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Reciprocal Connections Between the Red Nucleus and the Trigeminal Nuclei: A Retrograde and Anterograde Tracing Study

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Summary

An anterograde biocytin and a retrograde WGA-colloidal gold study in the rat can provide information about reciprocal communication pathways between the red nucleus and the trigeminal sensory complex. No terminals were found within the trigeminal motor nucleus, in contrast with the facial motor nucleus. A dense terminal field was observed in the parvicellular reticular formation ventrally to the trigeminal motor nucleus. The parvicellular area may be important for the control of jaw movements by rubrotrigeminal inputs. On the other hand, the contralateral rostral parvicellular part of the red nucleus receives terminals from the same zone in the rostral part of the trigeminal sensory complex, where retrogradely labelled neurones were found after tracer injections into the red nucleus. Such relationships could be part of a control loop for somatosensory information from the orofacial area.

Key words

Red nucleus – Trigeminal sensory complex – Intertrigeminal region – WGA-colloidal gold – Biocytin – Rat

Introduction

The red nucleus is considered to play a role in the control of distal limb muscles (Alstermark and Kümmel 1986, Ten Donkelaar 1988, Robinson *et al.* 1987, Houk *et al.* 1988) and orofacial movements (Bodian 1946, Pompeiano and Brodal 1957, Vinay and Padel 1990). The red nucleus receives projection fibres from the lateral part of the anterior interposed nucleus of the cerebellum (Cohen *et al.* 1958, Angaut and Bowsher 1965, Courville 1966, Flumerfelt *et al.* 1973, Asanuma *et al.* 1983, Angaut *et al.* 1986, Ralston 1994, Teune *et al.* 1995) and cortical fibres from the jaw, lips and tongue area of the sensorimotor cortex (Ruigrok and Cella 1995). It projects to laminae V through IX of the spinal cord (Holstege 1987, Holstege *et al.* 1988, Padel 1993), to the motor nucleus of the facial nucleus (Piliavskii *et al.* 1972, Courville and Brodal 1966, Arnault *et al.* 1994), the intertrigeminal region (Travers and Norgren 1983) and in sensory relay nuclei such as the dorsal column nuclei (Wild 1992) and the trigeminal sensory complex (Eisenman *et al.* 1964,

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Davis and Dostrovsky 1986). These anatomical characteristics indicate that, in addition to motor control, the red nucleus may play a role in sensory informations processing (Steffens and Padel 1991).

Little is known about the pathways involved in the transmission of information from the orofacial region to the red nucleus. Anatomical evidence has previously been reported (Cajal 1909, Eisenman *et al.* 1963, Edwards 1972) and a physiological study has pointed out that stimulation of the red nucleus modulates the sensory response in trigeminal oralis neurones (Davis and Dostrovsky 1986). The aim of this study was to investigate the relationship between the red nucleus and the trigeminal sensory complex and its surroundings. Combined retrograde and anterograde tracing techniques were used to investigate the efferent pathways from the trigeminal sensory complex to the red nucleus and the possible reciprocal connections between these two structures.

Methods

The experiments were carried out in Sprague Dawley male rats (225–250 g). Animals were anaesthetized with ketamine (IMALGENE 500: 90 mg/kg i.p) and supplemented whenever necessary. Injections of a 0.1 μl solution of colloidal gold adsorbed to wheat germ agglutinin (Sigma Chem. Co., St. Louis), using the procedure of Geoghegan and Ackerman (1977) were performed into the red nucleus in six rats. The rats were transcardially perfused with a Ringer solution followed by 500 ml of a 0.1 % glutaraldehyde-3 % paraformaldehyde solution in a 0.1 M phosphate pH 7.4 buffer. The brain was then removed and cryoprotected in 10 % sucrose in the same buffer. Frontal serial frozen sections of 50 μm were processed for colloidal gold intensification with silver, according to Menétrey (1985), and then counterstained with cresyl violet.

Biocytin (0.25 μl, 5 % in 0.1 M Tris buffer) was injected stereotactically in 12 rats, either into the rostral trigeminal sensory complex (main sensory trigeminal nucleus, 2 rats; rostral trigeminal oralis nucleus, 6 rats) or into the red nucleus (4 rats). Animals were transcardiacally perfused with a Ringer solution 24 h later, followed by 500 ml of 4 % paraformaldehyde in a 0.1 M phosphate buffer (pH 7.4) according to Lachica *et al.* (1991). The brains were removed and postfixed for a few hours, then cryoprotected in 10 % sucrose in the same buffer. Serial frontal sections were cut at 50 μm on a freezing microtome, incubated in avidin-biotine-peroxidase complex (ABC, Vector Laboratories), followed by DAB (3,3'-diaminobenzidine tetrahydrochloride; Sigma Chemical Co.) according to the method of Gee *et al.* (1991).

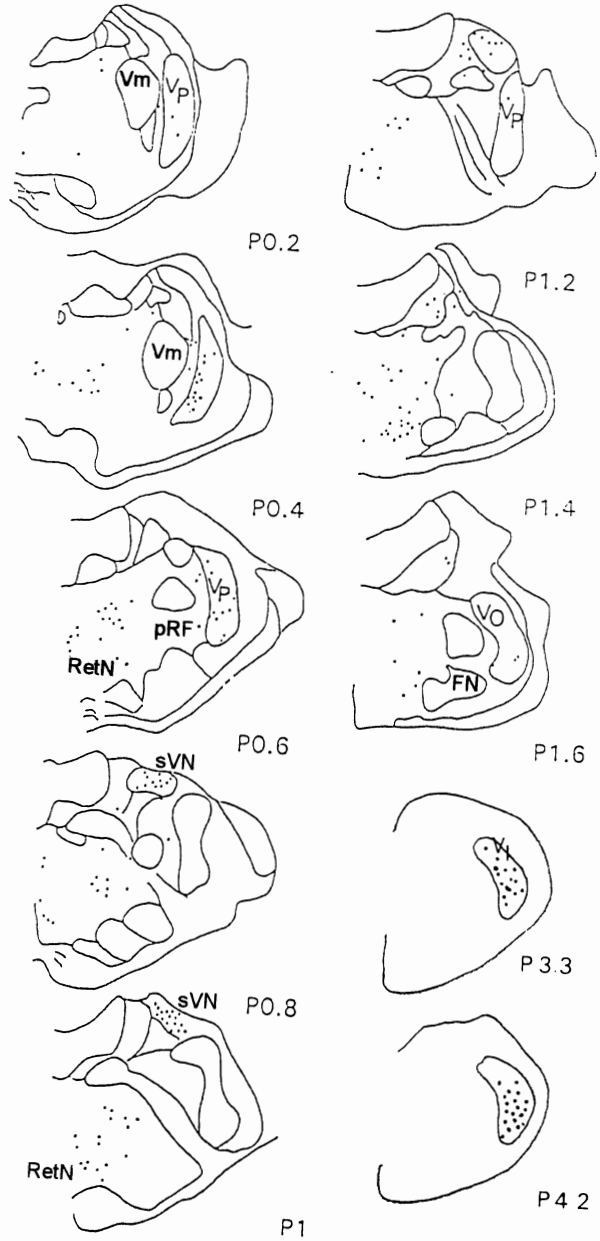

Fig. 1. *Brain stem WGA-colloidal gold labelling after injection of the medial part of the red nucleus. Abbreviations: Vp: trigeminal main sensory nucleus, pRF: parvicellular reticular formation. RetN: reticular nucleus, sVN: superior vestibular nucleus, Vo: trigeminal oralis nucleus, Vi: trigeminal interpolaris nucleus. FN: Facial motor nucleus.*

Results

Retrograde transport of WGA-colloidal gold

Injections into the medial and caudal part of the red nucleus provided retrograde labelling in several structures of the pons (Table 1, Fig. 1). Injections into the parvicellular part of the red nucleus (Fig. 2E) resulted in weaker labelling.

