Collagen-tailed asymmetric acetylcholinesterase (AChE) forms are believed to be anchored to the synaptic basal lamina via electrostatic interactions involving proteoglycans. However, it was recently found that in avian and rat muscles, high ionic strength or polyanionic buffers could not detach AChE from cell-surface clusters and that these buffers solubilized intracellular non-junctional asymmetric AChE rather than synaptic forms of the enzyme. In the present study, asymmetric AChE forms were specifically solubilized by ionic buffers from synaptic basal lamina-enriched fractions, largely devoid of intracellular material, obtained from the electric organ of Torpedo californica and the end plate regions of rat diaphragm muscle. Furthermore, foci of AChE activity were seen to diminish in size, number, and staining intensity when the rat synaptic basal lamina-enriched preparations were treated with the extraction buffers. In the case of Torpedo, almost all the AChE activity was removed from the pure basal lamina sheets. We therefore conclude that a major portion of extracellular collagen-tailed AChE is extractable from rat and Torpedo synaptic basal lamina by high ionic strength and heparin buffers, although some non-extractable AChE activity remains associated with the junctional regions.

The enzyme acetylcholinesterase (AChE) plays a key role in cholinergic neurotransmission (1). Its predominant form at the neuromuscular junction is the collagen-tailed asymmetric form, A12, which is located on the extracellular surface positioned for the hydrolysis of acetylcholine. Most of this junctional AChE is associated with the basal lamina (BL), located between the nerve ending and the muscle plasma membrane (2, 3), and can be removed from the cell surface of muscle tissue (4, 5) and mouse myotubes (6) by treatment with collagenase, indicating that the collagenic tail of the enzyme is involved in its anchorage to the BL (7, 8). Although the precise mechanisms by which asymmetric AChE forms are anchored to the BL remain elusive (9), there is compelling evidence to suggest that heparan sulfate proteoglycans (HSPGs) or related proteoglycans are involved (7, 10). This evidence includes the recent finding that A12 has two heparin-binding consensus sequences in its collagenic tail (11). Asymmetric AChE forms have a high binding affinity for BL components, particularly HSPGs (12) which are themselves major constituents of basement membranes (13, 14). Heparin and heparan sulfate have also been shown to release asymmetric AChE activity from rat muscle end plate regions (15) and BL sheets purified from the electric organ of Discogyrus (16). The demonstration that A12 could bind and be selectively eluted from heparin-agarose columns, whereas non-collagenous forms and A12 after collagenase treatment could not, proved the direct interaction of A12 with heparin in vitro (11, 17). Direct interactions with heparin/heparan sulfate moieties in vivo have also been demonstrated. Asymmetric AChE forms were shown to bind the surface of HSPG-rich cells, such as mouse myotubes and CHO-K1 cells, in a saturable and time-dependent manner, whereas pretreatment of these cells with heparitinase almost abolished this binding. In addition, the binding of A12 AChE was reduced by 80% in Chinese hamster ovary clone 606, a mutant expressing undersulfated HSPGs (10). Similarly, purified BL sheets from electric organ were found to release only asymmetric AChE forms when treated with heparitinase but not chondroitinase ABC (16). Finally, the assumption that HSPGs were likely involved in the intracellular assembly, transport, and cell surface deposition of asymmetric AChE is supported by the finding that a mutant variant of rat PC12 neuronal cells lacking HSPGs expressed a predominantly internal distribution of asymmetric AChE in contrast to normal PC12 cells in which almost all asymmetric AChE was extracellular (18, 19).

Despite the overwhelming evidence supporting the notion that asymmetric AChE forms are associated with the BL through electrostatic bonds, it was recently suggested that the enzyme displaced by high ionic strength and heparin buffers was in fact non-junctional and originated in intracellular compartments (20, 21). In quail muscle fibers and myotube cultures, these ionic buffers did not disaggregate previously formed surface AChE clusters, as detected by immunofluorescence techniques; however, the presence of heparin impeded their formation. Hence the authors formulated the hypothesis that only the newly secreted pool of asymmetric AChE was capable of binding heparin, as a transient event prior to its permanent, covalent association with the BL (21).

