Introduction to the Superior Olivary Complex

The superior olivary complex (SOC), a group of interconnected nuclei bilaterally located in the basal brainstem, is part of the mammalian central auditory system consisting of various neural sites connected to each other by multiple parallel pathways in which many projections are tonotopically organized. The functions of the SOC include the processing of cochlear signals via the ascending auditory pathway, the detection of interaural sound intensity and time differences as the basis of spatial mapping, as well as feedback control of cochlear mechanisms (see Moore, 1994; Tsuchitani and Johnson, 1991; Warr, 1992). Although the SOC is also involved in non-auditory functions, and some auditory information bypasses the SOC, there is no doubt that it plays a pivotal role in hearing processes.

A wide range of techniques have been employed to unveil these functions, ranging from single-unit electrophysiology to recording of the auditory brainstem response, from histochemistry to in situ hybridization, and from neuronal tracing to lesions and the production of hearing trauma. In the present volume of Microscopy Research and Technique, several groups investigating the SOC survey their results and highlight recent advances in the field.

The cells responsible for the perception of sound are the inner and outer hair cells (IHC, OHC) of the organ of Corti in the cochlea. They are arranged parallel to the longitudinal axis of the cochlear duct. Both types of sensory cells are contacted by afferent dendrites from spiral ganglion neurons. Hair cell information is, thus, transmitted to the cochlear nucleus (CN) complex where spiral axons terminate. They branch to make synaptic contacts in the anterior and posterior ventral and in the dorsal CN.

The CN of both sides project to the SOC, which is composed of three principal nuclei, i.e., the lateral and medial superior olivary nuclei (LSO, MSO) and the medial nucleus of the trapezoid body (MNTB) and of some less-defined periolivary neuronal groups. The location of the SOC in the guinea pig brainstem is shown in Figure 1.

The comparative study of the SOC in many mammals revealed that considerable differences between species exist in morphology, extent, and function of the nuclei (for review see Schwartz, 1992). For example, the periolivary groups and, in particular, the MSO (usually associated with processing of interaural time differences) are prominent in the human SOC (see Moore et al., 1999; Moore, pages 403–412 this issue).

The superior olivary complex sends, via the lateral lemniscus, ascending axons to the nuclei of the lateral lemniscus (LL) and to the subdivisions of the inferior colliculus (IC), the target of virtually all parts of the ascending auditory pathway (for overviews see Aitkin, 1989; Webster, 1995).

The anatomical patterns and roles of the ascending projections have been reviewed previously (Helfert et al., 1991). There is evidence that the ipsilateral MSO and contralateral LSO projections to the central nucleus of the IC are excitatory, while those from the ipsilateral LSO are inhibitory (Oliver et al., 1995). The modes through which SOC information is integrated with those from CN and LL to regulate processing in the IC are important for auditory functions such as hearing and sound localization. The routes involved and their functional roles are discussed by Oliver in this issue (pages 355–363). The major ascending pathway then connects the IC to the medial geniculate body (MGB) and, in turn, with the primary auditory cortical complex. In the human brain, the auditory cortex is located in the transverse gyri of Heschl (areas 41 and 42 of Brodmann).

In addition to its ascending projections, the SOC also exhibits a descending projection directed to the cochlea. Axons of SOC neurons build the so-called olivo-cochlear bundle (Papez, 1930; Rasmussen, 1946) and make direct synapses with OHC or synapse at afferent processes of spiral ganglion cells at the base of IHC. In the rat, a predominantly ipsilateral projection stems from small neurons with polar dendrites in the lateral SOC. The other group is located in the medial SOC and consists of larger multipolar neurons that project mainly to the contralateral cochlea (White and Warr, 1983). The organization of the descending auditory systems and, in particular, of olivo-cochlear projections have been comparatively described in detail (Spangler and Warr, 1991; Warr, 1992). Some recently discovered aspects of the descending projections are mentioned in this issue (Reuss and Riemann, pages 318–329; Robertson and Mulders, pages 307–317).

In addition, there is evidence that a small, third group of neurons exists that provides both ascending and descending projections. This was found upon double retrograde neuronal tracing following injection of different tracer substances into the IC and the ipsilateral cochlea (Reuss et al., 1999; Riemann and Reuss, 1998).

The neuroactive substances found in SOC neurons include acetylcholine, amino acid transmitters such as glutamate (Moore and Moore, 1987), glycine (Bledsoe et al., 1990), GABA (Wynne et al., 1995), and various neuroactive peptides. Cholecystokinin, somatostatin, substance P, and enkephalins were detected in afferent fibers (which is also the case for serotonin and noradrenaline). Their sources and possible functional roles were reviewed previously (Caspar and Finlayson, 1991; Wenthold, 1991) and are discussed here (Robertson and Mulders, this issue, pages 307–317). Found in neurons were calcitonin gene-related peptide, enkephalins and dynorphins, which may co-exist in SOC neurons (Safieddine and Eybalin, 1992). Some of these cells were related to the olivo-cochlear projections that comprise medial and lateral systems (MOC, LOC). They have various functions including frequency selectivity, augmentation of signal-to-noise ratio and protection of the cochlea from sound damage, probably by suppressing cochlear sensitivity utilizing contractile responses of OHC (see Warr, 1992).
Fig. 1.  

