Major heat shock gene of Drosophila and the Escherichia coli heatinducible dnaK gene are homologous

(DNA sequence comparison/gene evolution/archaeobacteria)

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ABSTRACT The Escherichia coli dnaK gene is homologous to the major heat shock-induced gene in Drosophila (Hsp70). The primary DNA sequence of the entire protein-coding region of the dnaK gene was determined and compared with that of the Hsp70 gene of Drosophila. The two sequences are homologous; the dnaK gene could encode a 69,121-Da polypeptide, 48% identical to the hsp70 protein of Drosophila. The homology between the Hsp70 gene of Drosophila and the E. coli dnaK gene illustrates the remarkable conservation of the heat shock genes in evolution. In contrast to Drosophila and Saccharomyces cerevisiae, both of which contain multigene families related to the Hsp70 gene, hybridization analyses indicate that E. coli contains only a single Hsp70-related gene, dnaK. Hybridization between the DNA of an archaeobacterium Methanosarcina barkeri and the Hsp70 genes of Drosophila, Saccharomyces, and E. coli has been detected, suggesting the existence of Hsp70-related genes in the three "primary kingdoms": eukaryotes, eubacteria, and archaeobacteria.

When cells from a variety of species are quickly heated to a few degrees above their normal growth temperature, the synthesis of a small set of proteins is strongly and rapidly induced. The heat shock response has been most extensively studied in Drosophila, but a similar response has been observed in cells of a broad spectrum of eukaryotes: Saccharomyces cerevisiae (1), Dictyostelium (2), tobacco, hamsters, chickens, and humans (3, 4).

The function of the heat shock proteins is not known. However, the synthesis of heat shock proteins has been correlated with the acquisition of resistance to heat in eukaryotic cells (5). Agents that interfere with oxidative phosphorylation, as well as various chemicals such as ethanol, elicit the heat shock response (5, 6). Thus, the induction is thought to be a general response to stress, not merely a response to an alteration in temperature.

Evidence is accumulating that indicates that these induced proteins have been conserved throughout eukaryotic evolution. In many organisms, heat induces the synthesis of a protein of about 70,000 Da. Antibodies raised to a 70,000-Da heat shock protein (hsp70) from chicken crossreact with heat shock proteins of similar molecular size in eukaryotic species as divergent as yeast and man (7). The predicted amino acid sequences of hsp70 proteins of yeast are 72% identical to the Drosophila hsp70 protein (ref. 8; unpublished observations).

The heat shock response has also been observed in a prokaryote, Escherichia coli. On temperature up-shift, the rate of synthesis of at least 14 polypeptides is enhanced. This induction is under the control of a gene called htpA (9). Four of these HTP (high temperature production) proteins have been identified: the groEL, groES, and dnaK gene products, and a lysine tRNA synthetase. The first three proteins are essential for the growth of bacteriophage λ (10, 11, 18). Furthermore, groEL-, groES-, and dnaK− mutants that are temperature sensitive for bacterial growth at 43°C have been isolated (11, 12), suggesting that these genes are essential for cell viability. In this paper, we report that the dnaK gene of E. coli is homologous to the Hsp70 heat shock genes of higher organisms, thus establishing a relationship between the prokaryotic and eukaryotic heat shock systems.

MATERIALS AND METHODS

Bacteriophage and Plasmids. λdnaK, a phage capable of transducing E. coli dnaK− to dnaK+, and λdnajdnaK phage were obtained from M. Feiss (13). Deletion derivatives of λdnaJdnaK were obtained from H. Uchida (14). Three plasmids containing yeast genes related to the Drosophila Hsp70 gene were used: YGI100 (8) and YGI102 (15) are 97% identical to each other and 67% identical to Drosophila Hsp70. Transcription of these three genes is enhanced by heat shock. YGI101 is 67% identical to YGI100 and YGI102, and 56% identical to Drosophila Hsp70. Another plasmid, B8, contains a single copy of a 87°C Drosophila Hsp70 gene (16). In all cases pBR322 is the vector.

General Methods. Gel electrophoresis, blotting of DNA to nitrocellulose, nick-translation, and DNA sequence analysis were carried out as described (16, 17). Labeling of DNA by polynucleotide kinase was as described (16) except that prior to labeling, blunt or recessed 5' ends of DNA were converted to protruding 5' ends using DNA polymerase Klenow fragment (New England BioLabs). Five units of enzyme were incubated with 20–30 μg of digested DNA in 50 mM NaCl/7 mM MgCl2/7 mM Tris-HCl, pH 7.4, for 30 min at room temperature (Z. Burton, personal communication).

