Resting Chondrocytes in Culture Survive without Growth Factors, but Are Sensitive to Toxic Oxygen Metabolites

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Abstract. Chondrocytes in dense suspension culture in agarose survive in serum-free DME because they secrete low molecular mass compounds supporting their own viability. This activity can be replaced by pyruvate, or sulfhydryl compounds, e.g., cysteine or dithioerythritol. Catalase, an enzyme decomposing H₂O₂, also protects the cells, whereas superoxide dismutase has no effect. Therefore, chondrocytes in culture are sensitive to toxic compounds derived from molecular oxygen, i.e., hydroxyl radicals or hydrogen peroxide spontaneously generated in DME containing ascorbate and ferrous ions. Poly-ADP-ribosylation is an important step in the cascade of events triggered by these compounds.

To survive, chondrocytes do not require stimulation by growth factors. They remain resting cells in fully defined, serum-free culture also at low density. Proliferation and hypertrophy can be induced by serum, but not by low cell density alone.

Due to respiration, cells reduce large amounts of molecular oxygen to water, but minor quantities of H₂O₂ and O₂⁻ or OH⁻ radicals are also formed. Aerobic cells protect themselves against these toxic oxygen species by decomposing them with superoxide dismutases, catalase, and/or peroxidases or with antioxidants, such as α-tocopherol, carotinoids, bilirubin, pyruvate, glutathione, or cysteine (for review, see Cadenas, 1989).

Hyaline cartilage is an avascular tissue with relatively few cells embedded in abundant extracellular matrix. Therefore, chondrocyte metabolism and differentiation depends on diffusion of nutrients and regulatory factors, either from surrounding tissues or from one cartilage cell to another. Cartilage matrix is penetrated even by large molecules because it consists of a loose network of collagen fibrils entrapping the highly charged, polyanionic proteoglycans which bind large amounts of water (Maroudas and Bannon, 1981). When compared with cells of vascularized tissues, chondrocytes in situ are exposed to very low oxygen tensions (Maroudas, 1973; Stockwell, 1983). It is conceivable, therefore, that they are exceptionally sensitive to oxygen, particularly at pressures normally encountered in tissue culture. In fact, development of the chondrocytic phenotype by mesenchymal cells in culture is favored by reduced oxygen pressures (Pawelek, 1969).

Chick embryo sternal chondrocytes in suspension culture survive even in the absence of serum when grown at high density. The conditioned media support the viability of similar cells at low density suggesting that chondrocytes produce factors required for their own survival (Bruckner et al., 1989). Here, we identify this activity as a low molecular weight antioxidant and as the only prerequisite for cell viability.

Materials and Methods

Agarose Cultures

Chick embryo sternal chondrocytes were cultured in agarose at densities between 0.08 and 1.0 × 10⁶ cells/ml (Benya and Shaffer, 1982; Bruckner et al., 1989). Briefly, 60-mm Petri dishes were coated with agarose and cell suspensions in low melting agarose were overlaid. To facilitate their observation, cells were sedimented at 37°C to the interface between the agarose layers. The low melting agarose was then allowed to gel by brief exposure of the cultures to 4°C. Cultures were supplied with appropriate media which were regularly replaced after 48 h.

Culture Media

The culture media were based on serum-free DME, containing 60 μg/ml of β-aminopropionitrile fumarate (Fluka AG, Buchs, Switzerland), and penicillin and streptomycin at 100 U/ml and 100 μg/ml, respectively. Other ingredients were added as specified. Conditioned media were obtained from cultures with high cell density and were subjected to ultrafiltration (model 8MC; Grace Amicon, Wallisellen, Switzerland). The concentrates were diluted with DME to appropriate concentrations. The filtrates were subjected to repeated ultrafiltration on PM 10, YM5, and YM2 membranes, respectively (separation limits: 10, 5, and 2 kD).

Determination of Cell Viability

Whole cultures were stained by adding to 60-mm culture dishes 100 μl of 0.1% (wt/vol) Trypan Blue in PBS. After 10 min, at least five randomly selected micrographs per dish were taken and cells were counted. Cell viability was determined as the fraction of dye excluding cells.
Collagen Synthesis

Cultures were metabolically labeled with radioactive proline. The collagens were extracted after pepsin digestion of the cultures and were analyzed as described (Bruckner et al., 1989).

Results

Primary chondrocytes of chick embryo sternum are viable at a density of $2 \times 10^4$ cells/ml in agarose gels in DME containing $50 \mu g/ml$ of ascorbate, but no growth factors or serum. Media conditioned by such cultures support viability of cells at lower densities. Upon ultrafiltration, the compound was not retained in the concentrate, even when the molecular mass cut-off of the membranes was 2 K. However, it bound to mixed bed ion exchange columns and was extractable, albeit in small quantities, into ethyl acetate independently of the pH of the aqueous phase. Therefore, the extractable, albeit in small quantities, into ethyl acetate in ever, it bound to mixed bed ion exchange columns and was analyzed as described (Bruckner et al., 1989).

