

Isolation and Characterization of Two Polypeptides That Form Intermediate Filaments in Bovine Esophageal Epithelium

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ABSTRACT Cells in the stratified squamous epithelium of bovine esophagus contain abundant tonofilaments measuring 6–10 nm in diameter. Two polypeptides, extracted from esophageal epithelium with 0.05 M Tris, pH 7.4, containing 8 M urea and 25 mM β -mercaptoethanol, comprise 35% of the total extractable protein. These polypeptides have apparent molecular weights of 46,000 and 56,000 daltons and are rich in glutamic acid-glutamine, glycine, and serine. Each polypeptide can be partially purified by DEAE-cellulose chromatography. Mixtures of the purified polypeptides form filaments *in vitro* that measured 6–10 nm in diameter. Neither polypeptide formed filaments by itself. Filaments formed *in vitro* give an α -keratin type x-ray diffraction pattern. These data indicate that the tonofilaments in esophageal epithelium are formed primarily from these two polypeptides.

Intermediate filaments are an abundant and characteristic cytoplasmic component of cells in stratified squamous epithelia. They are often referred to as tonofilaments and are morphologically similar in different epithelia: they are 6–10 nm in diameter, they form undulating, unbranched curves in the cytoplasm, their length is often several hundred times their diameter, they often terminate in desmosomes, and they have a tendency to form parallel arrays.

Proteins that form the tonofilaments in cutaneous epithelia have been isolated from calf snout (8, 12, 16, 17), hoof epidermis (18), human epidermis (21), and rat epidermis (2, 23). A large fraction of the extractable protein in such epithelia (as much as 60% in stratum corneum of epidermis) consists of families of polypeptides that can form filaments *in vitro*. The filaments formed *in vitro* are morphologically similar to the tonofilaments seen in the intact tissue (12, 16, 18, 21, 23). Each filament-forming polypeptide (FFP) within a given tissue appears to be the product of a separate gene (6); no one is a product or precursor of any of the others (11). Some FFP's found in different cutaneous epithelia, such as in bovine hoof and snout, are identical but other FFP's in these epithelia appear to be tissue-specific (9, 10).

The purpose of this study is to identify the major FFP's in a noncutaneous, stratified squamous epithelium. Several recent immunofluorescence microscopy studies have demonstrated that tonofilaments in noncutaneous epithelia are immunologically related to the tonofilaments in cutaneous epithelia

(5, 22). The morphologic and immunochemical similarities of tonofilaments in different epithelia suggest that the proteins that form tonofilaments in noncutaneous epithelia might be the same as those that form tonofilaments in cutaneous epithelia. This report describes the isolation and characterization of the two major FFP's from the epithelium of calf esophagus. Biochemical comparison of these FFP's with the well characterized FFP's from calf hoof is the subject of a separate report (13).

MATERIALS AND METHODS

Tissue Preparation

Segments of esophagus, extending from the level of the thyroid gland to 3 cm above the stomach (rumen), were obtained from freshly slaughtered calves. The surrounding musculature was trimmed away and the epithelium was separated from underlying connective tissue by heating to 56°C for 30 s in water.

Light Microscopy

Transverse sections of esophagus, 0.3 \times 1.0 cm, were fixed overnight in buffered 10% formalin and embedded in paraffin. 5- μ m sections were stained with hematoxylin and eosin and photographed with Panatomic-X through a green filter.

Electron Microscopy

1 \times 2-mm pieces of esophagus, from which the musculature had been removed, were placed in half-strength Karnovsky's fixative (7) for 2 h at 4°C, washed with

acetate-veronal buffer, postfixed with 1% buffered osmium tetroxide, washed, stained in block with uranyl acetate, rapidly dehydrated, and embedded in Epon (4). Silver sections of tissue were placed on carbonized, formvar-coated copper grids, stained with uranyl acetate and lead citrate (24), and examined at 80 keV in a Siemens 101 electron microscope.