Table 1. Labelled structures after WGA-colloidal gold injection into the red nucleus

IPSILATERAL	CONTRALATERAL
Laterodorsal tegmental nucleus	Laterodorsal tegmental nucleus
	Superior parabrachial nucleus
Pontine reticular nucleus	Pontine reticular nucleus
Trigeminal main sensory nucleus	Trigeminal main sensory nucleus
	Parvicellular reticular formation
Locus coeruleus	Locus coeruleus
	Lateral parabrachial nucleus
	Superior vestibular nucleus
	Trigeminal oralis nucleus, ventrorostral part
Lateral vestibular nucleus	Lateral vestibular nucleus
	Trigeminal oralis nucleus, ventrocaudal part
Gigantocellular reticular nucleus	Gigantocellular reticular nucleus
Trigeminal interpolaris nucleus	Trigeminal interpolaris nucleus

Table 2. Labelled structures after biocytin injection into the red nucleus

IPSILATERAL	CONTRALATERAL
Laterodorsal tegmental nucleus	Laterodorsal tegmental nucleus
	Lateral parabrachial nucleus
Pontine reticular nucleus	Pontine reticular nucleus
Trigeminal main sensory nucleus	Trigeminal main sensory nucleus
	Parvicellular reticular formation
Locus coeruleus	Locus coeruleus
	Lateral parabrachial nucleus
	Superior vestibular nucleus
	Trigeminal oralis nucleus, ventrorostral part
Lateral vestibular nucleus	Lateral vestibular nucleus
	Trigeminal oralis nucleus, ventrocaudal part
	Facial nucleus
Gigantocellular reticular nucleus	Gigantocellular reticular nucleus
Trigeminal interpolaris nucleus	Trigeminal interpolaris nucleus

Cells with black silver granules were distributed all along the contralateral sensory complex except in the caudalis nucleus (Fig. 2A). Labelling in the oralis nucleus was weaker than in the main sensory nucleus. Labelled neurones were distributed mainly along the border zone between these two nuclei. Numerous labelled cells lay in the parvicellular reticular formation at the trigeminal motor nucleus level. The labelled cells were of different shapes and orientations according to their location. Three types of retrogradely labelled cells appeared in the trigeminal complex.

- Numerous small round neurones with short-stained dendrites in the ventrocaudal part of the main sensory nucleus and in the ventrorostral part of the oralis nucleus (Fig. 2B).
- Large multipolar neurones with complex dendritic trees. They were mainly located in the parvicellular reticular formation, ventrally to the Vth motor nucleus and ventrally in the caudal part of the main sensory trigeminal nucleus. All these neurones had axons facing the reticular formation and dendrites facing the main sensory nucleus. Some of them were located in the intertrigeminal area (Fig. 2C).