Our aims were to study the solubilization properties of junctional AChE first by quantifying the extraction capacity of high salt- and heparin-containing buffers, and second by evaluating the effect of these buffers on the AChE activity associated with BL-enriched preparations derived from rat muscle end plate regions and Torpedo californica electric organ. Our results

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1 The abbreviations used are: AChE, acetylcholinesterase; BL, basal lamina; HSPG, heparan sulfate proteoglycan; LDH, lactate dehydrogenase; iso-OMPA, tetraisopropyl pyrophosphoramide.
strongly suggest that both high salt and heparin buffers solubilize a major portion of extracellular-collagen-tailed AChE and demonstrate the capacity of these buffers to dissolve AChE-rich regions from neuromuscular junctions, as detected by histochemical staining.

EXPERIMENTAL PROCEDURES

Preparation of BL-enriched Fractions—The tissues used were frozen samples of *T. californica* electric organ, obtained from Pacific Bio-Marine (Venice, CA), and end plate regions of rat diaphragm muscle. The latter were obtained from anesthetized female Sprague-Dawley rats (250–250 g) by removing the diaphragm muscles together with the surrounding ribs and dissecting 2-mm strips of end plate region (1 mm on either side of the phrenic nerve) (2, 15). The end plate strips were maintained in ice-cold saline solution (0.9% NaCl). The tissues were then homogenized for 5 min using a glass-to-glass homogenizer at full speed, in 1:10 (w/v) detergent buffer: 10 mM Tris-HCl, pH 7.4, 1% Triton X-100, and protease inhibitors (1 mM N-ethylmaleimide, 1 mM benzamidine, 0.1 mg/ml bacitracin, 100 mM caproic acid, 5 mM EDTA) (22). The homogenates were centrifuged at 15,000 rpm for 25 min in a fixed rotor using a Kubota KR-20000T centrifuge. The supernatants were then removed and assayed for activity, and the pellets were resuspended and rehomogenized as above. This wash cycle was repeated a total of four times, recovering the majority of AChE globular forms and yields a fibrous BL-enriched preparation for both rat muscle end plate tissue and *Torpedo* electric organ (23, 24). All procedures were carried out at 4 °C. Aliquots were taken from the initial tissue homogenates for activity assays and from the BL-enriched preparations for activity and histochemical analyses.

Quantifying Residual Intracellular Material in the BL-enriched Preparations—Lactic dehydrogenase (LDH) was used as a quantitative marker for intracellular contamination of the BL-enriched preparations, before and after undergoing extractions. LDH activity was measured using the Promega kit according to the manufacturer’s instructions, and the percentage of remnant activity was calculated from the activity measured in the initial tissue homogenates (100%). Sialidase transferase activity, a marker of the Golgi apparatus (25), was used in some experiments to assess the presence of Golgi vesicles, and therefore intracellular contaminants, in our BL fractions.

Solubilization of Asymmetric AChE Activity from the BL.—The BL-enriched preparations were divided into 3 groups, and duplicate samples for each group were homogenized for 5 min in 1:10 (w/v) of one of the following buffers: control buffer, 10 mM Tris-HCl, pH 7.4, containing several protease inhibitors (as above); heparin extraction buffer, 1 mg/ml heparin in control buffer; or high salt extraction buffer, 1M NaCl in control buffer. The homogenates were then centrifuged at 15,000 rpm for 25 min and the supernatants removed, and the extraction procedure was repeated. All procedures were carried out at 4 °C. Aliquots were taken from the extraction supernatants for activity assays and sedimentation analyses. The post-extraction pellets were kept at 4 °C for subsequent histochemical studies and collagenase digestion.

Perfusion of Asymmetric AChE Activity from Rat Diaphragm Muscle Strips—Adult rat diaphragm muscle was dissected and cut into thin strips, pinned, and perfused for 1 h with high salt borate extraction buffer, in the presence or absence of heparin, as described by Rossi and Rotundo (20). After washing with phosphate-buffered saline, the muscle fibers were incubated with the histochemical reaction buffer of Karnovsky and Roots (26). In addition, the AChE activity released by these buffers was assayed in parallel experiments.