Negative Staining of Filaments and Tissue Extraction

Suspensions of filaments were spread on carbon-coated mica chips, transferred to carbon-coated holey grids, and stained with 1% uranyl acetate.

Heat-separated, esophageal epithelium was homogenized for 1 min in a ground-glass homogenizer in 25 vol of 0.05 M Tris, pH 7.4, and centrifuged for 10 min at 20,000 g at 4°C. The supernate (the low-salt extract) was removed and the pellet was stirred for 2 h at 37°C in the original vol of 0.05 M Tris, pH 7.4, containing 8 M urea and 0.025 M β -mercaptoethanol (β -ME). Centrifugation for 10 min at 20,000 g resulted in a supernate (the urea extract) and a pellet which defied further extraction even with boiling 1% SDS-0.025 M β -ME. Stock solutions of 10 M urea were deionized before use by passage over a mixed ion exchange resin (Crystalab, Inc., Hartford, Conn.). All buffers contained 0.1 mM phenylmethylsulfonyl fluoride.

SDS Polyacrylamide Gel Electrophoresis and Isolation of Individual Polypeptides

SDS polyacrylamide electrophoresis was performed on 14 × 14 × 0.15-cm gel slabs consisting of a 12.5% separating gel and a 5% stacking gel as described in the accompanying paper (13).

Single-well, SDS polyacrylamide slab gels, prepared as described above, were loaded with extracts containing 100-300 μ g of protein, and individual polypeptides were separated by electrophoresis and recovered from the gels described in the accompanying paper (13).

Amino Acid Analysis

Single polypeptides, isolated by preparative SDS polyacrylamide electrophoresis as described above, were redissolved in 0.01 M sodium borate, pH 7.6, containing 8 M urea, incubated for 30 min at 37°C with an equal volume of Dowex AG1-X2 (Bio-Rad Laboratories, Richmond, Calif.) to remove the SDS (25), dialyzed against two changes of 1,000 vol of 0.01 M sodium borate, pH 7.6, and lyophilized. 20 μ g of each polypeptide were hydrolyzed in 6 N HCl at 110°C, and the amino acids were quantitated on a Durrum-500 analyzer (Durrum Instrument Corp., Sunnyvale, Calif.). Cysteic acid was measured in samples hydrolyzed by performic acid-H₂O (14). Tryptophan was measured in samples hydrolyzed by mercaptoethanesulfonic acid (15). Values for serine and threonine were extrapolated to zero time following hydrolysis for 24, 63, and 100 h.

X-Ray Diffraction

A pellet of filaments was dried between two wire supports at 5°C. The resulting fiber, 10-20 μ m in diameter, was exposed to CuK α radiation for 48 h as described by Steinert et al. (20). An internal calcite standard was used for calibration.

DEAE-Cellulose Column Chromatography

A 2 × 20-cm column of DEAE-cellulose (DE-52 Whatman, Inc., Clifton, N. J.) was equilibrated with buffer containing 0.02 M Tris, pH 7.6, 8 M urea, 0.025 M β -ME, 1 mM EDTA, and 2% 1-propanol. The urea extract of esophagus was dialyzed against column buffer and applied to the column. The proteins were eluted by step gradients of KCl at a gravity flow rate of 0.5 ml/min.

Protein Quantitation

Protein was assayed by the method of Bramhall et al. (1) using bovine serum albumin (Miles, Laboratories, Inc., Elkhart, Ind.) as standard. The relative amount of protein in Coomassie Blue-stained bands on SDS polyacrylamide gels was approximated by scanning the gels with a scanning densitometer (Helena Laboratories, Beaumont, Tex.).

RESULTS

Morphology of Esophageal Epithelium

The entire length of bovine esophagus is lined by a parakeratotic, stratified squamous epithelium that is uninterrupted

by mucous glands, sweat ducts, or other adnexal structures (Fig. 1 a). The cytoplasm of the epithelial cells contains profuse arrays of 6-10-nm filaments, but there are no keratohyalin granules or keratinosomes (Fig. 1 c). The esophageal epithelium is cleanly separated from the underlying connective tissue by immersing the tissue in water at 56°C for 30 s (Fig. 1 b).