In calculating the percentage amino acid identity, perfect amino acid matches were counted and divided by the sum of the total number of residues and the number of gapped residues. To calculate percentage nucleotide identity, matching bases were counted and divided by the sum of the total number of base pairs and the number of gaps.

DNA-DNA Hybridizations. Hybridization of DNA labeled by nick-translation to DNA bound to nitrocellulose filters was carried out under nonstringent conditions. The hybridization solution was 30% formamide/0.75 M NaCl/0.075 M sodium citrate/0.1% NaDodSO4/1.0 M EDTA/10 mM Tris-HCl, pH 7.5/1× Denhart’s solution (8). The filters were incubated with probe overnight at 37°C after a 4-hr incubation in hybridization buffer in the absence of probe. The filters were then washed in 0.75 M NaCl/0.075 M sodium citrate/0.2% NaDodSO4 at 37°C for 4 hr with three changes of the wash solution.

RESULTS

Hybridization of Eukaryotic Hsp70 Genes to the E. coli dnaK Gene. To determine whether E. coli contains se-

Abbreviation: kb, kilobase(s).
DNAJ and derivatives. Nitrocellulose.

FIG. 1. Hybridization of a yeast heat shock gene and the dnaK gene to E. coli genomic DNA. Three-microgram portions of E. coli DNA were digested with restriction enzymes, electrophoresed on a 0.7% agarose gel, and transferred to nitrocellulose. (A) A fragment of a yeast Hsp70 gene, YGI02, encompassing the codons of amino acids 118-639 was labeled with 32P by nick-translation and hybridized to the filter under low stringency. (B) A fragment of the dnaK gene encompassing the codons of amino acids 174-412 was labeled with 32P by nick-translation and hybridized to the filter under conditions of low stringency.

sequences related to eukaryotic 70,000-Da heat shock genes, hybridization experiments were carried out. E. coli genomic DNA was digested with restriction enzymes, subjected to gel electrophoresis, and transferred to nitrocellulose. The DNA was hybridized to a protein-coding portion of the yeast gene, YGI02, which is related to the Drosophila 70,000-Da heat-shock gene. As shown in Fig. 1A, a single band of hybridization was observed after independent digestion with four different restriction enzymes. DNA of a transducing phage containing the dnaK and dnaJ genes was fixed to nitrocellulose and probed with a portion of the protein-coding region of an Hsp70-related gene from yeast (YGI01). dnaK was tested because it is a major heat shock gene in E. coli (9). An intense hybridization signal was observed, indicating probable similarity between the dnaJ and dnaK region and the yeast gene. To map the region of hybridization on these phage, a yeast heat shock gene probe was hybridized to a series of lambda dnaK deletion derivatives. The dnaK gene had been previously mapped between the left end of the HindIII insert and the bottom of the figure.

FIG. 2. Mapping of the hybridization between E. coli and eukaryotic heat shock genes to the dnaK gene. (A) DNA from lambdaJ and deletion derivatives derived from lambdaJ dnaK were cleaved with Sma I and HindIII (Hd3), electrophoresed through 0.7% agarose, and transferred to nitrocellulose. A fragment of the yeast heat shock gene YGI02 encompassing the codons of amino acids 118-639 was hybridized to the filter. (B) The physical structures of the lambda deletions shown were determined by Saito (14) using heteroduplex analysis. E. coli DNA is represented by the thick lines. Thin lines represent flanking phage vector. (C) The dnaK and dnaJ phenotypes of these phages were determined by Saito (14) by testing the ability of each of these deletion mutants to plaque on bacterial strains containing mutations in the dnaK and dnaJ genes. The limits of dnaJ and dnaK designated at the bottom of the figure are based on such tests of these deletion derivatives.
in λdnaK and the end point of the deletion in λdnaJ-dnakA195 (ref. 14; Fig. 2B) by testing the ability of the deletions to complement dnaK mutations. DNA from these phages were cleaved with restriction enzymes that excise the bacterial DNA from phage DNA and also separate the dnaK gene from the dnaJ gene. When the DNA was hybridized to a yeast heat shock gene probe, a band of hybridization was observed only with those deletion derivatives that contained DNA from the dnaK gene region (Fig. 2A). The only fragments that hybridized were those containing the dnaK sequences. A labeled plasmid (B8) containing a copy of the Drosophila Hsp70 gene was also hybridized to a similar blot of the λdnaJ-dnakA deletions, and it showed a similar pattern of hybridization (results not shown).