These results show that oxygen toxicity caused the loss of viable cells in serum-free chondrocyte culture. The findings emphasize the importance of $H_2O_2$ or OH', rather than $O_2^{-}$ . Moreover, the toxic compounds appeared to originate from the media rather than intracellularly.

Andrae et al. (1985) and O'Donnell-Tormey et al. (1987) have shown that mammalian cells in culture secreted pyruvate and related α-keto acids to protect themselves against hydrogen peroxide-induced cytotoxicity. When cultures without cysteine were supplied with pyruvate, cells survived to an extent similar to that observed with cysteine (Fig. 5). Glucose is available to the cells at a large excess. Therefore, the intracellular pool of pyruvate probably is not affected by 1 mM of exogenous pyruvate indicating again that hydrogen peroxide toxicity was derived from the media.

Berger (1985) proposed that the toxic effects of hyperoxia and hydrogen peroxide are indirectly mediated by "suicidal" poly-ADP-ribosylation of intracellular proteins with concomitant depletion of the cellular NAD+ pools. If this mechanism is operative, cell viability ought to be improved by specific inhibitors of poly-(ADP-ribose)polymerase, e.g., benzamide or 3-aminobenzamide. Gille et al. (1989) have shown that certain cell types were protected by 3-aminobenzamide while others were not. Chondrocytes in our culture system, however, were protected by 0.5 µg/ml of benzamide documenting the low toxicity of this drug. However, long term viability was not supported by the drug alone, but also required the presence of cysteine (Fig. 5). These observations indicated that the effects of toxic oxygen species were not entirely abolished by benzamide implying that, under our conditions, poly-ADP-ribosylation was an important, but not the only, cause of cell loss. Interestingly, Baker et al. (1989) reported that ATP levels were suppressed in chondrocytes exposed to $H_2O_2$ because of oxidation of glycolytic enzymes.

In serum-free culture, chondrocytes did not proliferate (Table I). However, after 7 d in culture, the cells produced radioactively labeled collagens II, IX, and XI, whereas collagen X, a marker for hypertrophic chondrocytes, was not detectable (Fig. 6, lanes 1 and 3). Therefore, the cells resem-
bled resting chondrocytes. When FBS was added to the media, the cells became hypertrophic and secreted large amounts of collagen X (Fig. 6, compare lanes 1 and 3 with lanes 2 and 4). In agreement with our recent results (Bruckner et al., 1989), this observation demonstrated that FBS could induce in vitro chondrocyte hypertrophy that was not prevented by antioxidants.

Discussion

The results presented here support two major conclusions. Firstly, chondrocytes in agarose suspension culture are sensitive to oxygen-derived toxicity arising in the culture media. The cells are effectively protected by antioxidants which are either supplied exogenously or produced by the cells themselves. Likely candidates for cellular products are glutathione or cysteine (Cadenas, 1989). Cellular NAD⁺ depletion following poly-ADP-riboseylation has tentatively been identified as a step in the sequence of events leading to cell death.

The high sensitivity of chondrocytes towards oxygen toxicity is plausible in view of the low oxygen pressures in cartilage and highlights possible mechanisms of tissue destruction in degenerative cartilage disease. During phagocytosis, inflammatory cells actively produce oxygen-derived radicals as a means to eliminate infectious agents. As a consequence, cartilage degeneration is induced either by direct damage or by stimulation of the production of proteolytic enzymes, including collagenases (Burkhardt et al., 1986).
does not depend on stimulation by hormones or growth factors.

Hypertrophy of chondrocytes at low density in agarose cultures is induced by FBS. However, it remains possible that the low cell density alone is responsible for this effect. Here, we show that resting cells can be maintained in serum-free culture also at low density. This implies that serum components are required for the late stages of chondrocyte differentiation.

Finally, the culture system described here offers advantages for studies on the regulation of chondrocyte differentiation. The culture media are fully defined and no conditioned media are necessary. The system is superior also to the one we have developed recently because the low cell density allows smaller amounts of regulation factors to be effective.

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References

Andrae, U., J. Singh, and K. Ziegler-Skylakakis. 1985. Pyruvate and related α-ketoacids protect mammalian cells in culture against hydrogen peroxide induced cytotoxicity. Toxicol. Lett. (Amst.). 28:93–98.

Andrews, H. J., T. A. Edwards, T. E. Caswell, and B. L. Hazleman. 1989. Transforming growth factor-β stimulates partial inhibition of interleukin-1-stimulated cartilage degradation in vitro. Biochem. Biophys. Res. Commun. 162:144–150.

Baker, M. S., J. Feigan, and D. A. Lowther. 1989. The mechanism of chondrocyte hydrogen peroxide damage: depletion of intracellular ATP due to suppression of glycolysis caused by oxidation of glyceraldehyde-3-phosphate dehydrogenase. J. Rheumatol. 16:7–14.

Barde, Y. A., D. Edgar, and H. Thoenen. 1983. New neurotrophic factors. Annu. Rev. Physiol. 45:601–612.

Bates, E. J., C. C. Johnson, and D. A. Lowther. 1985. Inhibition of proteoglycan synthesis by hydrogen peroxide in cultured bovine articular cartilage. Biochim. Biophys. Acta. 838:221–228.

