td>62</td>
<td>-30</td>
<td>12</td>
<td>3.39</td>
<td></td>
</tr>
<tr>
<td>L inferior temporal</td>
<td>-46</td>
<td>-72</td>
<td>3</td>
<td>2.39</td>
<td></td>
</tr>
</tbody>
</table>

ity score of the control group (3.78, P = 0.03). No other significant differences were observed in either the laterality index or CBF values between the meditation and control group. Interestingly, the laterality index in the meditation group moved toward the value of the control group on the meditation scans. However, this change in laterality index was not statistically significant.
The figure shows an illustration related to the study on the effects of meditation on brain activity. The illustration depicts different brain regions and imaging techniques used in the study. The text accompanying the image discusses the results of the study, highlighting changes in brain activity observed during meditation compared to baseline conditions. The study found increased activity in specific brain regions associated with attention and emotional processing, suggesting the benefits of meditation on cognitive and emotional health. The text also mentions the importance of controlled studies and the need for further research to understand the mechanisms underlying these changes.
with meditation, which includes both cognitive and affective responses.

Finally, that the meditation group had a significantly different thalamic laterality index at baseline compared to controls supports the notion that meditating subjects may have changes in their brain at rest. This is an interesting finding that needs to be explored by examining a larger sample of subjects. We only examined eight laterality scores and for this reason failed to perform a Bonferroni correction; however, only the thalamic laterality was found to be significantly different.

Moreover, if baseline differences between the two groups are substantiated in future studies, the question arises as to whether this alteration in function is related to many years of meditation practice, or if these subjects were born with such a distinction which might have predisposed them to adopt meditation during their lives. Answers to such questions remain purely speculative at this time.

We present this preliminary study to illustrate several points regarding the measurement of rCBF during meditation. We have shown a simple method by which HMPAO SPECT can be used to detect changes in rCBF during Tibetan Buddhist meditation. Also, this type of study can be applied to other forms of meditation (i.e., passive forms) to explore whether different types of meditation are associated with different neurophysiological correlates.

Potential confounding problems with this study include the fact that the subjective sense during the meditation is difficult to measure. We had subjects fill out questionnaires after the study, but found that the subjective responses were impossible to quantitate or analyze in a useful manner. However, all subjects felt that they had had an adequate meditation session. Other physiological measures, while potentially providing additional interesting information, would also not have been able to confirm the specific subjective state, such as the depth of the meditation, of each subject during the study. We also did not feel that EEG was necessary to exclude the possibility that the subject had fallen asleep because required hand signals demonstrated that subjects were awake. However, now that we have shown evidence for changes occurring during meditation, future studies will need to explore how cerebral activity as measured by EEG patterns and neuroimaging studies correlate with each other as well as physiological measures such as blood pressure, heart rate, and respiratory rate. This study also measured rCBF at a single point during meditation, which is obviously a lengthy process that requires time for various cognitive and affective responses to occur. Thus, the images are taken only during the assumed peak of meditation and, in fact, reflect activity during some other component of the meditation. The study has a limited number of meditation subjects since it is most difficult to find highly experienced meditators. While this complicates the statistical analysis, the number of subjects is comparable to that in previous studies of other types of meditation and was enough to reveal statistically meaningful results. Finally, while fMRI and PET have taken the lead in brain activation studies and both methods provide technical advantages over SPECT, meditation presents the particular problem of requiring a quiet, distraction-free environment. To provide this, fMRI would be too noisy and fluorodeoxyglucose for PET studies is often not available during the times that these studies are best performed. However, future efforts to make such techniques more amenable to the study of meditation may be fruitful in helping to better define the underlying physiological basis of such practices.

5. Conclusion

The results from this initial study have begun to elucidate the neurophysiological correlates of complex cognitive functions such as meditation. The findings also support our hypotheses that meditation is associated with increased activity in the frontal lobes and that such activity is correlated with decreased activity in the posterior parietal lobes. These two findings, respectively, may be attributable to the increased attention of subjects and the experience of alteration of the sense of space. That there were also changes in activity in the thalamus, sensorimotor cortex, and midbrain suggests that there is an intricate level of central nervous system interactions during this type of meditative practice. Future imaging research should explore the cerebral correlates of meditation in a larger number of subjects as well as incorporate other physiological and neurophysiological measures. Such studies will be essential to elucidate the basic mechanisms that underlie subjective and clinical observations during the complex neurocognitive task of meditation.

References


