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THE FORMATION OF ROOT HAIRS IN WATER

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In undertaking as a problem for research, the effects of different substances in solution upon the rate of cell enlargement, it was planned to study the development of root hairs in aquaeous media, Brink[2] has used pollen tubes in a similar way; and there are numerous studies of the rate of enlargement of multicellular tissues of the higher plants when the latter were supplied with various nutrient or toxic substances. Robbins [13] has used detached roots for his investigations along this line. The root hairs present some advantages in that they are single cells so largely enveloped by external media that it is likely that they are much affected by it, and to a much less extent affected by the substances which come from the remainder of the plant. Furthermore the root hairs of most plants are ordinarily of uniform diameter, so that the increase in length is an index of the increase in cell volume. Finally the measurement of the length of root hairs can be readily and accurately made with the eyepiece micrometer, especially in view of the definite base line which the surface of the root affords.

Before beginning such study it is advisable to choose very carefully the species of plant to be studied. Not all of the higher plants will produce root hairs in water, and many of those that do are not suited for such a study. Seedlings are preferable to cuttings. Some seedlings produce more than one rootlet early in development. In some plants the root hairs are not straight; or they do not lie at right angles to the root; or they may not be parallel with each other.

A review of the literature shows that the following species of plants have been found to produce root hairs in water by the authors named thereafter.

CHARACEAE:	Chara sp. (Zacharias)
HYDROPTERIDINEAE:	Azolla caroliniana (Sokolowa, Osterhout)
PINACEAE:	Abies ovata (Schwarz)
HELOBIALES:	Hydrocharis morsus ranae (Küster, Prowazek, Schaede)
	Vallisneria spiralis (Küster)
	Zostera mariana (Osterhout)
	Potomogeton lucens (Küster)

GRAMINEAE:	Bromus secalinus (Schwarz)
	Panicum miliaceum (Schwarz, Seidel)
	Setaria italica (Schwarz)
	Triticum vulgare (Schwarz, Seidel, Bardell, Persecke, Micheels)
	Avena nuda (Schwarz)
	Avena sativa (Schwarz, Seidel, Bardell)
	Hordeum vulgare (Seidel, Persecke)
	Phleum pratense (Stiehr)
	Secale cereale (Stiehr, Persecke)
	Zea mays (Schwarz, Bardell, Persecke, Snow)
CYPERACEAE:	Cyperus alternifolius (Bardell)
	Eriophoram angustifolium (Schwarz)
ARACEAE:	Philodendron dipinnatifidum (Schwarz)
COMMELINACEAE:	Tradescantia albiflora (Sokolowa)
	Tradescantia fluminensis (Osterhout, Bardell)
LILIACEAE:	Allium cepa (Persecke)
	Hyacinthus orientalis (Persecke)
SALICACEAE:	Salix fragilis (Persecke)
	Salix lasiandra (Bardell)
	Populus canadensis (Persecke)
URTICACEAE.	Urtica cannabina (Seidel)
POLYGONACEAE:	Fagopyrum esculentum (Schwarz, Seidel, Persecke)
	Rheum Emodi (Seidel)
CHENOPODIACEAE:	Chenopodium Quinoa (Seidel)
	Beta vulgaris rapa (Seidel)
	Spinacia oleracea (Seidel)
	Salicornia sp. (Hill)
	Suaeda maritina (Hill)
	Atriplex patulum (Hill)
CARYOPHYLLACEAE:	Agrostemma Githago (Seidel)
	Lychnis coronaria (Seidel, Osterhout)
	Spergula arvensis (Stiehr)
	Dianthus barbatus (Osterhout)
	Gypsophila sp. (Osterhout)
	Saponaria sp. (Osterhout)
	Silene sp. (Osterhout)
	Nympbaeaceae Nuphar luteum (Schwarz)
ACERACEAE:	Acer macrophyllum (Bardell)
PAPAVERACEAE:	Papaver somniferum (Stiehr)
CRUSIFERAE:	Biscutella auriculata (Schwarz)
	Brassica oleracea (Sokolowa, Howe)
	Brassica napus (Schwarz, Seidel, Sokolowa)
	Lepidium sativum (Schwarz, Zacharias, Coupin)
	Raphanus sativus (Roberts, Bardell, Howe)
	Sinapis alba (Sokolowa)
LEGUMINOSAE:	Ornithopus sativus (Seidel)
	Phaseolus communis (Persecke)
	Phaseolus multiflorus (Persecke, Bardell)

