 0014-4754/95/111090-04$1.50 + 0.20

Weak static magnetic fields increase the speed of circumnutation in cucumber (*Cucumis sativus* L.) tendrils

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Received 27 December 1994; accepted 10 May 1995

Abstract. Tendrils are thread-like organs whose function is to support the stems of many species of climbing plants. Tendrils naturally move (circumnutate) in space. Individual tendrils of cucumber (*Cucumis sativus* L.) 'Poinset' had the vertical component of their mean velocity vector of circumnutation changed when exposed to a range of weak static magnetic fields between 1 and 16 mT. The speed (modulus) of the velocity vector was significantly increased ($p = 0.016$) in the vicinity of a magnet, but its direction did not show a definite trend with respect to the magnet. Although cucumber tendrils bear static positive charges, they did not behave as charged bodies do in a magnetic field, neither did they show a magnetotropic response. In fact, tendrils showed a nastic response to magnetism. Magnetic fields affected some processes underlying the movement of circumnutation, but no clear interpretation of them can be given presently on the basis of the known effects of magnetism on plants. It is clear that cucumber tendrils, because of some inherent susceptibility to magnetism or their particular size and shape, are very sensitive to relatively low static magnetic field strengths.
Key words. Static magnetic fields; tendrils; circumnutation; cucumber; *Cucumis sativus*; magnetonastism.

The image of a plant as an immobile organism is belied by the diversity of movements shown by most of its organs[1]. Those movements are broadly of two kinds: those independent of external stimuli, like the circumnutation of e.g. tendrils, sprouts, and roots[2]; and those evoked by diverse external stimuli such as light, gravity, mechanical shocks, etc.[3]. Those movements may be dependent (tropisms) or not (nastisms) on the position of the stimulus source.

Cucumber tendrils carry a standing positive surface charge. This can be easily shown, as has been done in sorghum leaves[4], by moving a rubbed plastic rod towards a tendril. The tendril is rapidly attracted to the rod and sticks to it. This indicates that cucumber tendrils can be regarded as moving charged objects, likely to interact with magnetic fields. The present work shows that tendril circumnutation was indeed modified in a magnetic field. Tendrils did not, however, behave in the way expected either for a charged moving body, or for one sensitive to magnetotropism[5]. Indeed, a magnetonastic effect on tendril circumnutation was observed. This kind of nastism has not been, to our knowledge, reported before.

Materials and methods

Cucumber 'Poinset' plants, potted in garden soil, were grown in a darkened room under a daily regime of 16 h of fluorescent white light. Ambient temperature fluctuated between 18 and 27 °C, depending on the light regime. Plants were amply watered with tap water every other day.

Tendrils borne on at least the 10th node of the main stem were used in the experiments. The portion of the main stem bearing the tendril was clamped upright; the axis of the tendril was hence slanted relative to the plumb line. Individual tendrils were used in each one of the six experimental runs. These runs are described in table 1. The procedure used for exposing a tendril to any one of the magnets described in table 2 was this: when a tendril was seen, after one or two complete revolutions, moving along a path close to and in the same direction as an earlier one, a magnet was put in a place where the tendril would be likely to pass nearby a few minutes later. This was done because the velocity of a tendril varies with its position in space[6]. Positions sampled are exemplified in figure 1, which represents the trajectory of the tendril of plant #29 projected in a vertical plane.

The mean velocity vector of a tendril between two successive positions $P_{i-1}(x_{i-1}, y_{i-1})$ and $P_i(x_i, y_i)$ in a projected vertical plane at times t_{i-1} and t_i, respectively, had speed (magnitude)

$$v_i = \sqrt{\{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2\}}/(t_i - t_{i-1}),$$

and direction

$$\theta_i = \tan^{-1}\{(y_i - y_{i-1})/(x_i - x_{i-1})\}.$$

The effect of the magnetic fields on the average mean speed and direction of tendrils was tested with Wilcoxon's Signed Rank test[7].