Sedimentation Analysis of AChE Forms—The molecular forms of AChE present in the tissue homogenates and BL-enriched fractions, and those solubilized from the latter, were resolved by sedimentation analysis on 5–20% linear sucrose gradients, as described previously (6, 27). To release all the molecular forms present in the homogenate samples, initial homogenates and BL preparations were homogenized in detergent buffer containing 1 mM NaCl for the purpose of sedimentation analysis.

AChE Activity Assay—AChE activity was measured by the method of Ellman et al. (28). All incubations were carried out at 37 °C for rat muscle samples and 25 °C for *Torpedo* electric organ, in a 1-mL mixture containing 100 mM sodium phosphate buffer, pH 7.0, 0.5 mM dithionitrobenzoic acid, and 0.75 mM acetylthiocholine iodide. 10 mM tetraisopropyl pyrophosphoramide (iso-OMPA) was also included as a specific inhibitor of butyrylcholinesterase activity. Absorbance was read at 412 nm in a Shimadzu UV-150–02 double-beam spectrophotometer.

Collagenase Digestion of the BL Preparations following Tonic Extractions—Collagenase digestions were carried out as described by Younkin et al. (29), to quantitatively determine the AChE activity extracted from the BL preparations as a function of the total AChE present. In short, the BL pellets were incubated following either control, high salt, or heparin extractions, at 25 °C for 4 h with 0.1 mg/ml collagenase (Sigma, type V) in 1:10 (w/v) of a buffer containing 20 mM Tris-HCl, pH 7.4, 0.5 mM N-ethylmaleimide, 2 mM Tris-EDTA. The reaction was stopped when the samples were centrifuged, and the supernatants were finally assayed for AChE activity.

Preparation of Rat End Plate Muscle Honeycomb Ghosts—Rat muscle end plate honeycomb ghost preparations were obtained using a method similar to that of Sannes and Hall (23), omitting the salt extraction step. End plates were washed before processing and were maintained in ice-cold saline solution (0.9% NaCl) before being thinly cut into transverse sections and washed twice for 1 h with detergent buffer as follows: 10 mM Tris-HCl, pH 7.4, 1% Triton X-100, and protease inhibitors. The end plate strips were then divided into three groups and incubated overnight at 4 °C with 1:25 (w/v) of detergent buffer alone, detergent buffer containing 1 mM NaCl, or detergent buffer plus 1 mg/ml heparin. The resultant honeycomb ghosts were then analyzed for residual AChE activity by histochemical staining, and solubilized AChE activity was also assayed in the preparation buffers.

Visualization of Surface End Plate AChE Activity by Histochemical Staining—AChE activity was detected by histochemical staining in the BL-enriched fractions of both rat muscle end plates and *Torpedo* electric organ, by using the semiautomated rat muscle plates and in the rat muscle end plate honeycomb ghost preparations, before and after their particular extractions. For this, the method of Karnovsky and Roots (26) was employed, using 2.2 mg/ml acetylthiocholine iodide, 0.71 mM malate buffer, pH 6.0, 0.1 mM sodium citrate, 30 mM copper sulfate, 5 mM potassium ferricyanide, and 3% neutral formal. All incubations were carried out at 4 °C, and all samples were processed simultaneously to make their staining intensities comparable. In the case of the BL-enriched preparations, samples weighed ~3 mg. For the honeycomb ghosts, multiple section samples were stained for each group. All samples were incubated for 20 min with iso-OMPA (10 mM), prior to the histochemical reaction, to inhibit butyrylcholinesterase activity. Control samples were incubated with 10 mM iso-OMPA plus either 50 mM sodium fluoride, 10 μM BW 286c54 to inhibit cholinesterase activity or specifically AChE activity, respectively. Samples were then viewed under the phase-contrast light microscope.

Purification of Asymmetric AChE from Torpedo Electric Organ—Affinity chromatography using an acridine-agarose column was used to purify the collagen-tailed form of AChE, as described previously (30). Both specific activity (4,000 units/mg protein) and staining intensities following polyacrylamide gel electrophoresis (a single band of 67 kDa) were used to verify purity. Sucrose sedimentation analysis was subsequently used to confirm that the purified protein corresponded to the asymmetric A12 form of AChE.