DNA Sequence Analysis of dnaK and Comparison to Hsp70 Gene. The 5.3-kilobase (kb) HindIII fragment containing sequences that hybridized to the Drosophila and yeast Hsp70 genes was subcloned into pBR322. Restriction enzyme mapping and hybridization analyses localized the region of Hsp70 hybridization to between an Nru I site in the middle of the insert and a HindIII site near the dnaJ gene.

The primary DNA sequence of this region (Fig. 3) was determined. A single long open-reading frame that could code for a protein of 69,121 Da was identified (Fig. 4). Both the predicted amino acid composition and the amino-terminal sequence agrees with that determined from the analysis of purified dnaK protein, except that the protein lacks an NH2-terminal methionine (C. P. Georgopoulos, personal communication). This modification would decrease the size of the protein to 68,990 Da. A stop codon immediately precedes the AUG designated as the start codon, thus prohibiting initiation of dnaK at a methionine upstream. A comparison of the protein-coding region of the dnaK and the Drosophila Hsp70 gene (16) reveals 57% identity at the nucleotide level and 48% identity at the amino acid level (Fig. 4). Some regions of the polypeptide show a greater similarity. Between amino acid 138 and amino acid 183, >90% of the amino acids are the same, and between amino acid 365 and 489, 64% are

![Fig. 4.](image-url) Comparison of the predicted amino acid sequence of E. coli dnaK protein and Drosophila (Dr.) hsp70. Those amino acids identical in both sequences are shown by an asterisk. The first amino acid (aa) of the dnaK protein is designated 1. Those amino acids deleted in one sequence relative to the other are shown by a triangle.
the same. If one divided the dnaK protein into five equal segments, the second and fourth are more conserved (66% and 58%) than the first, third, and fifth (46, 42, and 23% respectively). dnaK is also homologous to the yeast Hsp70-related genes used as hybridization probes. At the nucleotide level, dnaK is 57% identical to two yeast genes, YGI101 and YGI102. The amino acid residues conserved from E. coli to Drosophila are nearly all conserved to yeast as well. These regions of high identity may represent functionally conserved regions of the protein.

**Hybridization of Isolated dnaK to E. coli Genomic DNA.**

Since it has been shown that the S. cerevisiae and Drosophila melanogaster genomes contain a family of Hsp70-related genes (8, 19), we wanted to determine whether E. coli also contained multiple Hsp70-related genes. The dnaK gene was hybridized under nonstringent conditions to fractionated E. coli genomic DNA. A single band was observed after hybridization to genomic DNA digested independently with three different restriction enzymes (Fig. 1B). Under similar hybridization conditions a yeast Hsp70 fragment hybridized to yeast genomic DNA reveals 8–10 Hsp70 homologous genes (8). The detection of only one band indicates that the E. coli genome contains a single Hsp70 homologous sequence—dnaK.

**Hybridization of 70,000-Da Heat-Shock Genes to an Archaeabacterium, Methanosarcina barkeri.** In an attempt to further establish the conservation of Hsp70 genes in evolution, M. barkeri genomic DNA was digested with restriction enzymes, electrophoresed, and transferred to nitrocellulose, and hybridized to protein-coding portions of Hsp70-related genes. Three probes, one from E. coli dnaK, one from yeast, and one from Drosophila Hsp70 were used in separate hybridizations. The same single band of hybridization was observed using either yeast and Drosophila or E. coli and Drosophila DNA as probe (Fig. 5). We suggest that M. barkeri contains Hsp70-related sequences.

**Fig. 5.** Hybridization of Hsp70 genes to DNA of an archaeabacterium. M. barkeri genomic DNA was digested with restriction enzymes, electrophoresed, and transferred to nitrocellulose. Three protein-coding fragments of Hsp70-related genes were used as hybridization probes: a fragment of the E. coli dnaK gene encompassing amino acids 23–325, a fragment of the yeast (S. cerevisiae) YGI102 gene encompassing amino acids 118–639, and a fragment of the Drosophila (D. melanogaster) Hsp70 gene encompassing amino acids 18–337.

