Path of Glucose Breakdown and Cell Yields of a Facultative Anaerobe, *Actinomyces naeslundii*

By B. B. BUCHANAN*

Department of Microbiology, Duke University Medical School, Durham, North Carolina, U.S.A.

AND L. PINE


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SUMMARY

*Actinomyces naeslundii* fermented glucose primarily by the Embden–Meyerhof pathway, as based on $^{14}$C-glucose fermentation data and enzyme studies. Enzymes of the oxidative pentose phosphate cycle were also present, but functioned only to a minor extent. Growth on glucose was increased 2- to 4-fold in the presence of substrate amounts of CO$_2$ or O$_2$. This increase was attributed to the additional energy (ATP) made available from the breakdown of pyruvate to acetyl coenzyme A. In the absence of CO$_2$ or O$_2$, pyruvate was reduced to lactate. The weight of organism produced/mole ATP ($Y_{ATP}$) was 15–18 g. units under anaerobic conditions with CO$_2$, dependent on the growth medium, and 20 under aerobic growth conditions.

INTRODUCTION

*Actinomyces naeslundii* is a pathogenic organism which ferments sugars and requires substrate amounts of CO$_2$ for maximal growth. Pine & Howell (1956) and Buchanan & Pine (1963) investigated the glucose fermentation of *A. naeslundii* and found that fermentation products depended on the conditions of culture. Without added CO$_2$ (gaseous or bicarbonate), growth was limited and glucose was fermented to lactate

\[
glucose \rightarrow 2 \text{lactate.} \tag{1}
\]

When substrate amounts of CO$_2$ were present, lactate formation was decreased, and, for each mole of CO$_2$ fixed, an equimolar amount of acetate, formate, and succinate was produced (Pine & Howell, 1956):

\[
glucose + CO_2 \rightarrow \text{formate} + \text{acetate} + \text{succinate}. \tag{2}
\]

The ratio of products with added CO$_2$ was not constant, and dependent upon the specific fermentation a combination of equations (1) and (2) was observed. Based on the average results of three fermentations (Buchanan & Pine, 1963, table 1, no. 3, 5, and 7), a general equation was derived:

* Present address: Department of Cell Physiology, University of California, Berkeley, California.
\[
3.5 \text{ glucose} + 3 \text{ CO}_2 \rightarrow 3 \text{ formate} + 3 \text{ acetate} + 3 \text{ succinate} + 1 \text{ lactate.} \quad (3)
\]

CO\textsubscript{2} was fixed into the carboxyl groups of succinate (Pine, 1956, 1960). Presumably CO\textsubscript{2} functioned in the formation of oxaloacetate and malate, both of which acted as electron acceptors and permitted the formation of acetate and formate (Buchanan & Pine, 1963) from pyruvate. CO\textsubscript{2} could be partially replaced by either malate or fumarate, with a simultaneous increase in the formation of acetate and formate. Recently, Buchanan & Pine (1965) found that CO\textsubscript{2} was also required for the biosynthesis of aspartate for which the organisms lacked a permease.

When \textit{Actinomyces naeslundii} grew aerobically, O\textsubscript{2} served as an electron (hydrogen) acceptor and CO\textsubscript{2} was required only to initiate growth (Pine & Howell, 1956). Buchanan & Pine (1963) found that glucose was degraded quantitatively to acetate and CO\textsubscript{2} in accordance with the equation:

\[
\text{glucose} + \text{O}_2 \rightarrow 2 \text{ acetate} + 2 \text{ CO}_2 + 2 \text{ H}_2\text{O}. \quad (4)
\]

As based on the above equations, glucose breakdown by \textit{A. naeslundii} might occur by several pathways, and there was until now no evidence concerning which pathway was involved. The present paper presents evidence that \textit{A. naeslundii} ferments glucose principally by way of the Embden–Meyerhof pathway, although the possible operation of other pathways to a minor degree is indicated from isotope data. Previous conclusions about the functions of CO\textsubscript{2} and O\textsubscript{2} in \textit{A. naeslundii} were confirmed in the present work, and CO\textsubscript{2} and O\textsubscript{2} are related to the energy which is available for the growth of this organism.