Association of Torpedo AChE with Rat Myotubes—Rat muscle primary cultures were prepared from the hindlimb muscles of an 18-day-old rat embryo and were maintained as described by Koenig (31). Approximately 5 × 105 cells were plated onto 35-mm plastic tissue culture dishes coated with gelatin. The myoblasts reached confluence 24 h after plating, and the onset of fusion and large myotube formation began at 48 h. Most of the myotubes presented spontaneous contractile activity around the 5th day in culture. The medium was then removed, and the myotubes were washed three times with Dulbecco’s modified Eagle’s medium containing 0.1 mM NaCl and 0.5 mg/ml bovine serum albumin. The myotubes were then incubated for 1 h at 4 °C with 50 milliliters of AChE enzyme, purified from *Torpedo* electric organ, in the presence or absence of 1 mg/ml heparin. The cells were then washed twice with 2.5 Dulbecco’s modified Eagle’s medium/phosphate-buffered saline and incubated for 15 min at 4 °C with phosphate-buffered saline buffer containing 2 mg/ml bovine serum albumin and 2 mg/ml heparin. The cell surface-associated AChE activity solubilized by this medium was then assayed. For the determination of total cell surface-bound AChE, an additional incubation with the same medium containing 1 mM NaCl instead of heparin was performed.

RESULTS

Asymmetric AChE Is Associated with BL-enriched Preparations—Since it was recently reported that neither high salt- nor heparin-containing buffers detached asymmetric collagen-tailed forms of AChE from the BL of the vertebrate neuromuscular junction (20, 21), we wanted to re-evaluate the solubilization properties of the asymmetric forms present in BL-enriched preparations, derived from both diaphragm muscle...
Attachment of Asymmetric AChE to the Synaptic BL

Molecular forms of AChE solubilized from the end plate regions of rat diaphragm muscle and from Torpedo electric organ. A corresponds to rat muscle end plates, and B corresponds to the Torpedo electric organ, in which ● represents the initial tissue homogenate and ○ represents the BL-enriched fraction. For the purpose of sedimentation analysis, fresh (rat) or frozen (Torpedo) tissue samples were homogenized in a high salt detergent buffer (1:10, w/v) as follows: 10 mM Tris-HCl, pH 7.4, 1 M NaCl, 1% Triton X-100, and protease inhibitors. By having submitted the rest of the tissue to 5 homogenization-centrifugation cycles with detergent buffer (10 mM Tris-HCl, pH 7.4, 1% Triton X-100, protease inhibitors) to remove the majority of globular forms, the resultant BL-enriched fractions were also solubilized in high salt detergent buffer for sucrose sedimentation analysis. The arrow indicates migration of the catalase marker at 11.3 S.

Remnant Cytoplasmic Material in the BL-enriched Preparations—To discard the possibility that intracellular asymmetric AChE, destined to be exported to the BL, may be contaminating our BL fractions (despite exhaustive washes with detergent buffer), we analyzed such preparations for the presence of two intracellular markers. First, LDH activity was used as an indicator of remnant-soluble cytoplasmic material. After repeated Triton X-100 extractions, some residual LDH activity (~6% of the total) was detectable in the final rat muscle end plate BL-enriched preparation (Fig. 3). Furthermore, two subsequent extraction steps with either high salt or heparin solubilized half of this remnant activity (see inset of Fig. 3), indicating that a residual intracellular material was probably trapped within or retained electrostatically by the BL sheets. Similar results were obtained for Torpedo electric organ preparations. These results indicate that asymmetric AChE is not trapped in vesicles as a soluble entity. Second, the absence of sialyltransferase activity, a Golgi marker, in both the rat and Torpedo BL-enriched preparations (data not shown), makes it unlikely that intracellular asymmetric AChE remained associated, as a contaminant, to the BL fractions used in these studies.

