TRANSLATION OF EUKARYOTIC MESSENGER RNA IN VARIOUS HETEROLOGOUS SYSTEMS

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INTRODUCTION

Our present view of protein biosynthesis in eukaryotic systems assigns a major role in this process to the messenger RNA involved. This paper deals mainly with some of the recent work on messenger RNA isolated from calf eye lenses. One may ask the question: why in particular lens mRNA? The answer is simple: the lens has several unique features which makes it particularly suitable for studies on protein biosynthesis and differentiation. The lens is an isolated tissue without blood vessels and is composed entirely of an epithelial monolayer and a close package of fiber cells (Fig. 1). The fibers arise from the epithelial cells and represent the final stage of cellular differentiation.

Fig. 1. Schematic representation of a cross section through a vertebrate eye lens.
Reeder and Bell (1965) presented evidence that in the intact lens DNA synthesis takes place exclusively in the epithelium, RNA synthesis in epithelium and the lens bow, whilst protein synthesis occurs in the epithelium and cortex. After treatment of cultured lenses with actinomycin D protein synthesis ceases in the epithelium while it continues in the lens body implying the activity of a messenger with long half-life. The chemical composition of the lens is also exceptional. It contains approximately 35% of protein of which almost 90% is represented by the so-called crystallins. The crystallins have as far as it is known, no enzymic function. There are three classes of these water-soluble structural lens proteins: α, β, and γ-crystallin. At least in calf lens the insoluble protein is an altered form of α-crystallin. From a biosynthetic point of view α-crystallin is most interesting as both epithelial and cortical fiber cells are specialized for the synthesis of that protein. In the epithelium 60% of the newly synthesized protein is α-crystallin whereas in the cortex this amounts even to 75% (Delcour and Papaconstantinou, 1972). From the foregoing it is clear that lens cells provide a good source for the isolation of stable and specific mRNA.

Some basic knowledge of lens proteins is required in order to enable the analysis of the products synthesized under direction of the lens messengers. The α-crystallin fraction consists of large aggregates with an average molecular weight of 800,000 dalton. All aggregates are composed of the same four kinds of polypeptide chains: αA, αA, αB, and αB, which migrate with different electrophoretic mobility in polyacrylamide gels containing 7 M urea at alkaline pH. αA is the major component. In embryonic lenses the αA chains are lacking. They arise gradually during aging, presumably by deamidation (Bloemendal et al. 1972a). The molecular weight of the individual polypeptide chain estimated in SDS or 7 M urea is approximately 20,000 dalton (Bloemendal, 1972). The NH₂-terminal sequence N-acetyl-Met-Asp-Ile-Ala as well as the occurrence of 2 methionine residues are common features of all four polypeptide chains. These characteristics have been used as analytical tools for the identification of newly synthesized products under direction of lens messenger.

THE ISOLATION OF EUKARYOTIC MESSENGER RNA

For a rather long time the availability of mRNA was hampered by a lack of convenient techniques in order to separate the very small amount of functional messenger from the bulk of RNA. A breakthrough came with the introduction of zonal rotors which enabled the isolation of viable amounts of eukaryotic messenger fractions. In most procedures polyribosomes are the starting material for messenger preparations. It stands to reason that polyribosomes from cells which manufacture only one or a very limited number of proteins are advantageous. In this connection reticulocytes and lens tissue have to be mentioned. However the isolation of one mRNA species from a population of different messengers is also possible. By means of immunoprecipitation a defined class of polyribosomes is isolated by virtue of the antigenic specificity of the nascent chains which are being synthesized. This procedure has e.g. been applied in studies upon the biosynthesis of albumin (Duerre, 1967), H and L chains of immunoglobulins (Williamson and Askonas, 1967; Schubert and Cohn, 1968; Boyd et al. 1971), myosin (Allen and Terrence, 1968), chick lens protein (Clayton et al. 1970) and catalase (Uenoyama and Ono, 1972). One has to keep in mind that unspecific precipitation cannot always completely be avoided, which is a serious drawback of this elegant method.

The isolation of lens polyribosomes has been described earlier (Bloemendal et al. 1966). As many as 1000-1200 lenses are required for a yield of about 5 mg polyribosomal RNA. The polyribosomes are suspended in Mg⁺⁺-free medium and treated with sodium dodecyl sulfate. With the aid of equivolumetric gradients under strictly standardized conditions a separation as depicted in Fig. 2 is possible.