**METHODS**

\textit{Actinomyces naeslundii} (\textit{A. bovis}, ATCC 10049), described previously (Buchanan & Pine, 1963), and \textit{Actinomyces propionicus} (Buchanan & Pine, 1962) were grown at 37°C in the casitone medium of Pine & Watson (1959) or in the casein hydrolysate medium of Pine & Howell (1956). Fermentation products were analysed as described previously (Buchanan & Pine, 1963). Lactate and succinate were isolated by Dowex-1 column chromatography (Busch, Hurlbert & Potter, 1952) as modified by Buchanan & Pine (1963). Purity was established by co-chromatography on paper of a sample of the isolated radioactive acids with authentic lactate or succinate. Chromatograms were developed descendingly by using ethanol + water + concentrated ammonium hydroxide (80 + 15 + 5, by vol.) as the solvent (Cheftel, Munier & Machebeuf, 1953). Acids were located as yellow spots against a blue background by spraying the chromatograms with bromcresol green (0.01 % (w/v) in 95\% (v/v) ethanol in water neutralized to pH12 with 0.1 N-NaOH) and by radioautography. In all cases, yellow spots coincided exactly with the darkened areas of the X-ray film. Acetate and formate were isolated by steam distillation and were identified by their Duclaux constants.

For radioactivity determinations, compounds were oxidized to CO\textsubscript{2} and counted as BaCO\textsubscript{3}. Oxidations were done in a combustion chamber equipped with a train of three collection tubes, one of which served as a KMnO\textsubscript{4} scrubber (5% (w/v) KMnO\textsubscript{4} in 0.3 H\textsubscript{2}SO\textsubscript{4}), leading from the chamber to two tubes containing a saturated solution of Ba(OH)\textsubscript{2}. Helium was used to flush the system continuously. The BaCO\textsubscript{3} was separated by centrifugation in stoppered tubes, washed three times with boiling water, and suspended in 95\% (v/v) ethanol in water. Suitable samples were pipetted into lightly greased planchets and dried under heat-lamps.
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Radioactivity was measured with a continuous flow counter equipped with a 'micro-
mil' window. 'Q-gas' (98.4\% (v/v) He + 1.6\% (v/v) butane) was used as the ionizable
gas. Samples were corrected for background and self-absorption by reference to a
standard curve obtained with known amounts of BaCO₃.

Succinate, lactate and acetate were wet-ashed by the method of Van Slyke, Plazin &
Weisiger (1951), and the specific activity of the BaCO₃ (c.p.m./μmole BaCO₃) was
multiplied by the number of carbon atoms in the molecule to give the average total
specific activity. Formate was converted to CO₂ in the presence of acetate by oxidation
with mercuric sulphate by the method of Friedemann (1938) as modified by Rabino-
witz & Barker (1956). The residual acetate was collected by steam distillation and its
purity verified by its Duclaux constants. Acetate was decarboxylated with the Schmidt
reaction (Phares, 1951). After decarboxylation, the solution was made alkaline
with KOH, and the methylamine was isolated by distilling into diluted HCl; methyl-
amine was oxidized to CO₂ with alkaline permanganate (Katz, Abraham & Chaikoff,
1955). Lactate was decarboxylated with chromic acid (Calvin et al. 1949); the acetate
formed was isolated and degraded as described above. Succinate was decarboxylated
by the method of Phares & Long (1955). The specific activity of the methylene carbons
of succinate was determined by subtracting the specific activity of the carboxyl
carbons from the total specific activity obtained by wet-ashing. The validity of this
method for determining the activity of the methylene carbons was established by
decarboxylating a sample of synthetic succinate 2,3-14C. No radio-activity was released
with decarboxylation and when the residual ethylenediamine was isolated on paper
chromatograms (Buchanan, 1962), its specific activity was in excellent agreement with
the specific activity of the original succinate.

For enzyme studies, the organism was grown in the Casitone medium containing
25 μmoles NaHCO₃/ml., under Na₂CO₃ + pyrogallol seals. A volumetric flask of
either 1 or 2 l. capacity filled to the base of the neck was inoculated with 10 ml. of an
actively growing culture and incubated for 3–4 days. Organisms were harvested by
centrifugation, washed three times with 0.01 M-potassium phosphate buffer (pH 7.0)
containing 0.01% (w/v) neutralized cysteine HCl. The packed cells were resuspended
in this buffer to give a 50% (v/v) suspension.

