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Research paper

Physiological differences between histologically defined subdivisions in the mouse auditory thalamus

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ABSTRACT

The auditory thalamic area includes the medial geniculate body (MGB) and the lateral part of the posterior thalamic nucleus (Pol). The MGB can be subdivided into a ventral subdivision, forming part of the lemniscal (primary) auditory pathway, and medial and dorsal subdivisions, traditionally considered (alongside the Pol) part of the non-lemniscal (secondary) pathway. However, physiological studies of the auditory thalamus have suggested that the Pol may be more appropriately characterised as part of the lemniscal pathway, while the medial MGB may be part of a third (polysensory) pathway, with characteristics of lemniscal and non-lemniscal areas. We document physiological properties of neurons in histologically identified areas of the MGB and Pol in the anaesthetised mouse, and present evidence in favour of a distinctive role for medial MGB in central auditory processing. In particular, medial MGB contains a greater proportion of neurons with short first-spike latencies and high response probabilities than either the ventral or dorsal MGB, despite having low spontaneous rates. Therefore, medial MGB neurons appear to fire more reliably in response to auditory input than neurons in even the lemniscal, ventral subdivision. Additionally, responses in the Pol are more similar to those in the ventral MGB than the dorsal MGB.

1. Introduction

The mammalian auditory thalamus is comprised of three main areas: the medial geniculate body (MGB), the lateral part of the posterior thalamic nucleus (Pol) and the auditory sector of the reticular nucleus (Jones, 1985). The MGB is considered the principal nucleus of the auditory thalamus and can be further subdivided into at least three major subdivisions (the ventral, dorsal and medial MGB) on the basis of anatomy, histochemistry and physiological response properties in a number of species (Anderson et al., 2007 [guinea pig]; Anderson et al., 2009b [mouse]; Calford, 1983 [cat]; Cruikshank et al., 2001 [mouse]; Gonzalez-Lima and Cada, 1994 [mouse]; Hackett et al., 1998 [monkey]; Morest, 1964 [cat]; Winer et al., 1999 [rat]). The relative positions of these subdivisions in the mouse MGB are shown in Fig. 1.

The auditory thalamus is an obligatory relay for information passing to the auditory cortex. As with the other sensory modalities, the ascending auditory thalamocortical pathways can be anatomically subdivided into two largely separate, parallel channels. The ventral MGB is considered to be part of the primary (lemniscal) pathway (dark grey in Fig. 1); that is, it receives strong projections from the central nucleus of the inferior colliculus and projects to layers III and IV of the primary auditory cortex (Oliver and Huerta, 1992 [review]; Winer, 1992 [review]; Winer et al., 2005 [review]). Traditionally, other parts of the auditory thalamus, the dorsal and medial MGB and the Pol, which receive input from all parts of the inferior colliculus and other brain areas, were thought to be part of the secondary (non-lemniscal) system (light grey fill Fig. 1) projecting more strongly to the non-primary (secondary) auditory cortices and terminating across layers I, II, III/IV and VI (Jones, 1985; Kimura et al., 2003; Winer et al., 2005).

The lemniscal and non-lemniscal pathways have classically been considered to engage in different auditory functions, with the lemniscal pathway providing a high-fidelity, primary-like representation of sound features (de-Ribaupierre, 1997), while the non-lemniscal pathway supplies more context-dependent information,

Abbreviations: APT, anterior pretectal nucleus; CF, characteristic frequency; CYO, cytochrome oxidase; LGN, lateral geniculate nucleus; MGB, medial geniculate body; Pol, lateral part of the posterior thalamic nucleus; PSTH, post-stimulus time histogram.

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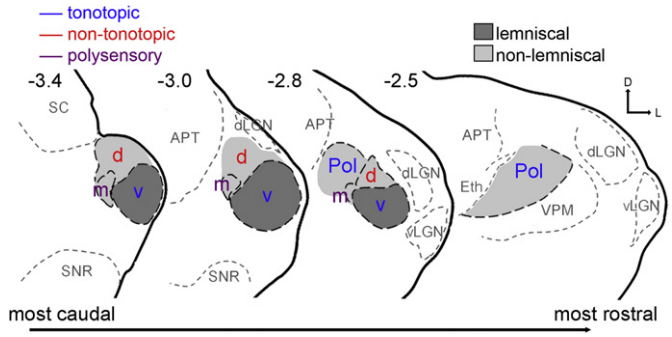

Fig. 1. Line drawings of four coronal sections through a typical mouse thalamus to show the relative position of the MGB subdivisions and the Pol. Borders have been ascertained on the basis of CYO staining; outlines are left unfinished where a precise border could not be determined in this animal. Auditory areas are outlined in black dashed lines; non-auditory areas are shown by grey dashed lines to help orientate the reader. Areas thought to belong to the lemniscal pathway are shown in dark grey and areas thought to belong to the non-lemniscal pathway are shown in light grey (grey fills are representative only, and are not intended to show definitive boundaries). Blue lettering indicates tonotopic areas, non-tonotopic areas are represented by red lettering and polysensory areas are shown in purple. Sections have a thickness of 40 μm, numbers at the top of each section give an indication of the section's distance (in mm) behind Bregma. Abbreviations: v, ventral MGB; m, medial MGB; d, dorsal MGB; Pol, lateral part of the posterior thalamic nucleus; APT, anterior pretectal nucleus; d/vLGN, dorsal/ventral lateral geniculate nucleus; Eth, ethmoid thalamic nucleus; PF, parafascicular thalamic nucleus; SC, superior colliculus; SNR, reticular substantia nigra; VPM, ventral posteromedial thalamic nucleus. Orientation bar, D = dorsal, L = lateral.