High Salt- and Heparin-containing Buffers Solubilized Extracellular Asymmetric AChE from the BL Preparations of Rat Muscle End Plates and Torpedo Electric Organ, and from Rat Muscle Honeycomb Ghost Preparations, but Not from Perfused Rat Muscle Strips—Having identified the source of collagen-tailed AChE as predominantly BL, a study of the solubilization properties of these forms was carried out at short extraction times. First, samples of purified BL material were submitted to two 5-min homogenization-centrifugation cycles with either high salt- or heparin-containing buffers. Both AChE activity and the molecular forms solubilized were then determined. As Fig. 4 shows, only asymmetric forms of AChE were released by either high salt or heparin from both rat (Fig. 4A) and Torpedo (Fig. 4B) BL preparations. Additional experiments were carried out using sectioned rat muscle end plates treated with detergent so as to generate honeycomb ghost preparations (23) with structurally integral junctional regions. The AChE activity released by the high salt- or heparin-containing buffers used for the ghost preparation was assayed; heparin was able to solubilize 50% of that released by NaCl (data not shown).
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AChE in rat end plate regions accounted for 23% of the total

tions indicated that the non-extractable pool of asymmetric
extractions. First, collagenase digestion after high salt extrac-
rich regions could be detected following high salt or heparin
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of BL-associated AChE activity and ascertain whether a
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muscles (20, 21). Therefore in the present study, we sought to
clusters in quail myotube cells or end plate regions of avian
unable to disrupt or diminish the number of cell-surface AChE
fraction (29, 32). However, a recent report suggested that all
lar, of which only 15–25% is considered to be a non-extractable
muscles, most of the asymmetric AChE activity is extracellu-
 situación.

Similarly, in rat muscle end plate BL, heparin extracted ap-
proximately 40% of the activity solubilized by high salt, as
shown in Fig. 5A, whereas in Torpedo electric organ, both
buffers solubilized similar quantities (80–90%) of asymmetric
AChE (Fig. 5B). The total fraction of asymmetric AChE solu-
ibilized by heparin was much greater in Torpedo electric organ
than in rat muscle end plate regions (80% compared with 30%)
(Table I), suggesting that a larger population of heparin-ex-
tractable asymmetric AChE exists in the former. When high
salt and heparin-containing buffers were used to perfuse rat
diaphragm muscle strips for 1 h, no AChE activity was detect-
able in the activity assays carried out on these buffers (data not
shown).

A Minor Portion of Junctional AChE Persists in the BL-
enriched Preparations following Extractions with High Salt- or
Heparin-containing Buffers—A population of collagen-tailed
AChE associated with the BL persists for long periods after
frog muscle denervation (3). In rat diaphragm and gracili
muscles, most of the asymmetric AChE activity is extracellu-
lar, of which only 15–25% is considered to be a non-extractable
fraction (29, 32). However, a recent report suggested that all
junctional asymmetric AChE formed part of this non-extract-
able pool, given that high salt and heparin buffers seemed
unable to disrupt or diminish the number of cell-surface AChE
clusters in quail myotube cells or end plate regions of avian
muscles (20, 21). Therefore in the present study, we sought to
quantify the extractable as well as the non-extractable fraction
of BL-associated AChE activity and ascertain whether a
change in the quantity and distribution in extracellular AChE-
rich regions could be detected following high salt or heparin
extractions. First, collagenase digestion after high salt extrac-
tions indicated that the non-extractable pool of asymmetric
AChE in rat end plate regions accounted for 23% of the total
BL-associated asymmetric AChE (Fig. 5A, see also Table I), in
agreement with Younkin et al. (29). Moreover, in Torpedo elec-
tric organ, a minor portion of junctional AChE remained after
high salt or heparin extractions, accounting for 9% of non-
extractable enzyme (Fig. 5B).