Like corynebacteria and lactobacilli (Gunsalus, 1955) the actinomyces organisms
were difficult to break. Treatment with lysozyme, grinding with glass beads, sonic
oscillation with a 12 kc. apparatus (50 W.), and treatment in a French pressure cell
were ineffective in releasing soluble protein. The only procedures found to break the
organisms were grinding with alumina or subjection to a 20 kc. (75 W.) sonic oscillator

For alumina-broken preparations, 8–10 g. alumina was added per g. wet wt.
organism, and the suspension was ground at 4° in a Sorvall Omnimixer (Ivan Sorvall,
Norwalk, Connecticut) for 10 min. in 30 sec. bursts at 1 min. intervals to prevent
heating. For sonic preparations, suspensions of organism were subjected to sonic
treatment at 4° for 10 min. in 30 sec. bursts at 1 min. intervals to prevent heating.
Treated suspensions were centrifuged for 15 min. at 23,500 g at 4° to remove debris
and unbroken organisms. The precipitate was discarded; the supernatant fluid was
dialysed for 4 hr against 0.01 M-potassium phosphate buffer (pH 7.0) containing 0.01% (w/v)
neutralized cysteine HCl. When the oxidation or reduction of nicotinamide
nucleotides (NAD) was to be measured, the dialysed extract was centrifuged for
60 min. at 100,000 g in a preparative ultracentrifuge. The supernatant fraction, which contained the soluble enzymes, was saved; the black precipitate, which contained a very active NADPH₂ oxidase system, was discarded.

Enzymes were assayed at room temperature (25° ± 2°). Oxidation and reduction of NAD were measured by the change in extinction at 340 mμ with a Beckman DU spectrophotometer. Fructosediphosphate aldolase (Enzyme Commission, subsequently referred to as E.C., no. 4.1.2.13) was assayed according to Sibley & Lehninger (1949) as modified by Bard & Gunsalus (1950), glucosephosphate isomerase (E.C. 5.3.1.9) according to Slein (1955), phosphate acetyltransferase (E.C. 2.3.1.8) according to Stadtman (1955) based on the reaction of acetyl phosphate with hydroxylamine (Lipmann & Tuttle, 1945), isocitrate dehydrogenase (E.C. 1.1.1.42) and malate dehydrogenase (E.C. 1.1.1.37) according to Ochoa (1955a, b), aconitate hydratase (E.C. 4.2.1.3) according to Anfinsen (1955), fumarate hydratase (E.C. 4.2.1.2) according to Massey (1955), and glutamate dehydrogenase (E.C. 1.4.1.3) according to Strecker (1955). Protein was estimated by the phenol method of Sutherland, Cori, Haynes & Olsen (1949) with bovine serum albumin as a standard. For each enzyme, the initial rate was directly proportional to the protein concentration. The rates varied little in different preparations.

The chemicals used were of reagent grade and were obtained from commercial sources.

RESULTS

One of the most useful techniques in elucidating metabolic pathways in microorganisms is the use of 14C-labelled substrates (Wood, 1961). For heterotrophic organisms, an organic substrate labelled in a specific position is supplied to growing cultures and the fermentation products isolated and degraded to determine the positions of the label. For saccharolytic organisms such as Lactobacillus casei and Streptococcus faecalis (Gibbs, Dumrose, Bennet & Bubeck, 1950), glucose 1-14C and glucose 6-14C have been used most frequently. In the Embden–Meyerhof pathway, 1-14C and 6-14C glucose are both converted to fermentation products, such as lactate, which show identical labelling patterns. When glucose is fermented by other mechanisms (for example, the oxidative pentose phosphate pathway) the lactate formed in glucose 1-14C and glucose 6-14C fermentations shows quite different labelling patterns.

Table 1 shows the results of the fermentation of glucose 1-14C and glucose 6-14C by Actinomyces naeslundii grown anaerobically in substrate amounts (25 μm./ml.) of CO₂ added to the medium as bicarbonate. The ratio of the fermentation products was essentially as is shown in equation (3). The radioactivity recovered in the formate, CO₂ and carboxyl groups of lactate and succinate was low. This eliminated the oxidative pentose phosphate cycle, Entner–Doudoroff, and hexose monophosphate pathways (see review by Wood, 1961) as major mechanisms for glucose dissimilation. Based on radioactivity recovered in the formate, CO₂ and carboxyl groups of acetate, formate and succinate, not more than 6% of the total glucose fermented was channelled through any one of these pathways.