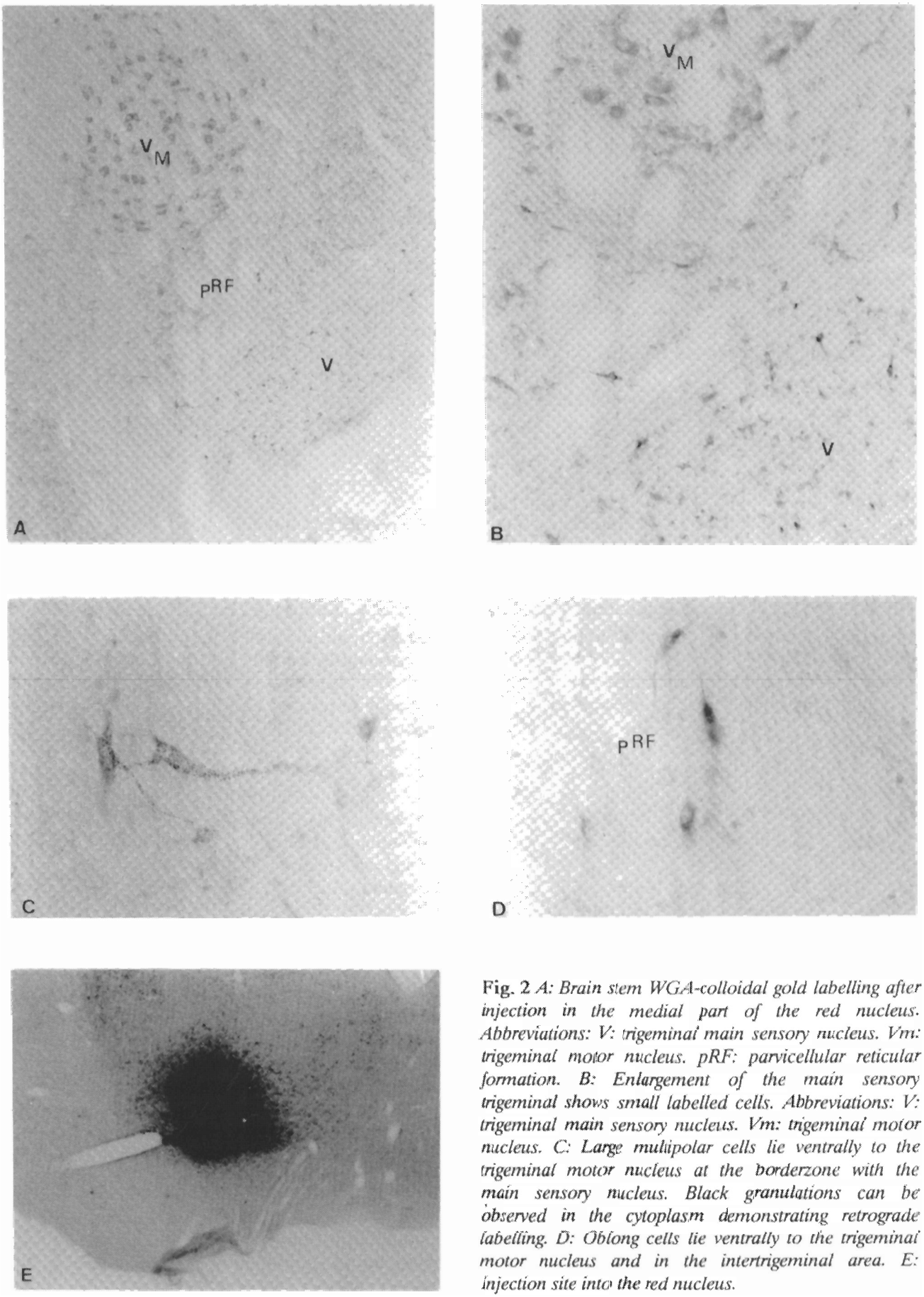

Fig. 2 *A: Brain stem WGA-colloidal gold labelling after injection in the medial part of the red nucleus. Abbreviations: V: trigeminal main sensory nucleus. Vm: trigeminal motor nucleus. pRF: parvicellular reticular formation. B: Enlargement of the main sensory trigeminal shows small labelled cells. Abbreviations: V: trigeminal main sensory nucleus. Vm: trigeminal motor nucleus. C: Large multipolar cells lie ventrally to the trigeminal motor nucleus at the borderzone with the main sensory nucleus. Black granulations can be observed in the cytoplasm demonstrating retrograde labelling. D: Oblong cells lie ventrally to the trigeminal motor nucleus and in the intertrigeminal area. E: Injection site into the red nucleus.*

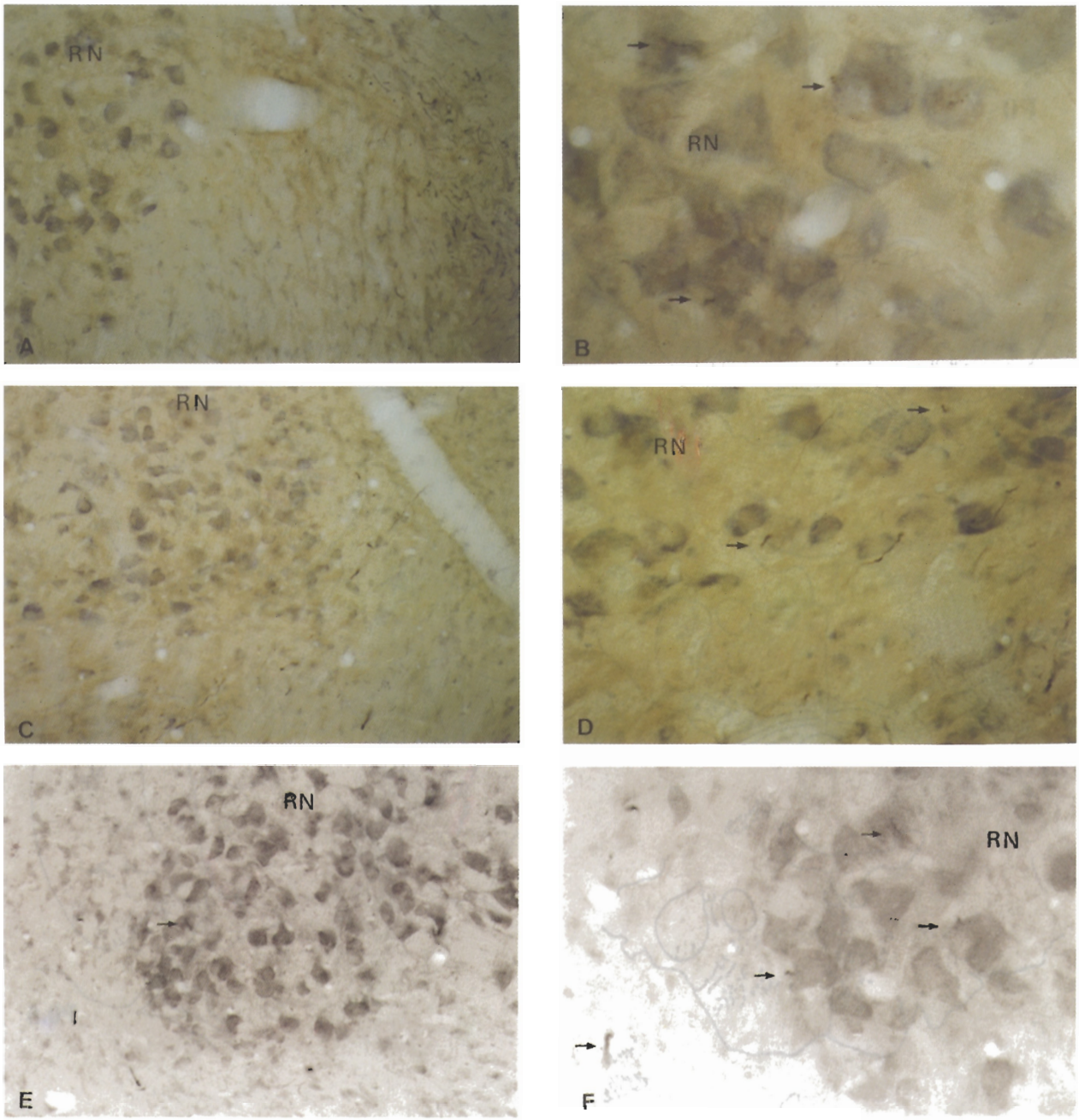

Fig. 3 *A: Labelled fibre bundles ascending the medial lemniscus. Some axonal collaterals enter the contralateral red nucleus. B: Labelled fibers within the contralateral magnocellular red nucleus (RN). C: Labelled fibre bundles ascending the medial lemniscus. Some axonal collaterals enter the parvicellular contralateral red nucleus (RN). D: Labelled fibers within the contralateral parvicellular red nucleus (RN). E: Labelled fibres ascending in the medial lemniscus and entering the ipsilateral red nucleus (RN). Arrows show trigeminal fibers inside the ipsilateral lemniscus. F: Labelled fibres within the ipsilateral magnocellular red nucleus (RN). Arrows indicate trigeminal fibers inside the ipsilateral lemniscus. G: Injection site in the main sensory trigeminal nucleus.*