Second, AChE activity was visualized by histochemical
staining before and after extractions on the BL-enriched frac-
tions obtained from rat and Torpedo tissues. In the former, the
morphological appearance, size, and organization of the histo-
chemically stained structures seen in Fig. 6 revealed the pre-
\[ένωση] of numerous isolated and well preserved motor end plates
with their synaptic gutters. These neuromuscular junctions,
rich in AChE activity, were also clearly visible in the rat muscle
BL fractions prior to high salt and heparin extractions (Fig.
7A). Following high salt treatment, most of the activity in these
end plates disappeared (Fig. 7B). Heparin extractions also pro-
duced a reduction in the size and staining intensities of the end
plates detected (Fig. 7C). Control experiments in the presence
of inhibitors specific for AChE did not show end plate hydro-
lytic activity (Fig. 7D). Histochemistry carried out on the BL
sheets purified from Torpedo electric organ demonstrated that
these samples contained isolated surfaces highly enriched in
AChE activity (Fig. 8A). On the other hand, the same prepa-
rations treated with either high salt (Fig. 8B) or heparin (Fig.
8C) showed only minimal residual AChE activity in both cases.
Controls treated with AChE inhibitors showed no activity (Fig.
8D). In the experiments using rat muscle end plate honeycomb
ghost preparations, histochemical staining of AChE revealed

![Fig. 3. A small portion of cytoplasmic material remained associated with the extracellular matrix fractions.](image3)

![Fig. 4. Solubilization of the molecular forms of AChE from the rat and Torpedo BL-enriched fractions.](image4)
an array of end plate regions in these muscle ghosts (Fig. 9A). However, when these samples were prepared in the presence of high salt, most of the AChE activity was removed from the end plate ghosts (Fig. 9B), whereas less activity was removed when heparin was present. Almost no AChE activity was visible in control samples incubated with 20 μm BW284c51 and 10 mM iso-OMPA (Fig. 9C). In contrast, when rat diaphragm muscle strips were perfused with a mixture of high salt and heparin buffers, no variation in AChE histochemical staining intensity was seen between the control and treated samples (data not shown). Together, these results clearly show that most of the junctional AChE is readily detached by either high salt or heparin from rat or *Torpedo* BL preparations as well as muscle end plate ghosts, which retain the basic cytoskeletal architecture of the muscle, but not from semi-intact rat muscle strips.

Association of *Torpedo* AChE to Rat Primary Culture Myotubes—Despite the fact that rat muscle and *Torpedo* electric organ are phylogenetically distant, the anchorage mechanisms of the collagen-tailed enzyme may not be fundamentally different in both systems. To determine the extent to which AChE association in these systems was compatible, a study of the binding properties of asymmetric AChE, purified from *Torpedo*, was carried out using rat primary muscle cultures. Fig. 10 shows that *Torpedo* AChE was capable of associating with rat myotubes in a reversible manner, as demonstrated by its subsequent detachment from the cell surface using a heparin-containing buffer. Of the total AChE activity associated (3.65 milliunits/ml), heparin was able to release approximately 70% (2.6 milliunits/ml). However, incubation with AChE in the presence of heparin eliminated the capacity of the enzyme to bind to the myotube cell surface. When fibroblasts were used instead of myotubes, no association was observed with or without heparin co-incubation (Fig. 10). These results suggest that specific AChE-binding sites are present on the cell surface of...
rat myotubes which are absent in fibroblasts. Moreover, such sites are also recognized by *Torpedo* asymmetric AChE, implying that the anchorage of the collagen-tailed form of AChE involves either similar extracellular molecules or similar interaction mechanisms in both species. Whether or not this association occurs in clusters over the myotube surface is a matter that deserves further study.

**DISCUSSION**

Prevailing opinion indicates that the collagen-tailed forms of AChE are anchored to the synaptic BL through electrostatic interactions with polyanionic components such as HSPGs (9, 10). This widely accepted hypothesis was later reinforced by the identification of two heparin-binding domains in the collagenous tail of the enzyme (11, 33). The objective of the present study was to determine directly whether the AChE molecules localized at the neuromuscular junction were quantitatively removed by high salt and heparin extractions, in view of the results of Rossi and Rotundo (20) in which perfusions with these buffers were unable to detach clustered cell-surface AChE from quail and rat muscle fibers. Furthermore, these authors suggested that the ability of heparin to solubilize asymmetric AChE, as reported for other systems, stemmed from its apparent ability to release mainly intracellular and non-junctional AChE molecules (20, 21). However, our biochemical and histochemical results demonstrate that these conventional ionic buffers do in fact specifically detach a major portion of asymmetric AChE from purified synaptic BL devoid of intracellular material and derived from two of the most studied neuromuscular junction systems, rat muscle end plates and *Torpedo* electric organ.