In the Embden–Meyerhof pathway, the glucose 1-carbon and the glucose 6-carbon atoms are precursors of the methyl-carbon atoms of lactate, of acetate, and of a methylene carbon of succinate (assuming succinate synthesis from a C₃ unit + CO₂). Chemically the two methylene carbons of succinate are indistinguishable, and therefore
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the total activity in both carbons must be considered. In general, the degradation data in Table 1 fit these requirements for formation by the Embden–Meyerhof pathway. The specific activities of acetate, lactate and succinate were approximately 50% of the original 14C-glucose molecules. For unknown reasons, the specific activity of acetate isolated from the glucose 6-14C fermentation was low and was only 33% of the original 14C-glucose. Of the total radioactivity in acetate and lactate, at least two-thirds resided in the methyl carbon atoms. Of the succinate, at least 90% of the total activity resided in the two methylene carbons.

Table 1. Fermentation of glucose 1-14C and glucose 6-14C by Actinomyces naeslundii

Organisms were grown anaerobically in 50 ml. Casitone medium (0.5%, w/v) containing either glucose 1-14C or glucose 6-14C with 25μmoles NaHCO3/ml. under Na2CO3 + pyrogallol seals. The following specific activities and total c.p.m., respectively, were used: glucose 1-14C 1012 c.p.m./μmole and 12.75 × 10⁶ c.p.m.; glucose 6-14C, 601 c.p.m./μmole and 7.25 × 10⁶ c.p.m. Assimilated glucose was determined by counting samples of washed organisms at infinite thinness. Other experimental details are given in the text.

<table>
<thead>
<tr>
<th></th>
<th>Glucose 1-14C</th>
<th>Glucose 6-14C</th>
<th>Glucose 1-14C</th>
<th>Glucose 6-14C</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ remaining</td>
<td>—</td>
<td>—</td>
<td>5.0</td>
<td>0.2</td>
</tr>
<tr>
<td>CO₂ fixed</td>
<td>52.5</td>
<td>54.9</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>CH₃-COOH</td>
<td>47.1</td>
<td>49.7</td>
<td>45.2</td>
<td>33.6</td>
</tr>
<tr>
<td>CH₃</td>
<td>—</td>
<td>—</td>
<td>40.0</td>
<td>21.4</td>
</tr>
<tr>
<td>—COOH</td>
<td>—</td>
<td>—</td>
<td>7.0</td>
<td>9.3</td>
</tr>
<tr>
<td>HCOOH</td>
<td>48.2</td>
<td>52.9</td>
<td>5.8</td>
<td>0.8</td>
</tr>
<tr>
<td>CH₃-CHOH-COOH</td>
<td>21.4</td>
<td>23.6</td>
<td>52.7</td>
<td>48.0</td>
</tr>
<tr>
<td>CH₃</td>
<td>—</td>
<td>—</td>
<td>37.8</td>
<td>37.8</td>
</tr>
<tr>
<td>—CHOH—</td>
<td>—</td>
<td>—</td>
<td>6.6</td>
<td>3.8</td>
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<tr>
<td>—COOH</td>
<td>—</td>
<td>—</td>
<td>4.0</td>
<td>6.5</td>
</tr>
<tr>
<td>HOOCC-CH₃-CH₂COOH</td>
<td>54.9</td>
<td>54.5</td>
<td>53.1</td>
<td>47.5</td>
</tr>
<tr>
<td>HOOCC</td>
<td>—</td>
<td>—</td>
<td>2.0</td>
<td>0.4</td>
</tr>
<tr>
<td>—CH₄—</td>
<td>—</td>
<td>—</td>
<td>23.6</td>
<td>23.5</td>
</tr>
<tr>
<td>Redox index</td>
<td>0.98</td>
<td>0.98</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Glucose assimilated</td>
<td>14.0</td>
<td>10.2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Carbon recovery (%)</td>
<td>77.9</td>
<td>76.7</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>14C Carbon recovery (%)</td>
<td>78.0</td>
<td>79.4</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Pertinent to demonstrating a particular metabolic pathway in an organism is the demonstration of its constituent enzymes. Aldolase is considered indicative of the Embden–Meyerhof pathway, and so far it has not been shown to function in other saccharolytic pathways (Buyze, van den Hamer & De Haan, 1957). Table 2 shows that aldolase was present in cell-free extracts of Actinomyces naeslundii and that its capacity was relatively high (cf. McDonald, Cheldelin & King, 1960). Extracts of a related organism, Actinomyces propionicus (Buchanan & Pine, 1962), also showed aldolase activity, with a rate about two-thirds that observed in A. naeslundii, thus indicating the Embden–Meyerhof pathway is possibly widespread in this group of organisms. Glucosephosphate isomerase, an enzyme of the Embden–Meyerhof pathway, and phosphate acetyltransferase, which often occurs in anaerobic bacteria (Stadtman, 1955), were also present in A. naeslundii (Table 2).