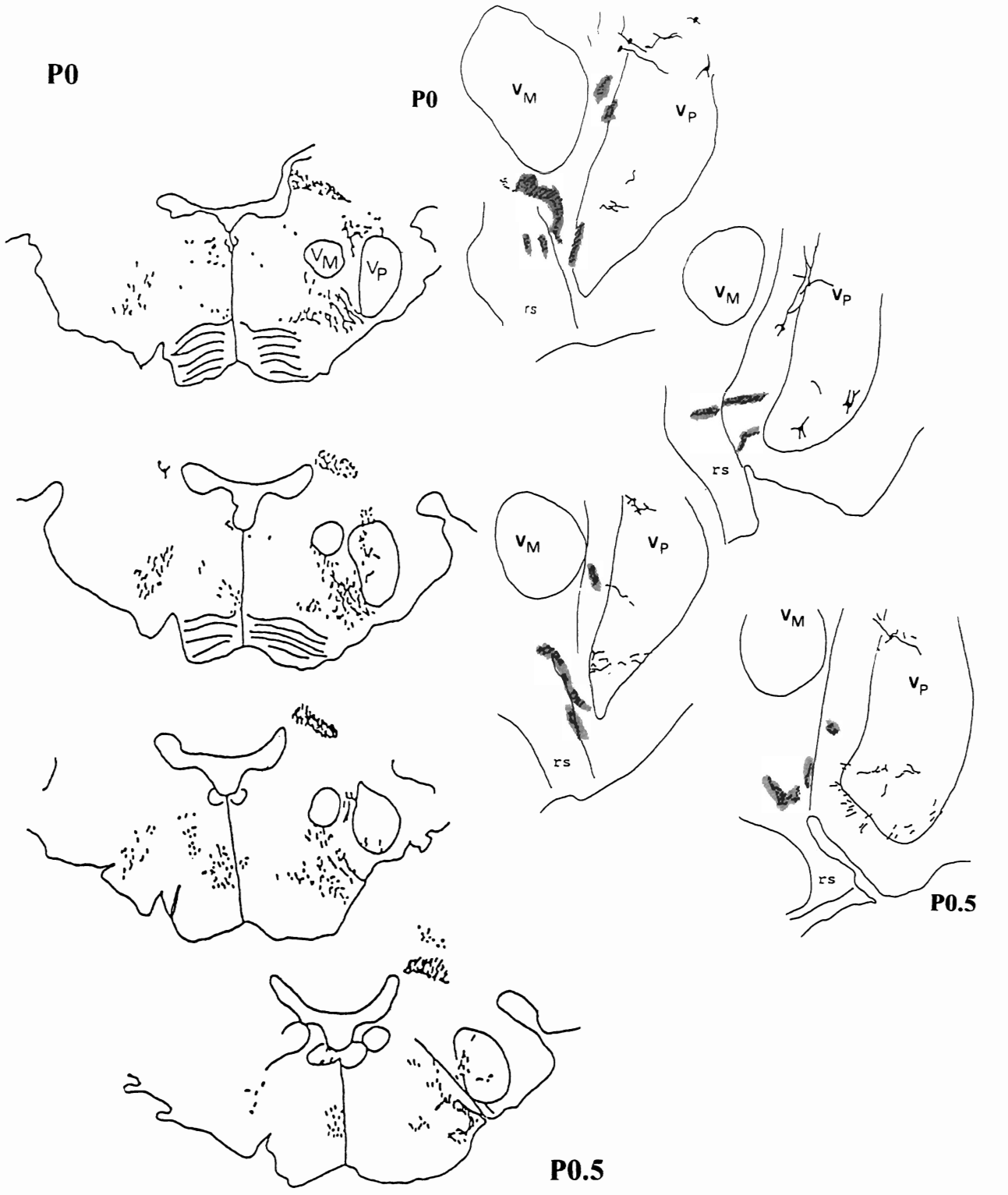

Fig. 4. *Line drawings of brain stem frontal sections, showing the biocytin-labelled fibres after injection into the medial part of the red nucleus. The left panel represents a x4 magnification of sections made at the trigeminal main sensory level. Biocytin-labelled fibres run through the rubrospinal tract and enter the main sensory nucleus. The right panel is a zoom of the left one at x25 magnification. Labelled rubral fibre are seen entering the trigeminal sensory nucleus and synaptic connections with buttons are located in the parvicellular reticular formation. Abbreviations: Vp: trigeminal main sensory nucleus. Vm: trigeminal motor nucleus. pRF: parvicellular reticular formation. rs: rubrospinal tract.*

– Oblong and bipolar neurones lying ventrally to the Vth motor nucleus in the contralateral parvicellular reticular formation circling around the nucleus and ascending in the intertrigeminal area. They always passed the Vth motor nucleus tangentially. These neurones were much more numerous in the intertrigeminal area than the previous ones (Fig. 2D).

No labelled neurones were found within the Vth motor nucleus. A group of labelled neurones was observed in the ventrocaudal neighborhood of the Vth motor nucleus which looked like an extension of the nucleus.

Anterograde transport of biocytin.

In all rats which had received an injection of biocytin into the rostral part of the trigeminal sensory complex, (Fig. 3G), many anterogradely labelled fibres were found crossing the reticular formation, the midline and entering the contralateral medial lemniscus. As they approached the caudal end of the contralateral red nucleus, some of them shifted medially towards the red nucleus, and terminated in a scattered and widely distributed fashion within both the magnocellular and parvicellular part of the nucleus (Figs 3A, 3B, 3C and 3D). Nerve fibres entered the nucleus from its lateral and inferior side. Many synaptic endings appeared in the magnocellular/parvicellular border zone. Some fibres also reached the magnocellular part of the ipsilateral red nucleus *via* the ipsilateral medial lemniscus and synaptic endings could be seen at this level (Figs 3E and 3F). Labelled lemniscal fibres terminated in the medial part of the thalamic contralateral ventrobasal complex, where many dense terminal fields could be observed.