	Pisum sativum (Persecke, Bardell)
	Trifolium hybridum (Stiehr)
	Vicia faba (Persecke, Snow)
BALSAMINACEAE:	Balsamina hortensis (Persecke)
ONAGRACEAE:	Oenothera biennis (Seidel)
SOLANACEAE:	Nicotiana rusticum (Seidel)
	Trianea bogotensis (Küster, Osterhout)
SCROPHULARIACEAE:	Verbascum thapsiforme (Seidel)
PLANTAGINACEAE:	Plantago lanceolata (Seidel)
CUCURBITACEAE.	Cucumis sativus (Sokolowa, Howe)
	Cucumis melo (Howe)
	Cucurbito pepo (Bardell)
COMPOSITAE:	Helianthus annuus (Snow, Persecke, Bardell)

This list embraces a total of 68 species. In some of these only a few root hairs are reported as being produced, as in *Abies*. In other cases the root hairs are said to be rudimentary, as in both species of *Phaseolus* and in *Pisum*. There is also some difference of opinion among authors. Persecke[11] reports no root hairs on the roots of *Ornithopus sativus,* whereas, as noted above, Seidel[17] finds them. Schwarz[6] places *Zea mays* in his list of plants on which he found no root hairs in water, but nevertheless he presents a figure of them. Persecke[11] states that they are rudimentary or isolated in this species.

In my studies I have tested some of the species given in the above list, and have confirmed the findings of the authors noted as to the occurrence fo root hairs in water on the roots of the following species:

Allium cepa, onion.
Avena sativa, oats.
Beta vulgaris, beet.
Brassica oleracea, cabbage.
Cucumis sativus, cucumber.
Dianthus barbatus, pinks.
Fagopyrum esculentum, buckwheat.
Gypsophila elegans, Baby's Breath.
Lepidium sativum, cress.
Panicum miliaceum, millet.
Pisum sativum, Alaska peas.
Raphanus sativus, radish.
Saponaria ocymoides, rock soapwort.
Secale cereale, rye.
Silene pendula alba, white catchfly.
Sinapis alba, white mustard.
Trifolium hybridum, alsyke clover.
Zea mays, Black Mexican corn.

In *Panicum, Raphanus* and *Zea* the root hairs produced in water are found to be shorter than those in air.

In addition I have found hairs formed in tap water on the following 18 species, making a total of 87 species so far reported as forming root hairs in water. This does not include the instances of rhizoid formation on the bryophyttes and fern prothallia.

GRAMINAE:	Euchlaena mexicana, teosinte
CRUCIFERAE:	Brassica campestris chinensis, Chinese cabbage
	Brassica nigra, black mustard
	Brassica rapa, rape
	Isatis tinctoria, indigo
POLYGRNOCEAE:	Rheum Rhaponticum, rhubard.
AMARANTHACEAE:	Amaranthus retroflexus, amaranth
NYCTAGINACEAE:	Mirabilis jalapa, four o'clock
CAUYOPHYLLOCEAE:	Lychnis chalcedonica, Bristol Flower.
EUPHORBIACEAE:	Ricimus communis, castor bean
MYRTACEAE:	Eucalyptus globulus, eucalyptus
	Pimenta officinalis, pimento
UMBELLIFERAE:	Daucus carota, carrot
BORRAGINACEAE:	Anchusa capensis, cape forget-me-not
SOLANACEAE:	Lycopersicum esculentum, tomato
CUCURBITOCEAE:	Cucurbito maxima, gourd.
COMPOSITAE:	Lactuca sativa, lettuce
	Cichorium intybus, chicory

The following species were tested, but no root hair production in water was observed. Three of these species, as noted by the reference in parenthesis, have been previously reported as producing at least rudimentary root hairs.