Berger, N. A. 1985. Poly(ADP-ribose) in the cellular response to DNA damage. Radiat. Res. 101:4–15.

Bruckner, P., I. Hörler, M. Mendler, Y. Houze, K. H. Winterhalter, S. G. Eich-Bender, and M. A. Spycher. 1989. Induction and prevention of chondrocyte hypertrophy in culture. J. Cell Biol. 109:2537–2545.

Burkhardt, H., M. Schwingel, H. Menninger, H. W. MacCartney, and H. Tschesche. 1986. Oxygen radicals as effectors of cartilage destruction: direct degradative effect on matrix components and indirect action via activation of latent collagenase from polymorphonuclear leukocytes. Arthritis Rheum. 29:379–387.

Cadenas, E. 1989. Biochemistry of oxygen toxicity. Annu. Rev. Biochem. 58:79–110.

Gille, J. J. P., C. G. M. van Berkel, E. Mulaart, J. Vug, and J. Jonje. 1989. Effects of lethal exposure to hyperoxia and to hydrogen peroxide on NAD(H) and ATP pools in Chinese hamster ovary cells. Mutat. Res. 214:89–96.

Ishikawa, Y., J. E. Chin, H. L. Hubbard, and R. E. Wuthier. 1985. Utilization and formation of amino acids by chicken epiphyseal chondrocytes: comparative studies with cultured cells and native tissue. J. Cell. Physiol. 123:79–88.

Lindahl, A., J. Isgaard, A. Nilsson, and O. G. P. Isaksson. 1987. Differential effects of growth hormone and insulin-like growth factor-I (IGF-I) on colony formation of epiphyseal chondrocytes in suspension culture in rats of different ages. Endocrinology. 121:1061–1069.

Maroudas, A. 1973. Transport through articular cartilage. In Symposium on Normal and Osteoarthrotic Cartilage. S. Y. Ali, M. W. Elves, and D. H. Leaback, editors. University of London, London. p. 30.

Maroudas, A., and C. Bannow. 1981. Measurement of swelling pressure in cartilage and comparison with osmotic pressure of constituent proteoglycans. Biochemistry. 18:619–623.

Mauviel, A., L. Teyton, R. Bhatnagar, H. Penfornis, M. Laurent, D. Hartmann, J. Bonaventure, G. Loyau, J. Sakkuvraja, and J. P. Pujol. 1988. Interleukin-1α modulates collagen gene expression in cultured synovial cells. Biochem. J. 252:247–255.

O'Donnell-Tormey, J., C. F. Nathan, K. Lanks, C. J. Deboer, and J. de la Harpe. 1987. Secretion of pyruvate: an antioxidant defense of mammalian cells. J. Exp. Med. 165:500–514.

Pawelek, J. M. 1969. Effects of thymine and low oxygen tension on chondroge- neic expression in cell culture. Dev. Biol. 19:52–72.

Reddini, F., P. Galera, A. Mauviel, and J. P. Pujol. 1988. Transforming growth factor β stimulates collagen and glycosaminoglycan biosynthesis in cultured rabbit articular chondrocytes. FEBS (Fed. Eur. BioL Soc.) Letts. 234:172–176.

Schalkwijk, J., W. B. van den Berg, L. B. A. van de Putte, and L. A. B. Joosten. 1985. Hydrogen peroxide suppresses the proteoglycan synthesis of intact cartilage. J. Rheumatol. 205:205–210.

Stockwell, R. A. 1983. Metabolism of cartilage. In Cartilage. Vol. 1. B. K. Hall, editor. Academic Press Inc., Orlando, FL. 253–273.

Tso, M. C., B. J. Waithall, and R. G. Ham. 1982. Clonal growth of human epidermal keratinocytes in a defined medium. J. Cell. Physiol. 110:219–229.

Tyler, I. A. 1985. Chondrocyte-mediated depletion of articular cartilage pro- teoglycans in vitro. Biochem. J. 225:493–507.

Vincent, F., H. Brun, E. Clain, X. Ronot, and M. Adolphe. 1989. Effects of oxygen-free radicals on proliferation kinetics of cultured rabbit articular chondrocytes. J. Cell. Physiol. 141:202–206.

Table I. Proliferation of Chick Embryo Chondrocytes in Serum-Free DME, 1 mM Cys

| Experiment | 0   | 1   | 3   | 7   | 13  |
|------------|-----|-----|-----|-----|-----|
| 1          | 1.00 ± 0.10 | 0.60 ± 0.09 | 0.70 ± 0.04 | 0.70 ± 0.09 | 0.60 ± 0.06 |
| 2          | 0.40 ± 0.06  | 0.40 ± 0.03  | 0.40 ± 0.09  | 0.30 ± 0.05  | 0.30 ± 0.07  |
| 3          | 0.08 ± 0.01  | 0.10 ± 0.02  | 0.07 ± 0.01  | ND            | 0.05 ± 0.01  |

Whole cultures were stained with trypan blue and representative light micrographs were taken. The number of viable cells was determined in four micrographs per culture dish.