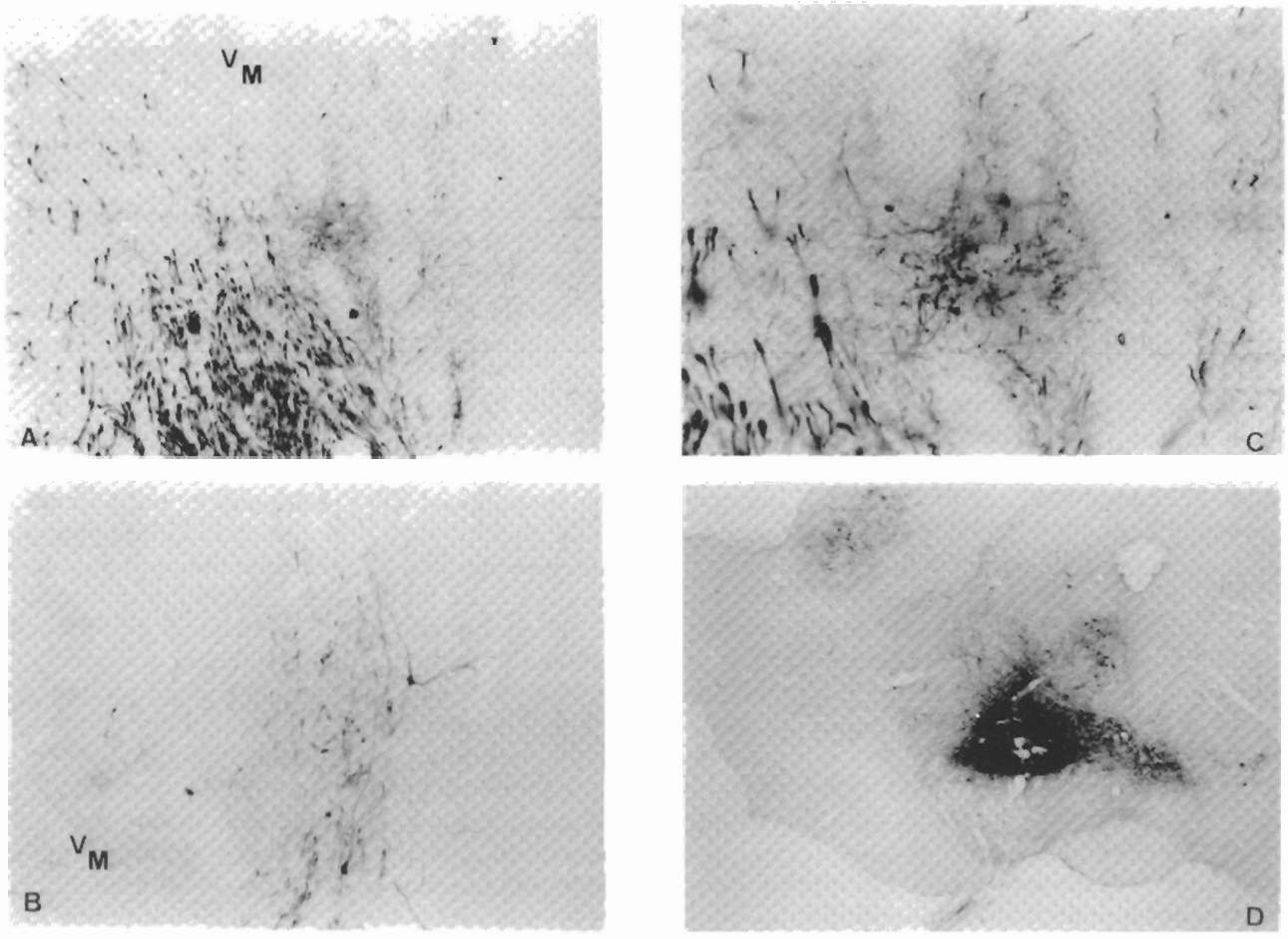

Fig. 5. *A: Labelled fibres within the brain stem after biocytin injection into the contralateral red nucleus. A large number of labelled rubral fibres are seen in the rubrospinal tract with an extensive field of synaptic connection ventrally to the trigeminal motor nucleus (Vm). B: Fibres ascending in the rubro-trigeminal tract and sending collaterals to the main sensory nucleus after biocytin injection into the contralateral red nucleus. Some cell bodies can be observed in the parvicellular reticular formation and at the border zone with the main sensory nucleus. Retrograde or transynaptic labelling of these neurons from the red nucleus can be seen. This fact supports the data obtained with WGA-colloidal gold. C: Enlargement of Fig 5A magnifying fibres and axon terminals in the parvicellular reticular formation ventrally to the trigeminal motor nucleus. D: Biocytin injection site into the red nucleus.*

Biocytin injections limited to the rostral part of the red nucleus (parvicellular part) did not label the trigeminal complex. On the contrary, injections into the core of the red nucleus labelled rubrospinal fibres and synaptic endings in the caudal part of the contralateral main sensory trigeminal nucleus.

Axonal anterograde transport from biocytin injections into the caudal part of the red nucleus (magnocellular part) labelled numerous fibres in the contralateral brain stem (Table 2, Fig. 4).

In the trigeminal sensory complex, few labelled fibres could be observed in the caudal part of the trigeminal main sensory nucleus, in the rostral part of the oralis nucleus and the intertrigeminal area. A dense field of axon terminals was observed in the reticular parvicellular formation ventrally to the trigeminal motor nucleus (Fig. 5A, 5B and 5C). Labelled fibres looped around the ventral part of the contralateral main trigeminal sensory nucleus, and projected laterally into the nucleus, sending terminals into the intertrigeminal area.

A moderate number of labelled fibres with some terminal buttons in the neuropil surrounding the cell bodies were observed in the lateral part of the contralateral facial nucleus. No labelling was seen in the olivary complex.

Discussion

Rubro-trigeminal pathway

After biocytin injections into the red nucleus, labelled efferent rubral fibres were observed in the rat brain stem at the trigeminal level in accordance with previous degenerative or autoradiographic studies (Cajal 1955, Courville 1966, Edwards 1972, Olsson and Landgren 1990). All rubral projections seemed to originate from the magnocellular part of the red nucleus as previously suggested by Edwards (1972). Dense terminal labelling was found in the contralateral subtrigeminal area between the rubrospinal tract and the motor Vth nucleus confirming the degenerative studies in the cat (Courville 1966) and monkey (Miller and Strominger 1973) and autoradiographic results in the cat (Edwards 1972). Groups of labelled fibres also entered the ventromedial part of the trigeminal main sensory nucleus and spray out into the nucleus in accordance with Edwards' results. Fewer fibres entered the trigeminal oralis nucleus, essentially in its border zones with the trigeminal main sensory nucleus. These last observations differed from those of Edwards (1972) in the cat where he found anterograde labelling in the gamma component of the oralis nucleus which probably corresponds to the overlap zone of the trigeminal main sensory nucleus and trigeminal oralis nucleus in the rat (Fukushima and Kerr 1979, Azérad *et al.* 1982).

Davis and Dostrovsky (1986) described a functional relationship between the red nucleus and the trigeminal oralis (Vo) nucleus in the cat. In this paper, modulation of the activity of trigeminothalamic efferents by the red nucleus was observed. These authors concluded that contralateral or ipsilateral red nuclei could modulate the activity of trigeminal neurones. They postulated that ipsilateral modulation could be modulated *via* other pathways such as the cerebral cortex or nucleus raphe magnus which are involved in the modulation of sensory information. They also considered the possibility of current spread to adjacent structures when stimulating the red nuclei, such as nucleus cuneiformis or lateral reticular formation, which have been shown to inhibit sensory responses in the spinal cord dorsal horns or the trigeminal caudalis nucleus.

Tracer diffusion through nigral descending pathways after injections into the red nucleus could also be involved. These pathways have been shown to end in the parvicellular reticular formation at the level of the trigeminal motor nucleus (Petrovicky 1988, Yasui *et al.* 1996). No traces of such diffusion could be detected in our study, either in the compacta or in the reticular substantia nigra efferents.

In the present study, bundles of labelled fibres were distributed in the trigeminal interpolaris nucleus and very few existed in the trigeminal caudalis nucleus in agreement with Edwards (1972). Using the degeneration method, Courville (1966), Miller and Strominger (1973) and Petrovicky (1975) observed *fibres de passage* into the trigeminal motor nucleus without terminal endings. However, no such labelled terminals were observed in the Vth motor nucleus in our study. Using HRP injections in the trigeminal motor nucleus, Travers and Norgren (1983) observed retrograde labelling into the contralateral red nucleus. They concluded that this was due to a probable uptake by damaged axons, which can be easily understood considering the density of rubral terminals observed in this study ventrally to the Vth motor nucleus.