A: Frontal section of the guinea pig brainstem demonstrating the location of the superior olivary complex (cresyl-violet stain). 

B–F: Higher magnifications from the different nuclei of the SOC. 

Numbers and abbreviations: 1, dorsal periolivary region (DPO); 2, lateral superior olive (LSO); 3, medial nucleus of the trapezoid body (MNTB); 4, medial superior olive (MSO); 5, superior paraolivary nucleus (SPO); 6, ventral nucleus of the trapezoid body (VNTB); py, pyramidal tract; 4V, fourth ventricle; 7n, facial nerve. 

Magnification bars = 300 μm (A), 20 μm (B–F; these panels are the same magnification).
transmitters used in the olivo-cochlear pathway were reviewed by Eybalin (1993) and Gil-Loyzaga (1995).

Only recently, it was shown that another neuroactive substance, i.e., nitric oxide (NO), is produced in the SOC. The enzyme responsible for NO-production, NO-synthase (NOS), was found in some SOC cells groups including the LSO, MSO, and, in particular, the MNTB. The neuronal isotype of the enzyme, nNOS, was demonstrated by immunocytochemistry and by in situ hybridization (Fessenden et al., 1999; Reuss, 1998; Riemann and Reuss, 1999a). Neuronal tracing showed that some of these neurons belong to the group with descending projection pattern (Riemann and Reuss, 1999a). The olivo-cochlear nNOS neurons are candidate sources of respective immunostaining of cochlear efferent terminals, whereas nNOS-immunoreactive afferent terminals may stem from spiral ganglion neurons. In addition, a trigeminal projection to the cochlea using nNOS has been shown (Riemann and Reuss, 1999b). The distribution in the SOC and in other auditory regions and the possible roles of NO in the physiology and pathophysiology of hearing is discussed in this issue (see Reuss and Riemann, pages 318–329).

Although some nNOS-cells of the SOC were shown to project to the IC (Reuss et al., unpublished observations), a large group of these SOC neurons were not identified yet with regard to their targets.

The functions of the SOC are regulated by afferents stemming from various sources. Ascending auditory afferents stem from the CN, descending afferents from the IC, NLL, thalamic subparafascicular nucleus, metathalamic MGB, and auditory cortex. There are also numerous intrinsic connections most of which originate from MNTB principal neurons (Kuwabara and Zook, 1991; Spangler et al., 1985). Many of the intrinsic MNTB projections terminate in the SPN but other principal nuclei and the periolivary region also receive afferents from MNTB neurons. In addition, there are non-auditory afferents that include noradrenergic and serotonergic fibers. The latter projection, probably stemming from the raphe and other nuclei, varies in intensity between the SOC subdivisions and shows considerable differences between species. Very recently, it was also shown that the trigeminal ganglion innervates the SOC (Shore et al., 2000). The sources, reciprocal connections, and functional implications of the systems providing afferents to the SOC are discussed here in an extensive review by Thompson and Schofield (pages 330–353).

An interesting feature of the SOC is its plasticity. During development, SOC neurons vary the expression patterns of substances produced. There is evidence that both activity-dependent and -independent processes contribute to the formation of auditory circuitry (see Friauf and Lohmann, 1999). The SOC seems to play a major role for the developmental and adaptive tuning of binaural processing, since its neurons respond to various kinds of hearing impairment with the expression of substances related to plasticity and learning. Adaptive changes during development, and the plasticity detected following loss of sensory input (e.g., upon experimental cochleotomy) are described and discussed by Illing et al. in this issue (pages 364–381), where the authors provide evidence for a pivotal role of the SOC in auditory brainstem plasticity.

The SOC is also well developed in the auditory specialists, bats, which use echoes of their own calls for orientation and identification of objects. A description of morphology and function of the different SOC nuclei in bats as compared to other mammals and the putatively specific roles of some of the nuclei are described by Grothe and Park in this issue (pages 382–402).

Finally, the last chapter in this issue by Moore (pages 403–412) reviews recent advances and views in the study of the human SOC. Compared to the mammalian non-human SOC, some differences in anatomy are evident. For example, while the nucleus of the trapezoid body apparently is absent and the LSO is much smaller, periolivary groups are prominent and the MSO is well developed. The putative functional consequences, the contribution of the SOC to the human auditory brainstem response (i.e., waves IV and V), and some observations made in patients with lesions of the brainstem are presented and discussed in this paper.

Although many data are presented in this issue, a number of open questions remain to be addressed. For example, what are the sources of the peptidergic (and other) inputs to the SOC? Where do specific target neurons project to? What are the distribution and functional implications of the co-localization of neuropeptides with other transmitters and modulating substances, or in neurons producing nitric oxide, in the SOC? What roles do the peptidergic outputs of the SOC play? How are the differences in SOC organization that are observed between species related to their auditory behavior, e.g., what is the functional effect of the reduction in the lateral efferent component in humans? These and many other questions warrant the further characterization of the SOC, which may promise important insights into the function of the whole auditory system.

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