In a previous study, Actinomyces naeslundii was grown anaerobically in 14CO₂ and
glutamate and aspartate were isolated and degraded (Buchanan & Pine, 1965). The labelling pattern observed in glutamate was consistent with its biosynthesis from α-ketoglutarate, formed by the tricarboxylic acid cycle. This conclusion is supported by results of the present investigation which show that isocitric dehydrogenase, aconitase, and NADP-linked glutamic dehydrogenase were present in relatively high amounts in A. naeslundii (Table 2).

Table 2. Demonstration of certain enzymes in cell-free extracts of *Actinomyces naeslundii*

<table>
<thead>
<tr>
<th>Enzyme</th>
<th>μmoles substrate used/mg. protein/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fructosediphosphate aldolase</td>
<td>1.6</td>
</tr>
<tr>
<td>Glucosephosphate isomerase</td>
<td>0.5</td>
</tr>
<tr>
<td>Phosphate acetyltransferase</td>
<td>18.0</td>
</tr>
<tr>
<td>Aconitate hydratase</td>
<td>1.7</td>
</tr>
<tr>
<td>Isocitrate dehydrogenase</td>
<td>8.5</td>
</tr>
<tr>
<td>Glutamate dehydrogenase (NADP linked)</td>
<td>7.5</td>
</tr>
<tr>
<td>Malate dehydrogenase</td>
<td>59.0</td>
</tr>
<tr>
<td>Fumarate hydratase</td>
<td>3.8</td>
</tr>
<tr>
<td>Glucose-6-phosphate dehydrogenase</td>
<td>0.5</td>
</tr>
<tr>
<td>Phosphogluconate dehydrogenase</td>
<td>2.6</td>
</tr>
<tr>
<td>Other enzymes of oxidative pentose phosphate pathway</td>
<td>0.1*</td>
</tr>
</tbody>
</table>

* This value does not represent the activity of any single enzyme, but instead is the over-all rate of conversion of ribose 5-phosphate to glucose 6-phosphate.

The mechanism by which CO₂ was incorporated into the carboxyl carbons of succinate by *Actinomyces naeslundii* was not determined unequivocally. However, a low but significant exchange reaction between ¹⁴CO₂ and the β-carboxyl carbon of oxaloacetate was demonstrated (Buchanan, 1962), and this provided evidence that the primary carboxylation reaction in *A. naeslundii*, leading to succinate, is the phosphopyruvate carboxylase (E.C. 4.1.1.32) reaction originally studied by Utter & Kurahashi (1954). Oxaloacetate would then be reduced to succinate by a reversal of the malic dehydrogenase, fumarase and succinic dehydrogenase (E.C. 1.3.99.1) reactions. The present demonstration (Table 2) of fumarase and malic dehydrogenase activities in *A. naeslundii* extracts supports this conclusion.

Glucose-6-phosphate dehydrogenase (E.C. 1.1.1.49) and phosphogluconate dehydrogenase (E.C. 1.1.1.44) were demonstrated in extracts of *Actinomyces naeslundii* (Table 2). As based on the reduction of NADP with ribose 5-phosphate as substrate (Table 2), the other enzymes of the pentose cycle which convert ribose 5-phosphate to glucose 6-phosphate were also present. These data therefore indicate that *A. naeslundii* has a complete oxidative pentose phosphate cycle but, as pointed out above, its operation as a major mechanism of glucose breakdown in *A. naeslundii* was excluded on the basis of the glucose 1-¹⁴C fermentation data (Table 1). These data indicated that, at most, 6% if the total glucose fermented could go by this pentose pathway. Similar results were obtained in independent glucose 1-¹⁴C fermentations carried out under aerobic conditions (Buchanan, 1962), thus eliminating the possibility of its function as a major pathway in aerobic growth.