Degeneration methods (Courville 1966, Martin and Dom 1970, Mizuno 1970, Miller and Strominger 1973, Petrovický 1975) demonstrated labelling ventrally to the trigeminal motor nucleus in the parvicellular reticular formation at the same level where terminal endings were observed in our study. Two hypotheses can be suggested concerning the nature of this target. Rubral neurones could project either on reticular interneurones ventrally to the trigeminal motor nucleus (Yasui *et al.* 1993, Mogoseanu *et al.* 1993, Yasui 1995), or onto the distal dendrites of motoneurones, extending outside the trigeminal motor nucleus (Mong *et al.* 1988). Selective targeting of these connections upon dendrites of motoneurones could enhance the priorities between afferents, as has been shown elsewhere in the CNS

(Conradi *et al.* 1979a,b, Holmes 1989, Pierce and Mendell 1993, Alkondon *et al.* 1996). Considering the results of the retrograde study of Yasui *et al.* (1996) after cholera toxin B injection into the Vth motor nucleus, where no labelling was observed in the cell bodies ventrally to this nucleus, these interneuronal axons probably do not enter the trigeminal motor nucleus. The synaptic relationship between trigeminal motoneurones and these subtrigeminal reticular interneurones must then be present outside the trigeminal motor nucleus, where the terminal fields observed in this study had taken place.

Ralston *et al.* (1988) demonstrated labelled terminals synapsing upon proximal dendrites of motoneurones in the ventral horn of the spinal cord after WGA-HRP injections into the red nucleus. They confirmed the monosynaptic connections between spinal motoneurones and the red nucleus previously described (Gurevich and Belozerova 1971, Shapovalov *et al.* 1972). Such monosynaptic connections with trigeminal motoneurones, which were not observed in this study, remain to be confirmed.

Labelled fibres with some terminal buttons in the neuropil surrounding the cell bodies were observed in the lateral part of the contralateral facial motor nucleus. This agrees with the finding of Cajal (1909), Courville (1966), Edwards (1972) and Petrovicky (1975) who used degeneration methods and autoradiography in the cat. Monosynaptic connections between the red nucleus and the facial nucleus have previously been demonstrated (Piliavskii *et al.* 1972) and emphasized the functional control of the red nucleus on facial motoneurones.

Apart from the marked fibres in the brain stem, some Golgi-like labelled neurones could be observed essentially in the parvicellular reticular formation at the trigeminal main sensory nucleus level. This particular labelling could be due to the high biocytin concentration used in the present study, with direct retrograde uptake by damaged axons. Moreover, relatively large injections we made into the red nucleus which could be responsible for such a phenomenon (King *et al.* 1989).

Trigemino-rubral pathway

Anterograde labelling with biocytin injected into the rostral trigeminal sensory complex disclosed fibre bundles ascending towards the medial part of the contralateral ventrobasal thalamic complex. This agrees with previous findings (Carpenter and Hanna 1961, Mizuno 1970, Peschanski 1984). Medial lemniscus axonal collaterals end in the contralateral red nucleus, mainly in its caudal region. Fibres and endings were mainly distributed in the magnocellular part of the red nucleus according to previous observations (Carpenter and Hanna 1961, Mizuno 1970). Mizuno questioned the origin of these degenerated fibres, as to whether they came from the ventral trigeminal tract or from the injured brachium conjunctivum. The present study excludes the later hypothesis, and confirms the trigeminal origin of these fibres. It also demonstrates labelled fibres in the contralateral rostral parvicellular part of the red nucleus. Few fibres could be observed in the ipsilateral red nucleus. This organization can be compared to the rubro-trigeminal projections, each red nucleus projecting mainly contralaterally, but also to a minor extent bilaterally. This demonstrates the existence of reciprocal connections between these two structures.

The retrograde axonal transport of colloidal gold/WGA injected into the red nucleus in the present study demonstrated labelled neurones in the contralateral main sensory nucleus, especially in its caudal part. In the oralis nucleus, labelled neurones were present only in its rostral part, while in the interpolaris trigeminal nucleus, numerous small round labelled neurones were more widespread. In the caudalis trigeminal nucleus, labelled neurones were occasionally demonstrated, both superficially and ventrally.

In the intertrigeminal area where nucleus K was described in the rat (Petrovicky 1975, Paxinos and Watson 1986), a group of oblong retrogradely labelled neurones was located between the Vth motor nucleus and the trigeminal main sensory nucleus. Neurones in a similar location were retrogradely labelled following cerebellar injections (Mantle-St.John and Tracey 1987). Another group located ventrally to the Vth motor nucleus could be observed containing multipolar neurones. These neurones also share similar morphological characteristics with those labelled by Jacquin *et al.* (1983) after injection of HRP into the trigeminal alveolar nerve and the trigeminal motor root. These authors localized such neurones into the reticular formation, ventrally to the Vth motor nucleus. According to Mizuno *et al.* (1982), these could be motoneurones or pre-motoneurones for jaw elevator muscles or tensor tympani muscle. Several authors (Appenteng and Girdlestone 1987, Donga *et al.* 1992, Saad *et al.* 1995) have identified neurones in the same area as motoneurones for masseter or digastric muscles in the rat and rabbit. This population of neurones remains to be clearly defined either as efferent neurones, or as reticular neurones, using a technique of double staining.

This conclusion provides information about reciprocal communication pathways between the red nucleus and the trigeminal complex. Anterograde axonal transport of biocytin injected into the main sensory trigeminal nucleus and retrograde axonal transport of WGA-colloidal gold injected into the red nucleus demonstrate labelled terminal endings and neurones in the contralateral main sensory trigeminal nucleus, the rostral part of the oralis nucleus, the interpolaris nucleus and the parvicellular reticular formation ventrally to the trigeminal motor nucleus

and in the intertrigeminal area. Axonal endings occur mainly in the magnocellular red nucleus but also in the parvicellular part of this nucleus. These results favour the existence of a trigemino-rubral pathway. Anterograde axonal transport of biocytin injected into the red nucleus demonstrates labelled terminal fields in the same areas where retrogradely labelled trigemino-rubral neurones were observed. The existence of reciprocal connections between the trigeminal complex and the red nucleus thus appear to have been established. This study indicates that the parvicellular reticular formation just ventrally to the Vth motor nucleus could act in the control of jaw movements.

References

ALKONDON M., PEREIRA E.F.R., ALBUQUERQUE E.X.: Mapping the location of functional nicotinic and gamma-aminobutyric acid A receptors on hippocampal neurons. *J. Pharmacol. Exp. Ther.* **279**: 1491–1506, 1996.

ALSTERMARK B., KÜMMEL H.: Transneuronal labelling of neurones projecting to forelimb motoneurones in cat performing different movements. *Brain. Res.* **376**: 387–391, 1986.

ANGAUT P., BATINI C., BILLARD J.M., DANIEL H.: The cerebellorubral projection in the rat: retrograde anatomical study. *Neurosci. Lett.* **68**: 63–68, 1986.

ANGAUT P., BOWSHER D.: Cerebello-rubral connexions in the cat. *Nature* **208**: 1002–1003, 1965.

APPENTENG K., GIRDLESTONE D.: Transneuronal transport of wheat germ agglutinin-conjugated horseradish peroxidase into trigeminal interneurones of the rat. *J. Comp. Neurol.* **258**: 387–396, 1987.

ARNAULT P., EBRAHIMI-GAILLARD A., ROGER M., ZILLES K.: Electron microscopic demonstration of terminations of posterior thalamic axons on identified rubrospinal neurons in the rat. *Anat. Embryol. (Berl.)* **189**: 383–392, 1994.