In this way approximately 50 μg mRNA can be obtained from 5 mg polyribosomal RNA. Recentrifugation in a swinging bucket rotor reveals that the separation in the zonal rotor yields fractions which seem to be rather homogeneous (Berns et al. 1971). Here only the 10S fraction is shown (Fig. 3).
Fig. 3. Recentrifugation pattern of the lens messenger 10S fraction in a swinging bucket rotor.

Taking into account the average size of lens polyribosomes (Benedetti et al., 1968) the 10S and 14S fractions (compare Fig. 2) seemed to be candidates for the role of messenger. These two RNA species can also be isolated from RNP particles which arise upon treatment of lens polyribosomes with EDTA. In Figs. 4A and B, the patterns of lens RNP particles and corresponding RNA fractions are visualized. For comparison a parallel experiment with reticulocyte RNP is also shown (Fig. 4A and 4B(a)). A particle which sediments at 16S yields the 10S messenger (Fig. 4A and (b)); a 21S particle the 14S messenger (Fig. 4A and 4B(c)).

Fig. 4. Zonal centrifugation patterns of RNP particles (A) and corresponding RNA fractions (B).
a) from rabbit reticulocytes; b,c,d) from calf lens.

It is well established now that various mRNAs contain poly A-rich regions. This property is the base of successful separation of biologically active messenger from inactive RNA.

The poly A-rich fraction anneals to poly U cellulose (Kates, 1970; Sheldon et al., 1972) or to oligothymidylic acid-cellulose columns (Aviv and Leder, 1972). Preliminary experiments in collaboration with Drs. Piperno and Bertazzoni (Institut de Biologie Moléculaire, Paris), revealed that 20% of the messenger preparation isolated by zonal centrifugation is retained by such dT-columns. After the purification step the A content of the messenger fraction appeared to be approximately 31%.

THE CHARACTERIZATION OF MESSENGER RNA

In principle several approaches can be utilized for the characterization of messenger.

1. A specific label
   In pulse experiments there is label to be found in association with polyribosomes. This label is predominantly due to the presence of mRNA.

2. A specific density
   mRNP particles reveal a buoyant density differing from the density of ribosomal subunits or naked RNA.

3. The base composition
   The significance of the base composition as specific property of mRNA is questionable as long as this RNA species is not highly purified and the composition of the corresponding polypeptide unknown.

4. Hybridization
   In hybridization experiments one has to keep in mind that unspecific annealing may occur.

5. Determination of nucleotide sequence
   A prerequisite for sequential studies on eukaryotic mRNA is the availability of a homogeneous preparation with high specific activity. It seems to be rather difficult to produce highly radioactive eukaryotic mRNA by in vivo incorporation experiments. However, recently a promising method was introduced in which the reversed transcriptase is utilized. With the aid of the enzyme isolated mRNA is first transcribed into DNA. This DNA can be retranscribed into mRNA by using polymerase and tri-nucleotides of high specific activity.

6. Translation in cross systems
   The ultimate proof of the messenger function is always: accurate translation upon addition of the presumptive messenger to a cross system.

ASSAY SYSTEMS FOR mRNA

Not only the appropriate isolation procedures for mRNA were lacking for a rather long period of time but also efficient cell-free or in vivo systems were unknown.

Recently investigations by Lockard and Lingrel (1969) and Mathews and Korner (1970) demonstrated the usefulness of crude cell-free systems derived from reticulocytes or ascites as assay system for exogenous messenger activity. An additional very effective test system was obtained from oocytes of Xenopus Laevis by Gurdon and coworkers (1971). It has to be mentioned here that Schapira and coworkers have been the first to
show that an RNA fraction from rabbit reticulocytes sedimenting between 4S and 16S transmitted information to a reticulocyte extract derived from another species (Kruh et al. 1964; Schapira et al. 1968). Up till now only a relatively small number of eukaryotic mRNAs has been identified in a functional assay and the complete translation achieved has practically been restricted to the three cross systems mentioned (Table 1).