Because of its relation to *Actinomyces naeslundii*, *A. propionicus* was tested for certain enzymes found in *A. naeslundii*. Other than the aldolase mentioned above, 6-
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Phosphogluconic dehydrogenase and isocitric dehydrogenase were found in extracts of *A. propionicus*, at essentially the same concentration as in *A. naeslundii* (Buchanan, 1962).

With the recognition that glycolysis was the major pathway used for the fermentation of glucose by *Actinomyces naeslundii*, and that the fermentation products depended on the availability and nature of the added electron acceptors, we tried to correlate the relative yields of organism to the energy theoretically released in a particular type of

![Graph](image)

Fig. 1. Dependence of the yields of *Actinomyces naeslundii* on the conditions of culture. I, Aerobic growth in Casitone medium with CO₂ = ●; without CO₂ = ○. II, Anaerobic growth in Casitone medium with CO₂. III, Anaerobic growth in casein hydrolysate medium with CO₂. IV, Anaerobic growth in casein hydrolysate medium minus CO₂ plus malate. V, Anaerobic growth in casein hydrolysate medium minus CO₂. Cells were grown in a rotary shaker in test-tubes containing 5 ml. Casitone medium under KH₂PO₄ + Na₂CO₃ seals to supply gaseous CO₂ (I); in side-arm fermentation tubes (Pine, 1956) containing 50 ml. Casitone medium with 25 μmoles NaHCO₃/ml. under Na₂CO₃ + pyrogallol seals (II); in 50 ml. volumetric flasks containing 48 ml. casein hydrolysate medium with 25 μmoles NaHCO₃/ml. under either Na₂CO₃ + pyrogallol seals (III) or without NaHCO₃ under NaOH + pyrogallol seals (IV, V). Sodium malate was added to IV to 0.5% (w/v). Above values represent the average growth observed in duplicate vessels. Aerobic tubes were inoculated with 1 drop of a homogenized 72 hr culture diluted with water to an extinction of 0.5; anaerobic vessels were inoculated with the equivalent of 1 mg. dry wt. organisms. Growth was measured by the extinction at 600 μm in a Spectronic-20 colorimeter. Extinction was related to dry weight by reference to a standard curve. The abscissa represents the initial concentration of glucose in the medium. All cultures were incubated 96 hr; maximum growth was usually attained in 48 hr; the ordinate represents the maximum value attained for each culture.
fermentation. The yields of organism obtained under various anaerobic or aerobic conditions of growth are given in Fig. 1. Except for anaerobic growth without CO\(_2\), the extent of growth in all cases was proportional to the initial glucose concentration, at least for the first two points. As observed previously (Pine & Howell, 1956; Buchanan & Pine, 1963), growth was better in the presence of CO\(_2\) or air, presumably owing in part to the additional energy released in pyruvate breakdown. In anaerobic growth without CO\(_2\), growth was not proportional to the initial glucose concentration, although it was approximately linear up to 9.4 \(\mu\)moles glucose utilized/ml. The non-linearity in the growth response was, in part, due to lack of aspartic acid, which could not be synthesized \textit{de novo} without CO\(_2\) and which could not be assimilated when added to the culture medium because of the absence of a permease (Buchanan & Pine, 1965).