In view of this apparent discrepancy, we wanted first to confirm the extracellular source of asymmetric AChE prior to its extraction. Asymmetric AChE occupies less than 0.1% of the total surface area of the BL at the rat neuromuscular synapse, yet its density increases severalfold specifically at junctional regions (34). In contrast, the electric organ of *Torpedo* is a tissue in which the synaptic junctions are overdeveloped (35, 36). Therefore, the use of both these tissues in the present study minimized the possibility that extra-junctional asymmetric AChE was being solubilized during the extractions. Furthermore, several end plates rich in junctional AChE were observed in the rat and *Torpedo* BL-enriched preparations prior to extraction. Treatment with high salt or heparin buffers reduced both the number, size, and staining intensities of these regions. The studies of Rossi and Rotundo (21) nevertheless demonstrated that neither high salt- nor heparin-containing buffers were able to reduce the number of immunoreactive AChE clusters on the surface of quail myotubes or quail muscle...
fibers. Yet by incubating the myotubes in the presence of heparin, newly synthesized asymmetric AChE accumulated in the medium and not as cell-surface clusters. The authors concluded that only a transient cell-surface interaction occurred in avian cell cultures between newly formed asymmetric AChE and heparin or HSPGs. However, in the present study, the use of purified BL, as seen under the electron microscope, eliminated the possibility that newly synthesized asymmetric AChE and its subsequent externalization to the cell surface could account for the enzyme detached during the extraction processes.

It should also be noted that in quail skeletal muscle only 40% of total asymmetric AChE is BL-associated, with the remainder being intracellular (37). Therefore, the subcellular localization of collagen-tailed AChE in avian muscle differs from most of the other systems studied, as virtually all findings agree that the majority of asymmetric AChE is extracellular. For instance, studies performed in rat diaphragm muscle in vivo showed that 22% of asymmetric AChE forms were intracellular in rat diaphragm end plate regions (29), 30% in rat gracilis muscle (32), and 20% in mouse C2 myotubes (38). Moreover, there is further evidence to support the notion that AChE attachment in the avian system may be unusual. For instance, chondroitinase ABC or AC was found to detach asymmetric AChE from chicken muscle (39) but not from mouse C2 myotube cultures or from Discopyge electric organ, in which only heparitinase released the enzyme (10, 16).

Altogether, the above evidence clearly indicates that differences in species' extractability of asymmetric AChE, extracellular to intracellular ratios and anchorage mechanisms, are likely to account for some of the differences obtained in the present study and the work of Rossi and Rotundo (20, 21). However, there is also a fundamental difference in the sample preparation and extraction methods used, subcellular fractionation versus intact muscle fibers and homogenization versus perfusion. This difference could explain the apparent controversy of different results obtained in the present study and the work of Rossi and Rotundo (20, 21). However, there is also a fundamental difference in the sample preparation and extraction methods used, subcellular fractionation versus intact muscle fibers and homogenization versus perfusion. This difference could explain the apparent controversy of different results obtained in the present study and the work of Rossi and Rotundo (20, 21).

FIG. 9. High salt treatment of honeycomb ghosts derived from rat muscle end plate regions released an important portion of junctional AChE activity. Honeycomb ghosts were prepared from sectioned rat muscle end plates by incubating the sections with detergent buffer overnight, either in the presence or absence of 1 M NaCl. Remnant end plate AChE activity was then stained histochemically and viewed by phase-contrast light microscopy. A, AChE activity was visible as large, densely stained end plate regions in the ghost preparations (control). B, honeycomb ghosts prepared in the presence of high salt, to extract asymmetric AChE, contained only small dispersed foci of histochemical activity, which displayed lower staining intensities than their control counterparts. C, no AChE activity was detected in honeycomb ghosts incubated with 20 μM BW284c51 dibromide and 10 mM iso-OMPA. (Magnification, ×400.)