Table 1. General description of the material, ambient conditions, and magnets used in each experimental session.

Plant #	Tendril size (mm)	T (°C)	PPF (μmol m^{-2} s^{-1})	Magnet type	Magnet position
17	170	25	56	C	⊥S
26	150	26	51	B	∥N
27	180	22	48	A	∥N
29	143	20	71	A	∥S
30	259	24	63	B	∥N
31	290	31	61	B	∥S

Tendril size was estimated by the length (measured with a ruler) of the chord subtended from the base of the tendril to its tip. T (temperature ±0.5 °C) and PPF (Photosynthetic Photon Flux, 400–700 nm) were measured near the tendril tip, at the beginning of each experimental run. Magnet types are described in table 2. The relative position of the magnet with respect to the tendril was such that the surface of the magnet was presented either normal (⊥) or parallel (∥) to the apical portion of a tendril, which approached either the compass North (N) or South (S) poles of the magnet.

Table 2. Field strengths and gradients at several heights above the surface of a magnet.

Magnet type	Magnetic field (mT)				Field gradient (T m^{-1})		
	10 mm	20 mm	35 mm	50 mm	10–20 mm	20–35 mm	35–50 mm
A	19.0 ± 3.4	7.7 ± 1.35	2.5 ± 0.37	1.0 ± 0.01	−1.09	−0.35	−0.10
B	18.0 ± 3.7	7.7 ± 1.45	2.7 ± 0.44	1.2 ± 0.01	−1.03	−0.33	−0.10
C	5.5 ± 1.60	1.5 ± 0.25	0.39 ± 0.059	0.14 ± 0.018	−0.40	−0.07	−0.02

Mean values ± SD (N = 21). Magnets were made of two magnetised ferrite blocks (poles) with their largest faces affixed side-by-side to a flat piece of aluminium. In magnets A and B, the poles were (L × W × T) 40 × 25 × 7 mm each. The gap between their adjacent sides was 11 mm in A, and 26 mm in B. In magnet C, the poles were (L × W × T) 31 × 18 × 10 mm each, with a 7 mm gap between their adjacent sides. The magnetic field was sampled at the centre, near the corners, and midway between the contiguous corners of each pole. The gap between the poles was sampled midway at three points, two of which were respectively collinear with contiguous corners in both poles, and the other was collinear with the centres of the poles. At each sampling point, the magnetic field strengths at three mutually orthogonal directions, one of which was normal to the surface of the magnet, were measured once with a gaussmeter probe.

Results

The six experimental sessions showed that, on the average, tendrils moved faster in a vertical plane when they were exposed to low-strength magnetic fields. Individual increases in mean speed ranged from 5% (plant # 31) to 207% (plant # 27). On the average, the mean speed near the magnet (22.9 mm min^{-1}) was significantly ($p = 0.016$) greater than when the magnet was not present (14.1 mm min^{-1}; table 3); i.e., a tendril was accelerated by a magnetic field. Tendrils were accelerated when their axes were either parallel (plants # 26, # 27, # 29, # 30, and # 31) or perpendicular (plant # 17) to the surface of a magnet (table 1), and when they approached a magnet from either the compass North pole (plants # 26, # 27, and # 30) or the compass South pole (plants # 17, # 29, and # 31) (table 1), for all temperatures and light fluxes present when observations were made (table 1). The other component of the mean velocity vector, its absolute direction, was not statistically significantly influenced by the magnetic fields (table 3). The relative direction of the mean velocity vector (table 3), which indicates whether a tendril is attracted to or repelled by a magnet, did not show a definite direction consistent with any of the effects it was intended to measure. The different field strengths (table 3) encountered by a tendril in the course of its movement above a magnet were due to the inclination of its path with respect to the surface of the magnet. The constancy of the magnetic field for plant # 17 was the consequence of the almost parallel displacement of the tendril apical