### Table 3. Yields of Actinomyces naeslundii under various conditions of growth

<table>
<thead>
<tr>
<th>Curve of Fig. 1</th>
<th>Medium and substrate</th>
<th>Conditions</th>
<th>Glucose concentration ((\mu)mole/ml.)</th>
<th>Equation no. (see text)</th>
<th>Net ATP/mole glucose*</th>
<th>Y(_{\text{ATP}})†</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Casitone, glucose</td>
<td>Air or air+CO(_2)</td>
<td>4.7 4-7</td>
<td>4 4</td>
<td>21-8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9.4 9-4</td>
<td>4 4</td>
<td>21-7</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Casitone, glucose</td>
<td>Anaerobic+CO(_2)</td>
<td>4.7 4-7</td>
<td>3 2-8</td>
<td>17-5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9.4 9-4</td>
<td>3 2-8</td>
<td>18-2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14.1 14-1</td>
<td>3 2-8</td>
<td>17-2</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Casein hydrolysate,</td>
<td>Anaerobic+CO(_2)</td>
<td>4.7 4-7</td>
<td>3 2-8</td>
<td>15-2</td>
<td></td>
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<tr>
<td></td>
<td>glucose</td>
<td></td>
<td>9.4 9-4</td>
<td>3 2-8</td>
<td>14-8</td>
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<td></td>
<td></td>
<td></td>
<td>14.1 14-1</td>
<td>3 2-8</td>
<td>14-7</td>
<td></td>
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<tr>
<td>IV</td>
<td>Casein hydrolysate,</td>
<td>Anaerobic, no CO(_2)</td>
<td>9.4 9-4</td>
<td>5 4</td>
<td>10-1</td>
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<tr>
<td></td>
<td>glucose + malate</td>
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<tr>
<td>V</td>
<td>Casein hydrolysate,</td>
<td>Anaraobic, no CO(_2)</td>
<td>4.7 4-7</td>
<td>1 2</td>
<td>12-3</td>
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<tr>
<td></td>
<td>glucose</td>
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* \(\mu\)g. dry wt. organism/\(\mu\)mole glucose fermented (Buchop & Elsdon, 1960).
† Based on the fermentation equations shown in the text, in which the formation of 1 mole of acetate represents a net gain of 2 moles of ATP and 1 mole of lactate or succinate/mole ATP.
‡ \(\mu\)g. dry wt. organisms/\(\mu\)mole ATP (Buchop & Elsdon, 1960).

Anaerobic growth in the absence of CO\(_2\) but with malate (curve IV, Fig. 1) showed that malate partially replaced CO\(_2\) by functioning as a source of aspartate and as an electron acceptor to become succinate, pyruvate being converted to acetate and formate. Analysis of fermentations done in absence of CO\(_2\) but with added malate showed that \textit{Actinomyces naeslundii} fermented glucose (at initial values not exceeding 10 \(\mu\)moles/ml.) in accordance with the equation:

\[
glucose + 2 \text{ malate} \rightarrow 2 \text{ formate} + 2 \text{ acetate} + 2 \text{ succinate.} \quad (5)
\]

At this low concentration of glucose, malate effectively substituted for CO\(_2\) with a yield of organism 80% of that observed for anaerobic growth with added CO\(_2\). At higher glucose concentrations, growth was no longer proportional to the glucose concentration and large amounts of lactate were formed. Analysis of the products showed the fermentation occurred according to the equation:

\[
2 \text{ glucose} + 2 \text{ malate} \rightarrow 2 \text{ formate} + 2 \text{ acetate} + 2 \text{ lactate} + 2 \text{ succinate.} \quad (6)
\]

Table 3 shows the yields of \textit{Actinomyces naeslundii} calculated from data presented in Fig. 1, where growth was proportional to the added glucose. Growth is expressed in
Glucose breakdown in *Actinomyces naeslundii*

the \( Y \) and \( Y_{ATP} \) units as defined by Bauchop & Elsdon (1960); the net moles ATP formed/mole glucose, as calculated from the appropriate fermentation equation given above, is shown also. For these calculations, we assumed that one net ATP is released in the formation of one mole of lactate or succinate; 2 ATP are formed in the production of acetate (one additional ATP being due to the breakdown of pyruvate to acetyl coenzyme A + CO\(_2\) in air, or to acetyl coenzyme A + formate anaerobically). Bauchop & Elsdon (1960) defined the \( Y \) value as the g. dry wt. organism formed/mole glucose fermented; the value found for most organisms is 22 (Senez, 1962). The \( Y \) values observed with *A. naeslundii* grown anaerobically with substrate concentrations of CO\(_2\) were 41·1–51·0, depending on the growth medium. These values are at least twice those reported for most other organisms. However, Gunsalus & Shuster (1961) reported a \( Y \) value of 37·5 of *Propionibacterium pentosaceum*, an organism which in many ways is closely related to the actinomyces species (Stanier & Van Niel, 1941; Buchanan & Pine, 1962). As a result of the high \( Y \) values observed with *A. naeslundii*, the \( Y_{ATP} \) values (g. dry wt. organism formed/theoretical mole ATP; Bauchop & Elsdon, 1960) are correspondingly 1·5–2·2 times higher than the \( Y_{ATP} \) value of 10·5 observed for most organisms (Senez, 1962). Similar but somewhat higher values were obtained for aerobically grown *A. naeslundii* (Table 3). However, when the fermentation was homolactic (curve V, Fig. 1) or when malate was substituted for CO\(_2\) (curve IV, fig. 1), the \( Y_{ATP} \) values were 10·1 and 12·3, respectively. If the \( Y_{ATP} \) value of 10·5 be accepted as a universal constant (Senez, 1962), the data in Table 3 imply that *A. naeslundii* obtains additional energy in its glucose fermentation in the presence of CO\(_2\), perhaps at some point in the formation of succinate. However, this suggestion is complicated by the observation that the aspartate necessary for growth must be synthesized from a C\(_4\)-dicarboxylic acid (Buchanan & Pine, 1965).