Extraction of Esophageal Polypeptides

Two polypeptides comprise ~35% of the total extractable protein of esophageal epithelium. Their molecular weights, estimated by relative mobility in SDS polyacrylamide electrophoresis, are 56,000 daltons (E₁) and 46,000 daltons (E₂) (Fig. 2). The insolubility of these two polypeptides in low-salt buffer allows them to be separated from the majority of other esophageal proteins by a serial extraction procedure. Extraction of the tissue with 0.05 M Tris, pH 7.4, solubilizes most of the esophageal proteins; extraction of the residue with 0.05 M Tris, pH 7.4, containing 8 M urea and 0.025 M β -ME, solubilizes E₁ and E₂ (Fig. 2). 40-50% of the E₁ and E₂ can be extracted with urea alone. Total extraction is possible only in the presence of β -ME. E₁ and E₂ can be only partially extracted with 5 M urea or 0.1 M sodium citrate, pH 2.6, or 1 mM NaOH. They cannot be extracted with 0.6 M KCl.

Filament Formation

Filaments form in the urea extract when the urea is removed by dialysis. Dialysis of a urea extract, containing 2 mg/ml of protein, against 5 mM Tris, pH 7.4, causes the solution to become opalescent. When the opalescent solution is spread on a holey grid, stained with uranyl acetate, and examined in the electron microscope, unbranched filaments are seen (Fig. 3). They are 6-10 nm in diameter and vary in length from 0.1 to 1.0 μ m. More long filaments and fewer short filaments are formed when β -ME is added to the dialysis buffer, a phenomenon previously described for in vitro filament formation in urea extracts from hoof epidermis (19). More than 90% of the protein in the opalescent solution is found in the pellet after ultracentrifugation at 200,000 g for 1 h, indicating that the bulk of the protein is in a filamentous form.

To study the interaction of E₁ and E₂, samples consisting predominantly of E₁ or E₂ were obtained by DEAE-cellulose column chromatography (Fig. 4). A fraction containing E₁ was eluted with 20 mM KCl and one containing E₂ at 80 mM KCl (Fig. 5). Each fraction was dialyzed against 5 mM Tris containing β -ME, stained with uranyl acetate, and examined for filaments. None were found. When fractions containing E₁ were mixed with fractions containing an equal amount of E₂, dialyzed against Tris- β -ME, and stained with uranyl acetate, long filaments were observed. The filaments were 6-10 nm in diameter, unbranched, and had a tendency to form side-to-side association. Pellets of these filaments were analyzed by SDS polyacrylamide gel electrophoresis, and E₁ and E₂ were present in equal amounts. Some E₂ fractions contained small amounts of a 48,000-dalton polypeptide. When such E₂ preparations were mixed with E₁ and the urea was removed by dialysis, the amount of the 48,000-dalton polypeptide found in the pellet was proportional to the amount in the original "E₂" preparation.

X-ray Diffraction

Filaments were formed in vitro from a combination of DEAE fractions 32 and 92 (see Fig. 5). X-ray diffraction