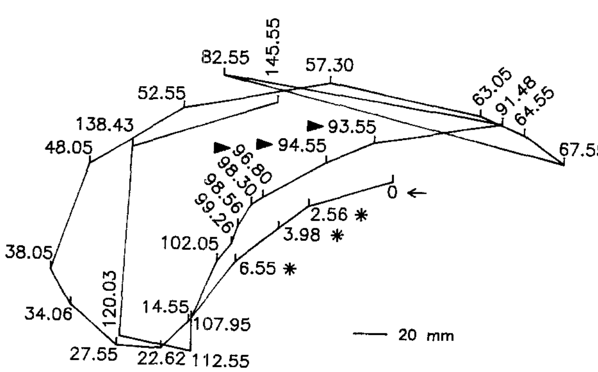

Figure 1. Example of the trajectory of a tendril (plant # 29) projected on a vertical plane. Points were drawn from coordinates obtained with a map-measuring device from black and white photographs taken at the indicated times. Numbers show the time (minutes) taken by a tendril to reach the indicated position. The arrow indicates zero time (initial position). Mean velocity vectors for the tendril were calculated at the positions marked with asterisks (control), or arrowheads (near the magnet).

Table 3. Effect of magnetic fields on the mean speed and direction of the vertical velocity vector of a tendril, and the time the latter was exposed to the magnet.

Plant #	Mean velocity vector					*B* (mT)	Exposure (min)
	speed		direction				
			absolute		relative		
	control (mm min^{-1})	magnet (mm min^{-1})	control (deg)	magnet (deg)	magnet		
17	3.3 (2)	7.4 (4)	333.5	289.1	↑	5	8.52
26	19.6 (2)	37.1 (3)	190.6	193.7	↓	6–14	1.70
27	5.2 (3)	15.8 (4)	355.1	356.3	↓	1–6	10.58
29	15.1 (3)	28.8 (3)	198.1	191.5	↓	1–16	3.07
30	15.8 (2)	19.5 (2)	357.5	349.8	↓	2–12	2.58
31	27.6 (2)	29.0 (3)	194.0	181.0	↑	6–14	1.60
Mean	14.4	22.9*	271.5	260.2			

Speed is the magnitude of the mean velocity vector, based on the number of observations indicated in parentheses. The absolute direction of the mean velocity vector was calculated from its components; angles were measured counterclockwise with respect to the horizontal. The relative direction indicates whether the movement of the tendril was away from (↑) or towards (↓) the magnet. *B* values were estimated by linear interpolation of the distance of a tendril from the surface of the magnet, measured with a map-measuring device on photographs, into the appropriate values of magnetic field strength (table 2). Exposure is the time a tendril spent in a space delimited by the surface of a magnet. *p = 0.016 (N = 6).

portion over the surface of the magnet. The foregoing results are pictorially summarised in figure 2, with a tendril moving in complete darkness. Here the tendril moved faster – as tendrils did in the light (table 3) – and (in this particular case) along a steeper path when it passed near the magnet.

Discussion

The change in the vertical velocity vector (table 3) in the vicinity of a magnet means that a tendril was subjected to forces there which were certainly produced by the magnetic field. Those forces were both external and internal to the tendril. The former were evoked when the electrostatically charged tendril traversed a magnetic field. These external forces, however, were much weaker than the internal forces driving the movement of the tendril; otherwise its path would have been reversed when the polarity of the magnet was changed, which did not happen (compare plants # 27 and # 29, and # 30 and # 31, table 1). Consequently, magnetic fields must have affected the forces driving the movement of a tendril. It is very likely that the forces affected were hydrostatic forces, since there is some evidence that turgor is essential for tendril circumnutation[8]. As tendrils circumnutate while they are growing actively[8], and turgor is necessary for growth, it is plausible that magnetic fields affected turgor, growth, or both. In plants magnetic fields are known to modify the growth of both whole individuals and individual organs[9]. The most remarkable effect observed (for its definiteness) was that the roots and shoots of many species grew down a magnetic field gradient (over 50 T m^{-1}) after about one hour of exposure to a 400 mT static magnetic field. This phenomenon was called magnetotropism[5].