### Table 1

<table>
<thead>
<tr>
<th>Source of mRNA</th>
<th>Protein</th>
<th>System</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>muscle (chick)</td>
<td>myosin</td>
<td>retic (chick)</td>
<td>Heywood (1969)</td>
</tr>
<tr>
<td>retic (rabbit)</td>
<td>hemoglobin</td>
<td>retic (chick)</td>
<td>Laycock &amp; Hunt (1969)</td>
</tr>
<tr>
<td>retic (mouse)</td>
<td>hemoglobin</td>
<td>retic (rabbit)</td>
<td>Lockard &amp; Lingrel (1971)</td>
</tr>
<tr>
<td>retic (mouse)</td>
<td>hemoglobin</td>
<td>ascites (mouse)</td>
<td>Mathews et al. (1971)</td>
</tr>
<tr>
<td>retic (rabbit)</td>
<td>hemoglobin</td>
<td>oocytes (frog)</td>
<td>Gurdon et al. (1971)</td>
</tr>
<tr>
<td>myeloma (mouse)</td>
<td>immunoglobulin (L chain)</td>
<td>retic (rabbit)</td>
<td>Stevermer &amp; Huang (1971)</td>
</tr>
<tr>
<td>ovuiduct (hen)</td>
<td>ovalbumin</td>
<td>retic (rabbit)</td>
<td>Rhoads et al. (1971)</td>
</tr>
<tr>
<td>lens (calf)</td>
<td>α-crystallin (A chain)</td>
<td>retic (rabbit)</td>
<td>Berns et al. (1972a)</td>
</tr>
<tr>
<td>lens (calf)</td>
<td>β-γ-crystallin</td>
<td>ascites (mouse)</td>
<td>Mathews et al. (1972a)</td>
</tr>
<tr>
<td>lens (calf)</td>
<td>α-crystallin (A chain)</td>
<td>oocytes (frog)</td>
<td>Berns et al. (1972a)</td>
</tr>
</tbody>
</table>

retic = reticulocyte

### THE TRANSLATION OF LENS mRNA IN VARIOUS CROSS SYSTEMS

The isolated lens 10S and 14S fractions have been tested in the three cross systems mentioned above. In all cases it appeared that the 14S messenger directs the synthesis of the αA chains whilst the 10S lens mRNA directs the synthesis of the αB chains and presumably β-crystallin chains. This is illustrated in Figs. 5 and 6 (compare also Fig. 8). No αA chains seems to be made. This is in accord with previous findings that the αA chain arises from αA, by deamidation (Bloemendal et al. 1972a). Deamidation of asparagine and glutamine, a posttranslational conversion process and presumably a more general aspect of aging, has previously been observed with rat cytochrome C (Flatmark and Sletten, 1968) and rabbit muscle aldolase (Lai and Horecker, 1971).

An intriguing observation is that the 14S messenger with a molecular weight of about 360,000 dalton apparently codes for the αA chain with a molecular weight of about 20,000 dalton whereas αB and β-crystallin chains which have somewhat higher molecular weights than αA, are synthesized under direction of a 10S messenger with a calculated molecular weight of 260,000 dalton. This is clearly demonstrated by translation of lens mRNA in the reticulocyte system. First both messengers are collected in several fractions after a prolonged zonal run (Fig. 7, compare also Fig. 2). Thereafter the individual fractions are assayed in the cell-free system. The result is shown in Fig. 8. This picture allows the following conclusions:

1. The 14S RNA preparation codes exclusively for αA chains.
2. The 10S fraction codes for several crystallin polypeptides but not for αA chains.
3. For the 10S fraction it is true that a slightly higher sedimentation value of the RNA fraction corresponds with a higher molecular weight of the product synthesized under direction of this RNA species.

*Fig. 5. SDS gel analysis of the newly synthesized products obtained in the ascites cell-free system under direction of lens messengers.*

*Fig. 6. Tracing of a polyacrylamide-urea gel electrophoretic pattern of the newly synthesized products in the reticulocyte cell-free system under direction of 14S lens messenger.*
Fig. 7. Zonal centrifugation pattern of polyribosomal RNA from calf lens (centrifugation time 25 h.).

Fig. 8. Autoradiography of the SDS gel pattern of the newly synthesized products obtained in the reticulocyte system under direction of the RNA fractions 2-7 visualized in Fig. 7.

Fig. 9. SDS gel analysis of newly synthesized products under direction of endogenous and exogenous messengers in the Krebs ascites cell-free system. a-d: Biosynthesis in the absence of added 0.5 M KCl wash from reticulocytes; e-h: in the presence of the KCl wash.
IDENTITY OF NEWLY SYNTHESIZED AND NATIVE \( \alpha_2 \) CHAINS

In order to determine the fidelity by which 14S lens messenger is translated an NH\(_2\)-terminal analysis and a complete peptide map of the tryptic digest of newly synthesized polypeptide was carried out. In Table 2 the NH\(_2\)-terminus analysis is briefly summarized.