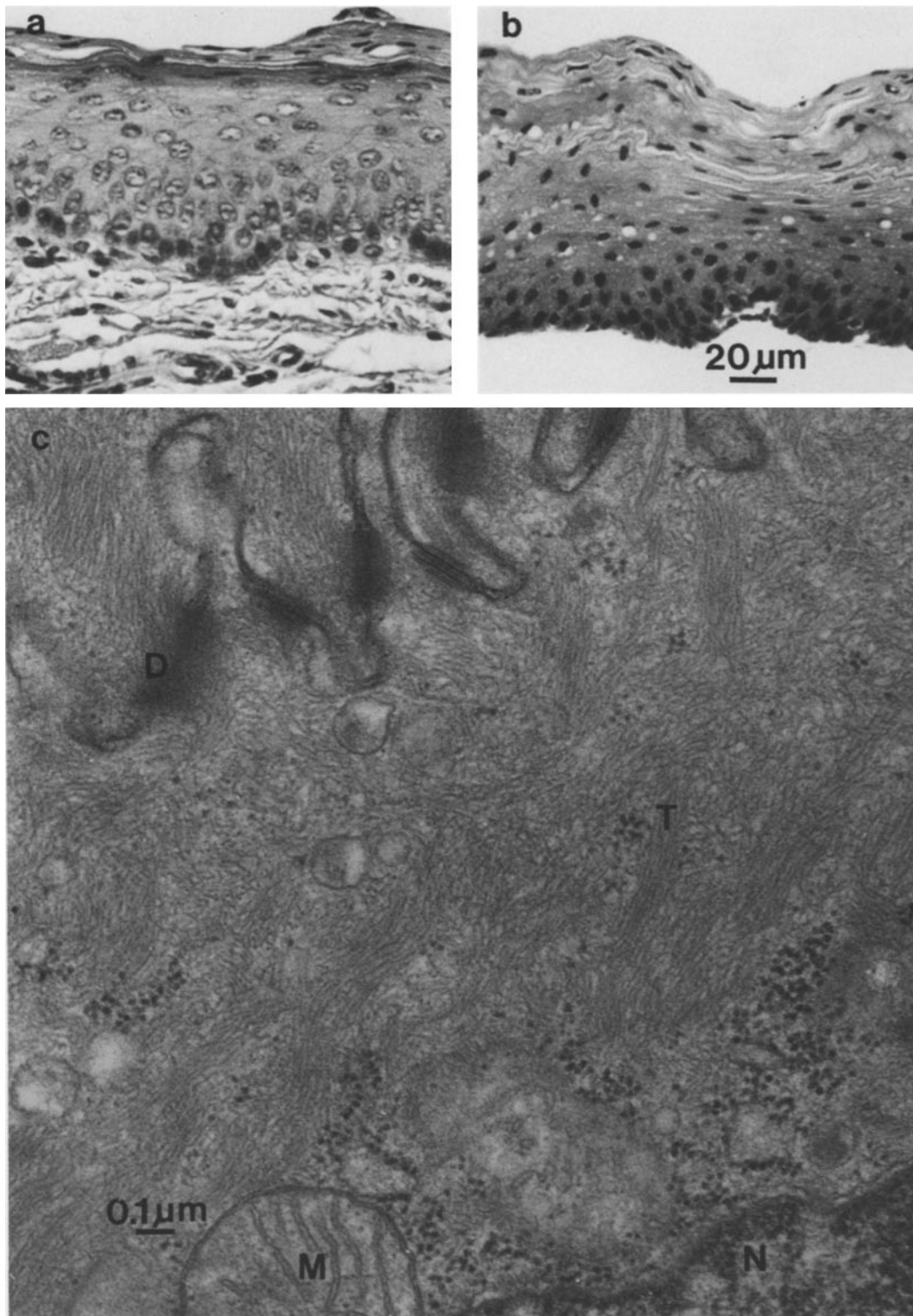


FIGURE 1 (a) Light micrograph of bovine esophagus. $\times 350$. (b) Light micrograph of esophageal epithelium after immersion in water at 56°C . The nuclei have become pyknotic and the tissue swollen because of fluid in intracellular spaces. $\times 350$. (c) Electron micrograph of cell in mid-portion of esophageal epithelium. Tonofilaments occupy most of the cytoplasm of these cells. *N*, nucleus; *M*, mitochondrion; *D*, desmosome; *T*, tonofilaments. $\times 57,000$.

analysis of these filaments revealed a meridional arc at 5.09 \AA and an equatorial arc at 9.8 \AA (Fig. 3).