ASANUMA C., THATCH W.T., JONES E.G.: Brainstem and spinal projections of the deep cerebellar nuclei in the monkey, with observations on the brainstem projections of the dorsal column nuclei. *Brain. Res. Rev.* **5**: 299–322, 1983.

AZÉRAD J., POLLIN B., LAPLANTE S.: Projection of rostral trigeminal sensory complex neurons to diencephalon and tectum: anatomical and electrophysiological demonstration. In: *Anatomical, Physiological and Pharmacological Aspects of Trigeminal Pain.* B. MATTHEWS, R.G. HILL (eds), Excerpta Medica, Amsterdam, 1982, p. 175.

BODIAN D.: Spinal projections of brain-stem in rhesus monkey deduced from retrograde chromatolysis. *Anat. Rec.* **94**: 512–513, 1946.

CAJAL S.R.: *Histologie du Systéme Nerveux de l'Homme et des Vertébrés.* Maloine, Paris, 1909.

CAJAL S.R.: Région de la calotte. In: *Histologie du Systéme Nerveux de l'Homme et des Vertébrés.* Institut Ramon Y Cajal, Madrid, 1955, pp. 252–269.

CARPENTER M.B., HANNA G.R.: Fiber projections from the spinal trigeminal nucleus in the cat. *J. Comp. Neurol.* **117**: 117–125, 1961.

COHEN D., CHAMBERS W.W., SPRAGUE J.M.: Experimental study of the efferent projections from the cerebellar nuclei to the brainstem of the cat. *J. Comp. Neurol.* **109**: 233–257, 1958.

CONRADI S., KELLERTH J.-O., BERTHOLD C.-H.: Electron microscopic studies of serially sectioned cat spinal motoneurons. II. A method for the description of architecture and synaptology of the cell body and proximal dendritic segments. *J. Comp. Neurol.* **184**: 741–753, 1979a.

CONRADI S., KELLERTH J.-O., BERTHOLD C.-H., HAMMARBERG C.: Electron microscopic studies of serially sectioned cat spinal motoneurons. IV. Motoneurons innervating slow-twitch (type S) units of the soleus muscle. *J. Comp. Neurol.* **184**: 769–782, 1979b.

COURVILLE J.: Rubrobulbar fibers to the facial nucleus and the lateral reticular nucleus (nucleus of the lateral funiculus). An experimental study in the cat with silver impregnation methods. *Brain. Res.* **1**: 317–337, 1966.

COURVILLE J., BRODAL A.: Rubro-cerebellar connections in the cat: an experimental study with silver impregnation method. *J. Comp. Neurol.* **126**: 471–485, 1966.

DAVIS K.D., DOSTROVSKY J.O.: Modulatory influences of red nucleus stimulation on the somatosensory responses of cat trigeminal subnucleus oralis neurons. *Exp. Neurol.* **91**: 80–101, 1986.

DONGA R., DUBUC R., KOLTA A., LUND J.P.: Evidence that the masticatory muscles receive a direct innervation from cell group K in the rabbit. *Neuroscience* **49**: 951–961, 1992.

EDWARDS S.B.: The ascending and descending projections of the red nucleus in the cat: an experimental study using an autoradiographic tracing method. *Brain. Res.* **48**: 45–63, 1972.

EISENMAN J., FROMM G., LANDGREN S., NOVIN D.: The ascending projections of trigeminal neurones in the cat, investigated by antidromic stimulation. *Acta. Physiol. Scand.* **60**: 337–350, 1964.

EISENMAN J., LANGREN S., NOVIN D.: Functional organization in the main sensory trigeminal nucleus and in the rostral subdivision of the nucleus of the spinal trigeminal tract in the cat. *Acta. Physiol. Scand.* **59***(Suppl.)* : 1–44, 1963.

FLUMERFELT B.A., OTABE S., COURVILLE J.: Distinct projections to the red nucleus from the dentate and interposed nuclei in the monkey. *Brain. Res.* **50**: 408–414, 1973.

FUKUSHIMA T., KERR F.W.L.: Organization of trigeminothalamic tracts and other thalamic afferent systems of the brainstem in the rat: presence of gelatinosa neurons with thalamic connections. *J. Comp. Neurol.* **183**: 169–184, 1979.

GEE B., WARHOL M.J., ROTH J.: Use of an anti-horseradish peroxidase antibody-gold complex in the ABC technique. *J. Histochem. Cytochem.* **39**: 863–869, 1991.

GEOGHEGAN W.D., ACKERMAN G.A.: Adsorption of horseradish peroxidase, ovomucoid and anti-immunoglobulin to colloidal gold for the indirect detection of concanavalin A, wheat germ agglutinin and goat anti-human immunoglobulin G on cell surfaces at the electron microscopic level. *J. Histochem. Cytochem.* **24**: 1187–1200, 1977.

GUREVICH N.R., BELOZEROVA T.V.: Rubrospinal synaptic influences on the lumbar motor neurons of rat. *Neurofiziologiia* **3**: 266-273, 1971.

HOLMES W.R.: The role of dendritic diameters in maximizing the effectiveness of synaptic inputs. *Brain. Res.* **478**: 127–137, 1989.

HOLSTEGE G.: Anatomical evidence for an ipsilateral pathway and for direct rubrospinal projections to motoneurons in the cat. *Neurosci. Lett.* **74**: 269–274, 1987.

HOLSTEGE G., BLOK B.F., RALSTON D.D.: Anatomical evidence for red nucleus projections to motoneuronal cell groups in the spinal cord of the monkey. *Neurosci. Lett.* **95**: 97–101, 1988.

HOUK J.C., GIBSON A.R., HARVEY C.F., KENNEDY P.R., VAN KAN P.L.E.: Activity of primate magnocellular red nucleus related to hand and finger movements. *Behav. Brain. Res.* **28**: 201–206, 1988.

JACQUIN M.F., RHOADES R.W., ENFIEJIAN H.L., AND EGGER M.D.: Organization and morphology of masticatory neurons in the rat: a retrograde HRP study. *J. Comp. Neurol.* **218**: 239–256, 1983.

KING M.A., LOUIS P.M., HUNTER B.E., WALKER D.W.: Biocytin: a versatile anterograde neuroanatomical tract-tracing alternative. *Brain. Res.* **497**: 361–367, 1989.

LACHICA E.A., MAVITY-HUDSON J.A., CASAGRANDE V.A.: Morphological details of primate axons and dendrites revealed by extracellular injection of biocytin: an economic and reliable alternative to PHA-L. *Brain. Res.* **564**: 1–11, 1991.

MANTLE-ST.JOHN L.A,. TRACEY D.J.: Somatosensory nuclei in the brainstem of the rat: independent projections to the thalamus and cerebellum. *J. Comp. Neurol.* **255**: 259–271, 1987.

MARTIN G.F., DOM R.: Rubrobulbar projections of the opossum (*Didelphis Virginiana*). *J. Comp. Neurol.* **139**: 199–214, 1970.