containing for example neurons which show ability to detect change (Anderson et al., 2009b; Kraus et al., 1994), which are sensitive to multimodal stimuli and reward stimuli (Komura et al., 2005; Komura et al., 2001) or which undergo rapid retuning following behavioural conditioning (Edeline, 1999; Hu, 2003 [review]). Basic physiological response properties recorded from the ventral and dorsal MGB are consistent with this view. In the ventral MGB, neurons are tonotopically organised and exhibit greater fidelity in response timing and frequency tuning than the majority of cells in the non-lemniscal dorsal MGB (Anderson et al., 2007; Calford, 1983; Calford et al., 1983; Redies and Brandner, 1991; Rodrigues-Dageff et al., 1989). However, while the high-fidelity lemniscal versus context-dependent non-lemniscal generalisation seems to hold true for the majority of neurons in the ventral and dorsal MGB, it is an oversimplification for the other subdivisions. Recordings from the medial MGB (typically also considered a non-lemniscal auditory thalamic area) not only show the full range of responses seen in both the dorsal and ventral MGB (Aitkin, 1973; Anderson et al., 2007; Calford, 1983; Calford et al., 1983; Rouiller et al., 1989) but include some neurons which exceed the capabilities of those in the ventral MGB, with extremely short response latencies (Anderson et al., 2006; Rodrigues-Dageff et al., 1989) and temporal following to very high rates (Anderson et al., 2005; Rouiller et al., 1981; Wallace et al., 2007). Likewise, the Pol has traditionally been considered part of the non-lemniscal system (Jones, 1985), but has been described as very similar to the ventral MGB in terms of its physiological properties, containing tonotopically organised neurons with short-latency, narrowly-tuned responses (Imig and Morel, 1985).

To overcome the pitfalls of imposing the anatomical lemniscal/non-lemniscal classification onto areas with overlapping physiological response patterns, a series of three parallel pathways has been proposed in the cat based on physiological as well as anatomical data (Andersen et al., 1980a; Andersen et al., 1980b; Calford and Aitkin, 1983; Rodrigues-Dageff et al., 1989; Rouiller and de-Ribaupierre, 1985; Rouiller et al., 1989). These three distinct parallel pathways – the tonotopic, non-tonotopic and polysensory projections (de-Ribaupierre, 1997; Rouiller, 1997) – originate in the midbrain and each encompasses one of the three major MGB subdivisions. The tonotopic pathway is comprised of the ventral MGB and Pol (blue lettering in Fig. 1), while the non-tonotopic pathway includes the dorsal MGB (red lettering in Fig. 1). The third, the polysensory pathway, encompasses the medial MGB (purple lettering in Fig. 1), which receives auditory input not only from all parts of the inferior colliculus but also from the ventral lateral lemniscus (Whitley and Henkel, 1984) and the cochlear nucleus (Anderson et al., 2006; Malmierca et al., 2002; Strominger et al., 1977), as well as sensory information from many non-auditory structures, including the amygdala, dorsal column nuclei, vestibular nuclei, trigeminal nuclei and spinal cord (Bordi and LeDoux, 1994b; Linke, 1999; Rouiller et al., 1989; Winer, 1992 [review]).

Here, we compare physiological responses of neurons in each of the major MGB subdivisions and the Pol of the mouse. Our data suggest that the tripartite subdivision of the ascending thalamocortical pathways previously proposed in the cat represents a more appropriate description of the mouse auditory thalamus than the more simplistic dichotomy between high-fidelity lemniscal and context-dependent non-lemniscal pathways. Moreover, our results indicate that, despite having low spontaneous rates, neurons in the medial MGB can fire more reliably in response to auditory input than other auditory thalamic neurons, even those in the lemniscal ventral MGB.

2. Methods

2.1. Animals

Twenty-six adult male CBA/Ca mice, 6-24 weeks of age, were used as subjects in this experimental study. Mice were anaesthetised with ketamine and medetomidine, prepared for recording and monitored using procedures similar to those described in Linden et al. (2003). A craniotomy approximately 2 mm in diameter, centred 2 mm lateral to midline and 3 mm caudal to bregma, was performed on either the left-hand (12) or right-hand (14) side, enabling vertical access to the MGB. The cortical surface was kept moist by regular application of warmed saline. All experiments were performed in accordance with the United Kingdom Animal (Scientific Procedures) Act of 1986.

2.2. Recording strategy

Extracellular recordings were made across all MGB subdivisions using custom-made tungsten-in-glass electrodes (tip sizes 10–20 μm, impedance typically 1–2 MΩ (Bullock et al., 1988)). Electrodes were positioned stereotaxically, and advanced using a hydraulic probe drive (FHC 50-12-1C) which was controlled from outside the sound-attenuated booth (Neurocraft MCM/MCU). The motor controller was zeroed as the tip of the microelectrode touched the cortical surface (confirmed microscopically and by an acoustic change in the electrode signal) to ensure consistency across penetrations. In all penetrations the electrode was moved down 2200 μm below the cortical surface, then left to stabilise for ~10 min. The first penetration was typically made rostro-medially within the craniotomy. Subsequent penetrations were made laterally every 200 μm until no further auditory activity was recorded at that particular rostro-caudal position; the electrode was then returned to a position 100 μm medial to the most medial position which yielded auditory activity and moved 200 μm caudally. As before, subsequent penetrations were made every 200 μm in a lateral direction. If a potential recording site overlapped with a large blood vessel that particular site was abandoned and the