Amino Acid Composition

The amino acid composition of E_1 and E_2 , purified (Fig. 2) by SDS polyacrylamide slab gel electrophoresis, is shown in

Table I. These polypeptides are rich in glutamine, glycine, and serine. Their amino acid compositions are similar to those of tonofilament polypeptides isolated from calf hoof epidermis (18). No tryptophane was detected; based on the sensitivity of the assay and the amounts of protein analyzed, there are fewer than two tryptophane molecules per molecule of polypeptide.

DISCUSSION

The criteria used by others to identify filament-forming polypeptides in cutaneous epithelia were that they should be abundant, relatively insoluble, and have the capacity to assemble in

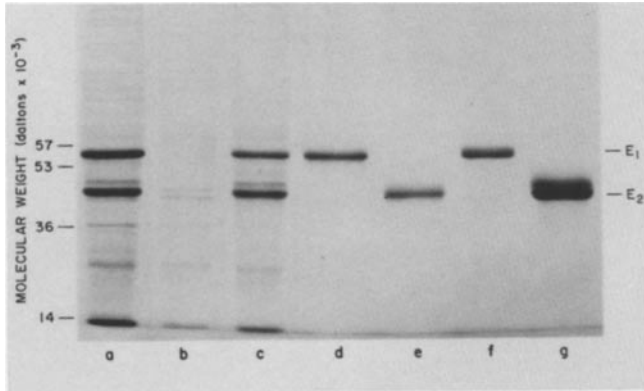


FIGURE 2 SDS polyacrylamide (12.5%) gel of esophageal proteins. (a) Total extractable protein, 20 μ l. 1 g of esophageal epithelium was sonicated and then boiled in 25 ml of 0.05 M Tris, pH 7.4, containing 1% SDS-0.025 M β -ME. (b) Low-salt extract, 20 μ l. 1 g of epithelium extracted with 25 ml of 0.05 M Tris, pH 7.4. (c) Urea extract, 20 μ l. Residue from b extracted with 25 ml of 0.05 M Tris, pH 7.4, containing 8 M urea and 0.025 M β -ME. (d) E₁, purified by preparative SDS PAGE. (e) E₂ purified by preparative SDS PAGE. (f) Fraction 32 from DEAE cellulose column. (g) Fraction 92 from DEAE-cellulose column.

vitro into filaments that were 10 nm in diameter and exhibited an α -keratin type x-ray diffraction pattern (8, 12, 16-18, 23). These operational characteristics were used to identify and isolate the FFP's from esophageal epithelium. The stratified squamous epithelium of calf esophagus was chosen for study because it was readily prepared free of nonepithelial elements and because the most completely characterized tonofilament proteins are those of bovine hoof epidermis.

The major polypeptides in the urea extract of esophageal epithelium have molecular weights of 46,000 and 56,000 daltons; those in urea extracts of hoof epidermis have molecular weights of 49,000, 51,000, 54,000, 57,000, 61,000, and 65,000 daltons in the same gel system (13). Because the urea extract of esophagus contains a family of polypeptides different from that in hoof, what is the evidence that E₁ and E₂ are indeed the esophageal tonofilament polypeptides? (a) The urea extract, as well as a mixture of partially purified E₁ and partially purified E₂, form filaments in vitro that are 6-10 nm in diameter. (b) The abundance of E₁ and E₂ is commensurate with the abundance of tonofilaments observed by electron microscopy in esophageal epithelial cells. (c) E₁ and E₂ can be extracted only with reagents that extract hoof and human epidermal FFP's, and their amino acid compositions are similar to those of hoof FFP's (18). A disulfide reducing agent is necessary for complete extraction of E₁ and E₂, just as it is required for extraction of hoof (18) and human epidermal (21) FFP's. (d) Filaments formed by a mixture of E₁ and E₂ exhibit an α -keratin type x-