MENÉTREY D.: Retrograde tracing of neural pathways with a protein-gold complex I. Light microscopic detection after silver intensification. *Histochemistry* **83**: 1–5, 1985.

MILLER R.A., STROMINGER N.L.: Efferent connections of the red nucleus in the brainstem and spinal cord of the rhesus monkey. *J. Comp. Neurol.* **152**: 327–346, 1973.

MIZUNO N.: Projection fibers from the main sensory trigeminal nucleus and the supratrigeminal region. *J. Comp. Neurol.* **139**: 457–471, 1970.

MIZUNO N., NOMURA S., KONISHI M., UEMURA-SUMI M., TAKAHASHI O., YASUI Y., TAKADA M., MATSUSHIMA R.: Localization of motoneurons innervating the tensor tympani muscles: an horsradish peroxidase study in the guinea pig and cat. *Neurosci. Lett.* **31**: 205–208, 1982.

MOGOSEANU D., SMITH A.D., BOLAM J.P.: Monosynaptic innervation of trigeminal motor neurones involved in mastication by neurones of the parvicellular reticular formation. *J. Comp. Neurol.* **336**: 53–65, 1993.

MONG F.S.F., CHEN Y.C., LU C.H.: Dendritic ramifications of trigeminal motor neurons innervating jaw-closing muscles of rats. *J. Neurol. Sci.* **86**: 251–264, 1988.

OLSSON K.A., LANDGREN S.: Primary afferent and descending cortical convergence on the interneurons in the border zone of the trigeminal motor nucleus: a comparison between trigeminal and spinal interneurons. In: *Neurophysiology of the Jaws and Teeth.* A. TAYLOR (ed.), MacMillan Press, London, 1990, pp. 162–191.

PADEL Y.: Les noyaux rouges magnocellulaire et parvocellulaire. Aspects anatomo-fonctionnels de leurs relations avec le cervelet et d'autres centres nerveux. *Rev. Neurol. (Paris)* **149**: 703–715, 1993.

PAXINOS G., WATSON C. *The Rat Brain in Stereotaxic Coordinates.* 2nd ed.. Academic Press, San Diego, 1986.

PESCHANSKI M.: Trigeminal afferents to the diencephalon in the rat. *Neuroscience* **12**: 465–487, 1984.

PETROVICKÝ P.: Rubrobulbare Bahnen. I. Zu den lateralen motorischen Kernen der Hirnnerven bei der Ratte. *J. Hirnforsch.* **16**: 3–14, 1975.

PETROVICKÝ P.: Double-labelled nigral compacta and reticulata cells from injections in the reticular formation and in the striatum. An experimental study using retrograde double labelling with HRP and iron-dextran in the rat. *J. Hirnforsch.* **29**: 243–253, 1988.

PIERCE J.P., MENDELL L.M.: Quantitative ultrastructure of Ia boutons in the ventral horn: scaling and positional relationships. *J. Neurosci.* **13**: 4748–4763, 1993.

PILIAVSKII A.I., LIMANSKY Y.P., GURA E.V.: Monosynaptic excitation of facial motoneurons during electrical stimulation of the red nucleus. *Neurofiziologiia* **4**: 272–279, 1972.

POMPEIANO O., BRODAL A.: Experimental demonstration of a somatotopical origin of rubrospinal fibers in the cat. *J. Comp. Neurol.* **108**: 225–252, 1957.

RALSTON D.D.: Cerebellar terminations in the red nucleus of *Macaca fascicularis*: an electron-microscopic study utilizing the anterograde transport of WGA:HRP. *Somatosens. Motor. Res.* **11**: 101–107, 1994.

RALSTON D.D., MILROY A.M., HOLSTEGE G.: Ultrastructural evidence for direct monosynaptic rubrospinal connections to motoneurons in *Macaca mulatta*. *Neurosci. Lett.* **95**: 102–106, 1988.

ROBINSON F.R., HOUK J.C., GIBSON A.R.: Limb specific connections of the cat magnocellular red nucleus. *J. Comp. Neurol.* **257**: 553–577, 1987.

RUIGROK T.J.H., CELLA F.: Precerebellar nuclei and red nucleus. In: *The Rat Nervous System.* G. PAXINOS (ed.), 2nd ed., Academic Press, San Diego, 1995, pp. 277–308.

SAAD M., DUBUC R., WIDMER C.G., WESTBERG K.G., LUND J.P.: Distribution of subpopulations of efferent neurones innervating compartments of the masseter muscle in rabbit. In: *Alpha and Gamma Motor Systems.* A. TAYLOR, M.H. GLADDEN, R. DURBABA (eds), Plenum Press, New York, 1995, pp. 230–236.

SHAPOVALOV A.I., KARAMJAN O.A., TAMAROVA Z.A., KURCHAVYI G.G.: Cerebello-rubrospinal effects on hindlimb motorneurons in the monkey. *Brain. Res.* **47**: 49–59, 1972.

STEFFENS H., PADEL Y.: Rubrospinal neurones of the cat responding to noxious skin stimulation. *Eur. J. Neurosci.* **4**: 34 1991.

TEN DONKELAAR H.J.: Evolution of the red nucleus and rubrospinal tract. *Behav. Brain. Res.* **28**: 9–20, 1988.

TEUNE T.M., VAN DER BURG J., RUIGROK T.J.H.: Cerebellar projections to the red nucleus and inferior olive originate from separate populations of neurons in the rat: a non-fluorescent double labelling study. *Brain. Res.* **673**: 313–319, 1995.

TRAVERS J.B., NORGREN R.: Afferent projections to the oral motor nuclei in the rat. *J. Comp. Neurol.* **220**: 280–298, 1983.

VINAY L., PADEL Y.: Spatio-temporal organization of the somaesthetic projections in the red nucleus transmitted through the spino-rubral pathway in the cat. *Exp. Brain. Res.* **79**: 412–426, 1990.

WILD J.M.: Direct and indirect "cortico"-rubral and rubro-cerebellar cortical projections in the pigeon. *J. Comp. Neurol.* **326**: 623–636, 1992.

YASUI Y.: Descending pathways of the basal ganglia to the orofacial premotor neuron pools. In: *Brain and Oral Functions.* T. MORIMOTO, T. MATSUYA, K. TAKADA (eds), Elsevier, Amsterdam, 1995, pp. 77–85.

YASUI Y., KAYAHARA T., SHIROYAMA T., NAKANO K.: Neurons in the intertrigeminal region of the rat send projection fibers to the superior colliculus. *Neurosci. Lett.* **159**: 39–42, 1993.

YASUI Y., TSUMORI T., ANDO A., DOMOTO T.: A nigro-rubro-bulbar pathway to the parvicelllular reticular formation in the rat. *Neuroreport* **7**: 1157–116, 1996.

YASUI Y., TSUMORI T., ONO K., KISHI T.: Nigral axon terminals are in contact with parvicellular reticular neurons which project to the motor trigeminal nucleus in the rat. *Brain. Res.* **775**: 219–224, 1997.

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