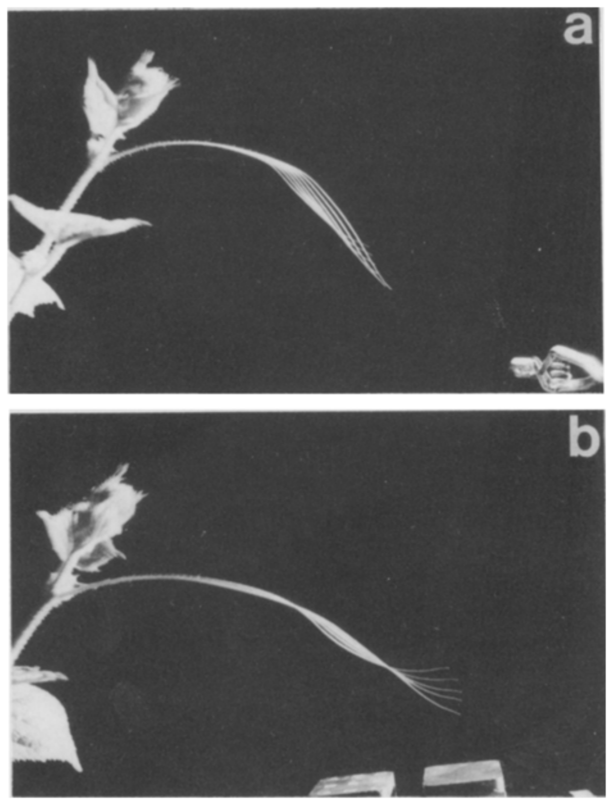

Figure 2. Cucumber tendril accelerated in the vicinity of a magnet. *a*) without magnet; *b*) the tendril, after a complete rotation in the light, is subjected to an estimated 7 mT field strength above the compass South pole of magnet A (table 2). Photographs of a tendril moving away from the camera were taken in the dark at 1 min intervals. Temperature was 24 ± 0.5 °C. Note that in *b*) the distance between two successive positions on the tendril apex is larger than in *a*), and also that the path of the tendril is steeper than in *a*).

The magnetic effect on the tendrils observed in the present study was not tropic. If it had been so, the tendrils should always have moved away from the magnet, in the direction of decreasing field gradients (table 2). Taking the tendril of figure 2 together with the other six tested, the variation in the relative direction (table 3) of their vertical velocity vectors shows that the chance of a tendril moving away from a magnet was roughly 50%, a proportion that does not correspond to a tropistic response; i.e., to an all-or-nothing phenomenon. However, there was a clear effect of the magnetic fields on speed, so that it can be stated that cucumber tendrils showed magnetonastism. At present, it cannot be ascertained whether the nastic response was evoked by the magnetic field strength per se, or by magnetic field gradients met by the moving tendril.

As for the processes related to turgor that could have been influenced by magnetic fields, it is worth noting that K^+ channels seem to be part of the mechanism of circumnutation in bean shoots[10], and a variety of electrolytes enhance the nutation of etiolated cucumber hypocotyls[11]; thus processes involving moving electrical charges appear to be involved.

The foregoing considerations, made on the basis of the behaviour of the vertical component of the velocity vector, can indeed be extended to the velocity vector of the movement of circumnutation, because the former is a component of the latter. They are also necessarily very speculative in view of the present state of knowledge of both the physiology of circumnutation[2,12], and the effects of magnetic fields on plants[9]. What seems clear is that cucumber tendrils were very sensitive to magnetism, because the effect of magnetic fields was evident in 11 min at most (table 3), and field strengths were not greater than 16 mT (table 3); i.e., much smaller than the values reported to have an effect on the growth and development of other plant entities (50 mT to 14 T)[9]. It is, however, an open question whether the sensitivity of cucumber tendrils to magnetism was due to some intrinsically large physiological susceptibility, or to their thread-like shape, which would have facilitated the complete penetration of a magnetic field.

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