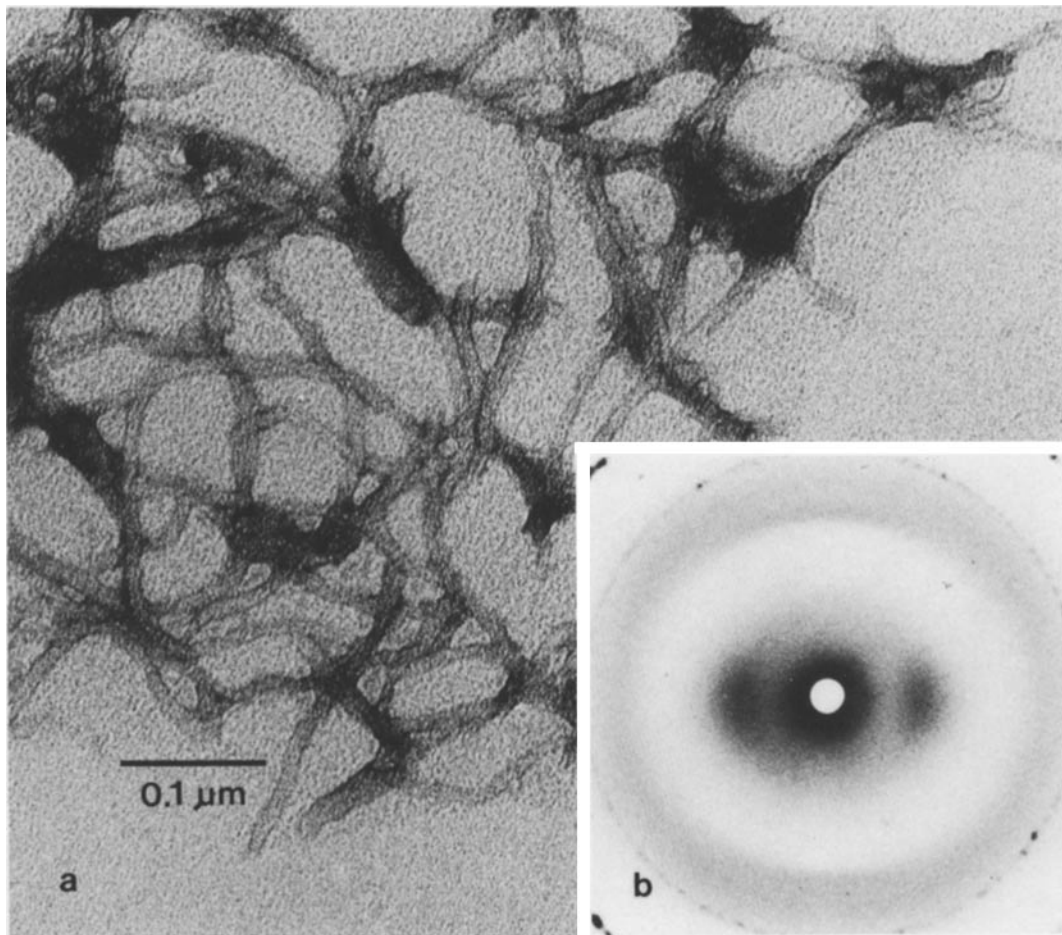


FIGURE 3 (a) Filaments formed from DEAE column fractions 32 plus 92 were spread on holey grids and stained with 1% uranyl acetate. Individual filaments measure 6-10 nm in diameter. $\times 189,000$. (b) Wide-angle x-ray diffraction pattern of filaments formed in vitro shows a 5.09 \AA meridional arc and a 9.8 \AA equatorial arc. The ring visible at the corners is produced by the calcite standard.

ray diffraction pattern. This diffraction pattern appears to be a common finding for a variety of 6–10-nm filaments (20) and implies a coiled coil arrangement for the polypeptides in the filament (3).

Although E₁ and E₂ are the major FFP's in esophageal epithelium, they may not be the only ones. Several minor polypeptides with molecular weights of 48,000, 51,000, and 53,000 daltons are also found in the urea extracts. When filaments are formed from urea extracts of esophagus, these minor polypeptides are quantitatively recovered through several cycles of assembly-disassembly-assembly. It remains to be shown whether these polypeptides can form filaments themselves, whether they are required for the formation of filaments by E₁ plus E₂, or whether they become associated with filaments that have already formed.