**DISCUSSION**

Because 70,000-Da heat shock-inducible genes exist in two distantly related species, D. melanogaster and S. cerevisiae, we wondered whether E. coli contained Hsp70-related sequences. A heat-inducible gene in E. coli, dnaK, is 57% identical to the major heat shock gene of Drosophila (Hsp70). This identity extends over the entire protein-coding region with some regions showing extreme conservation. A comparison of the predicted amino acid sequences of the dnaK and Drosophila Hsp70 genes showed 48% overall identity. This identity increased to >90% in one 46-amino acid segment. The dnaK gene is also homologous to a yeast Hsp70 gene. The sequence of the yeast gene is 57% identical to dnaK and 67% identical to the Drosophila Hsp70. Given the high degree of similarity observed between dnaK and other 70,000-Da heat shock genes, we assert that these genes have diverged from a common ancestor rather than converged from unrelated sequences. These results are a remarkable demonstration of prokaryotic-eukaryotic sequence homology.

Based on comparison of SS RNA sequences, Hori and Osawa (20) have estimated that the prokaryotes and eukaryotes diverged about 1.8 x 10^9 years ago. Only a very few proteins have maintained recognizable sequence similarity between prokaryotic and eukaryotic species (21). c-type cytochromes, serine proteases, and the p-subunit of the ATP synthetase complex are among those that have been well conserved. Cytochrome c shows 10–48% similarity between eukaryotic and prokaryotic species. Bacterial trypsin from Streptomyces griseus is 26–31% identical to eukaryotic serine proteases. One very highly conserved protein is the p-subunit of ATP synthetase (23). Sequences from maize chloroplasts and beef mitochondria are 64% and 69% identical to the E. coli p-subunit. The homology between the dnaK protein and Drosophila hsp70 is thus comparable with the homology seen between some of the most highly conserved proteins known.

The archaeabacteria composed of the methanogens, extreme halophiles, and acidophiles form a unique biological grouping phylogenetically distant from typical bacteria (eubacteria) and eukaryotes. Three primary kingdoms have been proposed (24)—the archaea, the eubacteria, and the archaeabacteria. The archaeabacteria differ significantly from eubacteria and eukaryotes. For example, all eubacteria contain muramic acid in their cell walls while archaeabacteria do not. Membranes of archaeabacteria contain unusual lipids not found in members of the two other groups and tRNA base modifications commonly found in eukaryotic and prokaryotic tRNA are absent in archaeabacteria. The two bacterial lines of descent appear to be no more related to one another than either of them is to the eukaryotes (24). The detection of Hsp70-related sequences in an archaeabacteria thus dramatically shows the extreme conservation of the Hsp70 gene throughout evolution.

Both the Drosophila and yeast genomes contain a family of Hsp70-related genes (8, 19). In both cases, some members are heat shock inducible while others are transcribed under normal growth conditions and not inducible by heat treatment. Evidence presented here indicates that there is only one Hsp70-related gene, dnaK, in the E. coli genome. However, under normal growth conditions, dnaK accounts for 1.4% of the weight fraction of cellular protein and is the seventh most abundant protein in the cell (25). Transcripts of one of the Drosophila Hsp70-related proteins (Hsc4) are very abundant in cells in all stages of development, comparable in abundance to some actin mRNAs (26). Therefore, in both eukaryotes and prokaryotes Hsp70-related proteins appear to be abundant under normal physiological conditions.
Although the function of the heat shock proteins is not known, the information from eukaryotic species including the abundance of these proteins suggests structural roles for the heat shock proteins either in the nucleo- or cytoskeleton. Studies of avian and mammalian heat shock proteins have shown that hsp70 is identical to a highly conserved polypeptide previously shown to copurify with intermediate filaments and microtubules (3). Antibodies to chicken hsp70 stains a pattern of stress fibers in the cytoplasm (27). Unfortunately, the information available concerning the dnaK protein does not obviously suggest its function in cellular metabolism. The dnaK protein is required for the replication of the phages λ and P22 but not T4, T7, φX174, or fd (28). Mutant λ phage able to grow on a dnaK strain contain an altered P gene product (10). The P gene product is thought to interact with the λ O gene product and the host dnaB gene product to form a replisome structure at λ ori (29). The temperature-sensitive phenotype of some dnaK mutants is strong evidence that the dnaK gene is required for the normal growth of E. coli. It has been suggested that dnaK is involved in host DNA replication (30). However, the existence of mutants that prevent λ DNA replication but do not affect host growth (30) suggests that the functions involved in host and phage metabolism may be different. Further genetic and biochemical analysis of dnaK and its protein product should help elucidate the role of hsp70 in both normal and stress situations.

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