FIG. 10. Association of purified Torpedo asymmetric AChE with rat myotubes. Fifty milliunits of asymmetric AChE, purified from Torpedo electric organ, were incubated for 15 min with 5-day-old rat myotubes in 35-mm culture dishes, in the presence or absence of 2 mg/ml heparin. Fibroblasts obtained from the same muscle primary cultures were used as controls and submitted to the same treatments. Cell surface-associated AChE was then released by incubating the cells with 2 mg/ml heparin buffer, and the activity solubilized was determined for cells incubated with AChE in the presence or absence of heparin (labeled as Heparin co-incubation and Heparin extractable, respectively). Total cell surface-associated AChE (Total extractable) was the total amount of activity solubilized from the myotubes by 2 mg/ml heparin followed by 1 M NaCl buffer. Asymmetric AChE associated only with rat myotubes, in a manner that was inhibited by heparin. No significant association of asymmetric AChE was detected in fibroblasts. Values represent the average of three experiments done in duplicate.
purified synaptic BL, we successfully solubilized asymmetric AChE but were unable to do so in muscle strips, we believe that perfusion of a semi-intact muscle sample is not the most appropriate method for the extraction of synaptic molecules such as AChE.

A non-extractable population of asymmetric AChE has been identified previously, which can only be released by collagenase treatment (29, 32). This non-extractable pool of AChE, in rat diaphragm end plates, accounts for 21% of the total asymmetric forms which in these regions exist principally as extracellular enzyme (29). However, the ultrastructure of this tissue may present a greater resistance to the extraction procedure than that of Torpedo electric organ, as in the latter there seems to be a larger pool of heparin-sensitive collagen-tailed AChE. Although some asymmetric AChE seems to be covalently associated with the synaptic BL, the majority of the extracellular enzyme is extractable using high salt- and heparin-containing buffers, indicating that electrostatic interactions must be involved in its anchorage at the neuromuscular junction.

The cell surface AChE binding studies, carried out using Torpedo enzyme and rodent muscle cultures, proved to be effective heterologous systems for such studies. Indeed, Rotundo et al. (40) recently carried out transplant experiments, in which frog neuromuscular synapses were incubated with purified quail asymmetric AChE, and binding was observed. These authors even suggest the presence of specific collagen-tailed AChE-binding sites at the synaptic BL of the vertebrate neuromuscular junction. In our case, the localization of the AChE bound to the myotube surface was not investigated. However, bound AChE would most likely appear as clustered foci of activity but would nonetheless present a “non-junctional” distribution due to the absence of neuronal stimuli. Therefore, the formation of AChE clusters in myotube cell cultures does not imply the presence of “junctional” AChE (as in Torpedo electric organ and muscle end plates), which is defined by the existence of the neuromuscular junction and requires the presence of motor neurons. For this reason, we suggest caution in the use of the term junctional when referring to the clustering of AChE on the surface of cultured myotubes. The fact that heparin could be used to release the asymmetric AChE bound to the myotube surface or block its association in our in vitro studies suggests first that HSPGs are involved in the binding of the Torpedo enzyme to the rodent muscle cells, and second that these proteoglycans may be universally recognized in such anchorage mechanisms. These possibilities are reinforced by the finding that HSPGs are indeed present in the extracellular matrix of rodent myotubes (41, 42), and it would be interesting to study the focalization of AChE exogenously added to myotube cultures, both in the presence and absence of motor neurons.

In conclusion, we have established that a major portion of junctional collagen-tailed AChE is in fact associated with the BL through electrostatic interactions. Extracellular asymmetric AChE foci can be disrupted by high salt- or heparin-containing buffers. These results are entirely consistent with previous work regarding the anchorage mechanism(s) of collagen-tailed AChE to the BL (10, 16) and with the current notion that HSPGs may interact with the heparin-binding domains present in the collagenic tail of the enzyme (11). Further studies using synthetic peptides, derived from the collagenic region, as well as molecular modeling and docking, should help us to elucidate the exact mechanisms involved in the anchorage of asymmetric AChE to the BL at the neuromuscular junction.

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