The relationship of the esophageal FFP's to other polypeptides that form intermediate filaments is unclear, and the

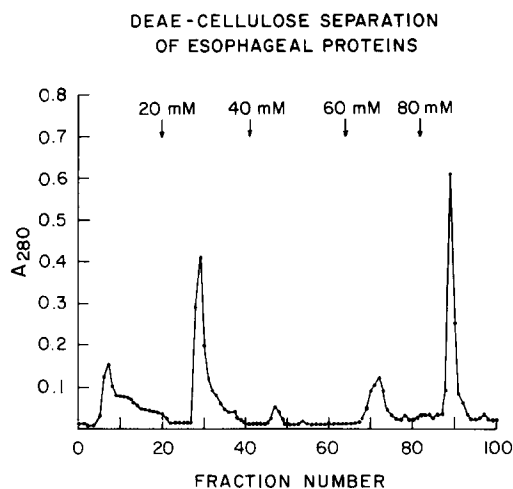


FIGURE 4 The urea extract from 1 g of esophageal epithelium was applied to a 2 × 10-cm column of DEAE-cellulose and eluted by a step gradient of KCl as indicated by the arrows. 10-ml fractions were collected at a flow rate of 0.5 ml/min.

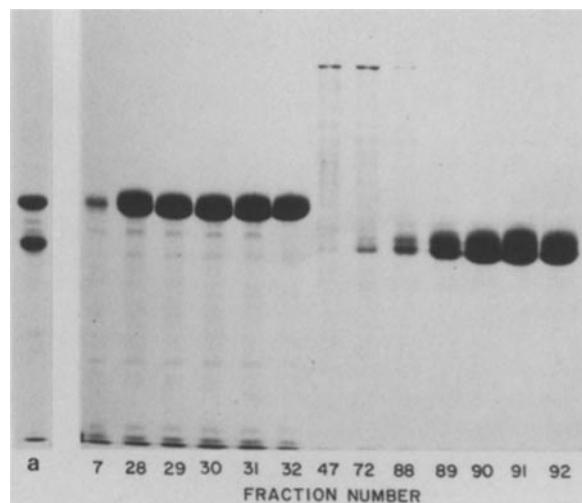


FIGURE 5 SDS polyacrylamide gel of fractions eluted from DEAE-cellulose column. 20- μ l aliquots from selected fractions were precipitated with 20% TCA, redissolved in sample buffer, and applied to a 12.5% polyacrylamide gel. Numbers below lanes correspond to DEAE fraction numbers (see Fig. 4). Lane a is an aliquot of the original urea extract.

TABLE I
Amino Acid Compositions

	Residues/100 residues	
	E ₁	E ₂
Asp	7.47	8.45
Thr	3.32	5.49
Ser	8.95	8.59
Glx	13.86	15.94
Pro	0.84	1.08
Gly	16.01	15.53
Ala	9.29	7.04
Val	7.51	4.11
Met	1.25	1.95
Ile	4.46	4.70
Leu	8.66	10.50
Tyr	2.10	2.31
Phe	3.80	3.33
His	0.08	0.33
Lys	5.91	4.53
Arg	4.65	5.39
CysA	1.83	0.74
Molecular weight	56,000	46,000

Amino acid analyses were performed on esophageal polypeptides that had been isolated and purified by sequential extraction and preparative gel electrophoresis. A three-point, timed hydrolysis was performed. Maximum values for Val and Ileu are shown. Values extrapolated to zero time are shown for serine and threonine. CysA and Tyr were determined on separate samples. The remaining values are the average of three determinations.

occurrence of so many different polypeptides that form intermediate filaments, even within a single tissue, raises many questions. Why are there so many and how did they arise? Do their biochemical differences imply different functions? What is the common biochemical basis for the similar morphology of the filaments they form? Identification and isolation of individual FFP's from different tissues is a necessary step toward answering these questions.

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