GRAMINEAE:	Oryza sativa, rice
	Zea mays, popcorn
	Sorghum vulgare, sorghum
MORACEAE:	Humulus japonicus, hops
PAPAVERACEAE:	Papaver somniferum, poppy (cf. Stiehr)
LEGUMINOSAE:	Cassia artemisioides, senna
	Glycine soja, soybean
	Lupinus albus, white lupine
	Mimosa pudica, sensitive plant
	Phaseolus coccineus
	Phaseolus vulgare, bean
	Phaseolus multiflorus, scarlet runner (cf. Persecke)
	Vigna catgang, cowpeas
TROPAEOLACEAE:	Tropaeolum canariense, canary-bird flower
LINACEAE:	Linum usitatissimum, flax
ANACARDIACEAE:	Schinus molle, pepper tree
MALVACEAE:	Hibiscus esculentum, okra
ONAGRACEAE:	Oenothera drummundi
UMBELLIFERAE:	Apium graveolens, celery
	Carum carvi, caraway

	Foeniculum vulgare, fennel
	Pimpinella anisum, anise
POLEMONIACEAE:	Cobaea scandens
	Ipoemoa hederacea, morning glory
LABIATAE:	Ocinum basilicum, basil
	Origanum marjorana, sweet marjorum
SOLANACEAE.	Datura stramonium, jimson weed
	Solanum melongena, egg plant
SCROPHULARIACEAE.	Digitalis ambigua, foxglove
VALERIANACEAE:	Valeriana alba, white valerian
CAMPANULACEAE:	Campanula carpatica
COMPOSITAE:	Anthemis nobilis, sweet fennel
	Calendula officinalis, marigold
	Helianthus tuberosus, Jerusalem articoke
	Helianthus annuus, sunflower (cf. Persecke)
	Tragopogon porrifolius, salsify
	Tanacetum vulgare, tansy

In addition the onion produced only 5 root hairs on one side and 8 on the other during 20 hours in tap water. This fact together with the slow rate of growth, reported below, makes it seem doubtful if onion should be listed as producing root hairs in water.

In the case of cabbage and tomatoes a number of varieties were tested for the production of root hairs in water. The following varieties of tomatoes gave positive results: Dwarf Stone; Marvel; Columbia; Norduke; Golden Queen; Stone; Globe; Earliana; Morton; Ponderosa; and Red Cherry. The following varieties of *Brassica oleracea* produced root hairs in water: Early Jersey Wakefield; Copenhagen Market; Late Flat Dutch; Brussels Sprouts; Georgia Collards; Kale; Early Copenhagen Market; Early Dwarf Flat Dutch; Broccoli.

Now that a number of species had been found which produced root hairs in water, an attempt was made to determine which of these are best suited for investigations on the effect of different conditions and substances upon the rate of root hair elongation. Wheat, rye, and oats were eliminated at once from consideration, on account of the fact that they produce a number of rootlets early in the seedling stage. It is obviously desirable to have practically all of the root hairs of a seedling under observation, if possible, at one time. This would be impossible if more than one rootlet had to be considered. It is also important that the form which is chosen have straight root hairs extending parallel to each other and preferably at right angles to the root. In the following species in the root hairs produced in water were found to be bent, curved, or crinkled: *Fagopyrum esculentum; Gysophila*

elegans; Saponaria ocymoides; Panicum milaceum; Amaranthus retroflexus.

Another consideration is the diameter of the root. It is sometimes difficult to optically isolate a root hair on the horizon of a large root, so that its length can be accurately determined over a period of several hours. Other root hairs are liable to obscure the base of the root hair which is being observed, so that the base line afforded by the root cannot be definitely distinguished. It is therefore desired that the root of the form studied have as small a diameter as possible. The diameters of the roots studied and listed above as having root hairs in water are as follows:

1600 microns: *Cucurbito maxima.*
1400 microns: Alaska peas.
1080 microns: Black Mexican Corn.
960 microns: Onion; Four O'Clock.
920 microns: *Cucumis sativus.*
760 microns: rhubarb.
700 microns: white mustard.
680 microns: broccoli.
640 microns: *Saponaria ocymoides.*
560 microns: radish; *Dianthus barbatus*; beet; rape; lettuce.
520 microns: *Eucalyptus globulus*; cress.
480 microns: teosinte; Norduke; brussels sprouts; chicory.
440 microns: early Copenhagen market; rye; red cherry.
400 microns: *Lychnis chalcedonica; Panicum miliaceum; Isatis; Anchusa capensis*; carrots; black mustard; oats; early Jersey Wakefield; kale; Copenhagen market; early dwarf flat Dutch; Columbia.
380 microns: dwarf Stone.
372 microns: marvel.
360 microns: alsyke clover; Stone; globe; Georgia collards; Morton; ponderosa.
336 microns: earliana.
328 microns: late flat Dutch.
320 microns: chinese cabbage, buckwheat, amaranth.
304 microns: *Silene pendula*; golden queen.
240 microns: *Gypsophila elegans.*

In view of the fact that four of the last five named in this list are found objectionable for reasons noted above, it appears that varieties of *Brassica* and *Lycopersicum* are preferable on the bases thus far considered.

However another matter to be taken into account is the proximity of the root hairs to each other. While this varies somewhat with different roots of the same species and with different media, yet a survey with this in mind doubtless contributes to a satisfactory choice of a subject for investigation. In the following

list is given the species under consideration classified according to the approximate number of root hairs on the horizon in a distance of 60 microns:

8: Copenhagen market.
6: *Eucalytpus globulus*; white mustard; teosinte; kale, Alaska peas, Black Mexican corn.
4: millet; alsyke clover; four o'clock.
3: *Tropaeolum cararense*; Norduke; dwarf stoen; amaranth; beet; cucumber; chicory.
2: *Lychnis chalcedonica*; *Saponaria ocymoides*; *Gypsophila elegans*; brussels sprouts; Georgia collards; Morton; early dwarf flat Dutch; rye; rape; lettuce; cress; red cherry.
1: *Anchusa capensis; Cucurbito maxima*; buckwheat; oats; black mustard; marvel; Columbia; golden queen; Stone; globe; earliana; ponderosa; early Copenhagen market; late flat Dutch; early Jersey Wakefield.

Finally a comparison was made of the rate of growth of these root hairs in tap water. The results are as follows in microns per hour:

4: onion.
4.5: amaranth.
6: cucumber; carrot.
12: Alaska peas.
14: *Silene pendula.*
17: alsyke clover; lettuce.
24: *Eucalyptus globulus*; Black Mexican corn.
27: chicory.
30: four o'clock.
33: rye; red cherry.
38: stone.
40: early Jersey Wakefield.
48: *Anchusa capensis*; *Dianthus barbatus*; *Gypsophila elegans*; *Isatis tinctoria*; buckwheat; white mustard; black mustard; chinese cabbage; marvel; Columbia; Norduke; golden queen; globe; earliana; late Flat Dutch; early Copenhagen market; brussels sprouts.
64: teosinte; Copenhagen market; cress.
72: early dwarf flat Dutch; dwarf Stone; kale.
78: rape; beet.
80: Georgia collards.

It thus appears that when all things are considered varieties of *Brassica* and *Lycopersicum* seem to be the most satisfactory of any yet investigated for a study of the rate of root hair elongation in water under different conditions. Wheat, rye, and oats have been eliminated, as noted above, on account of their production of multiple primary rootlets. *Gypsophila, Saponaria,* buckwheat, millet, and amaranth have root hairs which are not straight, and

hence they are also undesirable. Of those that remain the gourd, cucumber; peas, corn; onion, four o'clock; rhubarb; white mustard; radish; *Dianthus barbatus*; beet; rape; lettuce; eucalyptus; cress; teosinte; chicory; *Lychnis; Isatis; Anchusa*; carrot; and black mustard have roots 400 microns or more in diameter. Of those still remaining alsyke clover grows only 17 microns per hour, and *Silene* only 14. This leaves chinese cabbage and various varieties of *Brassica oleracea* and *Lycopersicum esculentum*. It is interesting to note that the practical application of such a study as is contemplated, namely the effect of different substances in solution on the rate of root hair production, would be most directly concerned with the transplanting of seedlings. In this connection varieties of cabbage and tomatoes are of primary importance. It thus appears that in this case the forms most acceptable for experimentation are the forms to which practical application is most direct.

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