Table 2

<table>
<thead>
<tr>
<th>Enzyme</th>
<th>Amino-acid sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pronase</td>
<td>acetyl-Met-Asp</td>
</tr>
<tr>
<td>Subtilisin</td>
<td>Met-Asp-Ile-Ala</td>
</tr>
<tr>
<td>Trypsin</td>
<td>Met-Asp-Ile-Ala-</td>
</tr>
<tr>
<td></td>
<td>-Ile-Gln-His-Pro-</td>
</tr>
<tr>
<td></td>
<td>-Trp-Phe-Lys(Arg)</td>
</tr>
</tbody>
</table>

In all cases co-electrophoresis or co-chromatography revealed identity of peptides released from native and newly synthesized lens polypeptide chains. A purified carrier \( \alpha_2 \) chain digest gives rise to about 20 ninhydrin positive spots. The radioactive spots obtained from the product obtained under direction of the 14S lens messenger coincide with the ninhydrin stained peptides. This result indicates the high degree of fidelity with which lens mRNA is translated (Borns and Bloemendal, 1972). The extent of identity of the newly synthesized chains as compared to native \( \alpha_2 \) chains goes even further. In our first experiments formyl-L\(_7\)Met-tRNA was used as radioactive precursor and as expected a polypeptide with a blocked NH\(_2\)-terminus was obtained (Borns et al. 1972a). However, to our surprise when in the reticulocyte system programmed with 14S lens mRNA \(^{14}S\) methionine was used as label the newly synthesized polypeptide carried an acetyl group in N-terminal position exactly like native \( \alpha_2 \) (Strous et al. 1972).

This was again proven by the analytical procedures summarized in Table 2.

1. Subtilisin treatment released a compound with identical electrophoretic behavior as the native NH\(_2\)-terminal tetrapeptide (Fig. 10).

![Figure 10](image-url)
terminal amino acid residues. In the case of α-crystallin one can think out a reason for the NH₂-terminal acetylation. The eye lens is a good if not the best source for the isolation of the enzyme leucine aminopeptidase. The acetyl group protects the protein against degradation by this enzyme. However, it cannot be concluded yet that protection against enzymic attack is the general meaning of NH₂-terminal amino acetylation. The question: does acetylation take place either short or later after initiation, the nascent chain still being attached to ribosomes or following the release of the completed polypeptide is a problem which is under investigation now.

Fig. 11. Paper chromatography of the methionine containing tryptic peptides of the α₂ chain.
A. Peptides obtained after [³⁵S] methionine labeling
B. Peptides obtained after labeling with [³⁵S] Met-tRNA<sup>Met</sup>
C. Peptides obtained after labeling with [³⁵S] Met-tRNA<sub>Met</sub>
D. Peptides obtained after labeling with [³⁵S] Met-tRNA<sub>Met</sub>

Table 3
Eukaryotic and viral proteins labeled in NH₂-terminal position.

<table>
<thead>
<tr>
<th>PROTEIN</th>
<th>ACETYLATED NH₂-Terminal AMINO ACID RESIDUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cytochrome C (plant)</td>
<td>Ala</td>
</tr>
<tr>
<td>Enolase</td>
<td>Ala</td>
</tr>
<tr>
<td>LDH</td>
<td>Ala</td>
</tr>
<tr>
<td>Keratin</td>
<td>Ala (?</td>
</tr>
<tr>
<td>Actine</td>
<td>Asp NH₂</td>
</tr>
<tr>
<td>Trypsomysin</td>
<td>Asp NH₂ Met</td>
</tr>
<tr>
<td>Ovalbumin</td>
<td>Gly</td>
</tr>
<tr>
<td>Cytochrome C (vertebrate)</td>
<td>Gly</td>
</tr>
<tr>
<td>α-crystallin</td>
<td>Met</td>
</tr>
<tr>
<td>Histone</td>
<td>Ser</td>
</tr>
<tr>
<td>Myosin</td>
<td>Ser</td>
</tr>
<tr>
<td>Agaferritin</td>
<td>Ser</td>
</tr>
<tr>
<td>α-MSH</td>
<td>Ser</td>
</tr>
<tr>
<td>Mitochondrial proteins</td>
<td>Ser</td>
</tr>
<tr>
<td>Fibrinogen</td>
<td>Thr</td>
</tr>
<tr>
<td>Cucumber virus</td>
<td>Ala</td>
</tr>
<tr>
<td>TYMV</td>
<td>Met</td>
</tr>
<tr>
<td>TMV</td>
<td>Ser</td>
</tr>
</tbody>
</table>

ACKNOWLEDGEMENT
This work was carried out partly under the auspices of the Netherlands Foundation for Chemical Research (S.O.N.) and with financial aid from the Netherlands Organization for the Advancement of Pure Research (Z.W.O.). We thank the medical students who processed the hundreds of thousands of calf eyes which have been utilized in the Department of Biochemistry (University of Nijmegen) since these investigations have been started.

REFERENCES