**DISCUSSION**

This communication shows that *Actinomyces naeslundii* ferments glucose primarily by the Embden–Meyerhof pathway. Enzymes of the oxidative pentose phosphate cycle are present, but isotopic data show that this is a minor pathway and does not account for more than 6% of the glucose fermented. The operation of phosphoketolase, although we have no direct evidence for its presence, could explain in part the low activity of 14C in the methyl carbons of acetate when glucose 6-14C was the substrate. It is possible that the pentose pathway is essential for providing certain intermediates, such as pentoses, which are used for growth and that it does not function in energy production. Such a role would restrict the function of the pentose pathway in *A. naeslundii* to the interconversion of sugars needed for biosynthesis.

The dependence of the fermentation products on the conditions of growth shows that the pyruvate (or phosphoenolpyruvate) formed from glucose can take alternative routes. In the absence of CO\(_2\) or O\(_2\), pyruvate is reduced to lactate. When substrate amounts of CO\(_2\) are present, lactate formation is relatively minor and CO\(_2\) is used in the synthesis of oxaloacetate and malate which function as electron acceptors to form succinate. CO\(_2\) is believed to be fixed into phosphoenolpyruvate to yield oxaloacetate, which is reduced to succinate by a reversal of the malic dehydrogenase, fumarase and succinic dehydrogenase reactions. The reduction of oxaloacetate to succinate requires four electrons, and four electrons are released in the conversion of a glucose molecule...
to two molecules of phosphoenolpyruvate. Therefore, when CO₂ is present, a second molecule of phosphoenolpyruvate is free and is converted to acetate and formate, by way of pyruvate. This over-all process establishes a redox index of unity in the hetero-lactic fermentation as shown in equation (3). In aerobic growth, oxygen serves as an electron acceptor and glucose is oxidized to acetate, CO₂ and H₂O; the mechanism by which the electrons react with oxygen has not been determined. The over-all mechanisms of glucose fermentation for Actinomyces naeslundii are depicted in Fig. 2, as determined from this and preceding reports (Buchanan & Pine, 1963, 1965).

Fig. 2. Proposed mechanism of glucose breakdown by Actinomyces naeslundii. Major anaerobic fermentation products are singly underlined; major aerobic fermentation products are doubly underlined. Reactions believed to be involved principally in energy production are shown with solid arrows; reactions believed to be involved principally in biosynthesis are shown with broken arrows. The enzymes found in extracts are shown.
Glucose breakdown in Actinomyces naeslundii

The breakdown of pyruvate to acetyl coenzyme A or acetylphosphate releases additional energy for growth. Under conditions promoting pyruvate breakdown, the yields of Actinomyces naeslundii/glucose molecule are higher than for most other organisms. Whether or not this is peculiar to the actinomyces (and the propionibacteria; Gunsalus & Shuster, 1961) is an interesting point that may be decided only by further experiments.

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REFERENCES


Note added in Press

Recent cell wall analyses of strain ATCC 10049 showed the major amino acids to be glutamic acid, alanine, lysine, and glycine. The major sugars were galactose and mannose. Large quantities of hexosamine were also present. On the basis of cell wall analysis this strain is more correctly classified as Actinomyces israelii than A. naeslundii.