Table 1. The mean cross-section areas of osteons in ribs is shown for nondiabetic and diabetic persons.

Age (yr.)	Cases (No.)	Sections (No.)	Cross-section area (mm^2)
	Nondiabetic (6500)		
0–9	10	20	0.035 ± 0.004 *
10–19	10	20	.040 ± .005 *
20–29	10	20	.045 ± .007 *
30–39	10	20	.041 ± .007 *
40–49	10	20	.037 ± .005 *
50–59	10	20	.033 ± .008 *
Mean †			.038 ± .007 * (9×10^{-5}) ‡
	Diabetic (2200)		
20–29	2	4	0.037
30–39	2	4	.035
40–49	3	6	.039
50–59	7	14	.036
Mean †	14	28	.037 ± .006 * (2×10^{-4}) ‡

* One standard deviation. The areas exclude the area of the Haversian canals. † Of 60 cases, 120 sections. ‡ Standard error of the mean.

the diabetics, 11 had been marked in vivo on one or more occasions with a tetracycline antibiotic in such a way that the thickness of the layer of new bone matrix added daily at actively forming Haversian systems could be measured.

The mean cross sectional areas of 6500 Haversian systems in the 60 nondiabetic subjects and of 2200 systems in 14 diabetic subjects were measured. These areas excluded the areas of the Haversian canals. The measurements were made with a Zeiss integrating eyepiece I, by a method described by Chalkley and by Hennig (*6*). The accuracy of each Haversian system measurement was ± 0.0015 mm^2 at one standard deviation, and precision was ± 5 percent. With a calibrated Zeiss eyepiece micrometer, the thickness of fluorescing tetracycline markers was measured in 43 sections from 11 labeled diabetic subjects by blue-light fluorescence microscopy. Each marker in 234 separate, labeled Haversian systems was measured at each of four equidistant points around its circumference and the mean of the four was recorded. The accuracy of each measurement was ± 0.5 micron at one standard deviation, and precision was ± 11 percent. Both measuring procedures have been described in detail (*6, 7*), as have been comparable values for the daily increment in new matrix added in actively forming Haversian systems in nondiabetic children and adults (*8*). The case material and data are listed in Tables 1 and 2.

Table 2. The mean thickness of new bone matrix added to the inner wall of tetracycline-labeled Haversian systems. The average time between deposition of the markers in the skeleton and the event which led to skeletal sampling (column 3) is noteworthy in that the markers were deposited long before the incidents which allowed the skeleton to be sampled, and so were unaffected by them. The difference between the means of the adult diabetics and nondiabetics, and adult diabetics and nondiabetic children, was highly significant ($p < .001$).

Mean age (yr)	Osteons measured (No.)	Av. time between labeling and sampling (mo)	M_f* (μ/day)
	6 Children, nondiabetic†		
7	298	11	1.53 ± .7‡
	13 Adults, nondiabetic†		
43	301	31	0.93 ± .4‡
	11 Adults, diabetic		
57	234	27	0.21 ± .07‡

* M_f is the depth of layer of new organic matrix added to underlying bone in microns per day. † From reference *8*. ‡ One standard deviation.

The measurements reveal the following. (i) Over the 60-year span of life that we studied, the mean area of the cross sections of Haversian systems remains within 20 percent of the mean value of 0.038 mm^2. The differences between diabetic and nondiabetic subjects are not significant and average less than 15 percent of their means. (ii) The thickness of the layer of new organic matrix added to an actively forming Haversian system ranges from 1.53 microns per day in nondiabetic 7-year-old children to 0.21 microns per day in 57-year-old diabetic adults. Since the sizes of the osteons in these two groups are comparable, these facts mean that there are inversely proportional changes in the time taken to make the average Haversian system, that is, it takes about seven times longer for the adult diabetic to make an equivalent amount of Haversian bone than it takes the nondiabetic child.

It can be concluded from this study that the agencies which somehow control the rate at which Haversian systems are formed, and those which control the amount of bone in them when they are finished, are different. This situation might exist in other modes of bone remodeling and in some soft tissues.

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References and Notes

1. A unit volume of bone, or absolute bone volume, is that volume remaining after the marrow space, vascular channels, lacunae, and canaliculi have been subtracted.
2. H. M. Frost, *Bone Remodelling Dynamics* (Thomas, Springfield, Ill., 1963), p. 122; R. H. Robinson and S. Y. Elliott, *J. Bone Joint Surg.* **40A**, 687 (1958).
3. R. A. Milch, D. P. Rall, J. E. Tobie, *J. Natl. Cancer Inst.* **19**, 87 (1957); H. M. Frost and A. R. Villanueva, *Stain Technol.* **35**, 135 (1960); H. M. Frost, S. Stanisavljevic, H. Roth, A. R. Villanueva, *Henry Ford Hosp. Med. Bull.* **9**, 312 (1962).
4. H. M. Frost, *Stain Technol.* **33**, 273 (1958); *ibid.* **34**, 135 (1959).
5. We thank Drs. E. S. Zawadski and R. H. Horn for supplying us with much of our material and for giving us access to the relevant records.
6. H. W. Chalkley, *J. Natl. Cancer Inst.* **4**, 47 (1943); A. Hennig, *Zeiss Werkzeitschrift* **30**, 78 (1958).
7. H. M. Frost, *Henry Ford Hosp. Med. Bull.* **10**, 267 (1962).
8. ———, *Can. J. Biochem. Physiol.* **41**, 1307 (1963).

25 May 1964

Ecological Design of Irrigation Canals for Snail Control

Abstract. *The snail hosts of schistosomiasis have found ideal conditions for rapid colonization in many irrigation and drainage canal systems. By studying the hydrodynamic aspects of snail dislodgment it may be possible to devise a control method based on engineering the snail's microenvironment. For* Australorbis glabratus, *a velocity exceeding 33 cm/sec at shell height produces a hydrodynamic drag force sufficient to dislodge the snail from its position on the solid boundary of a canal.*

The agricultural benefits provided by the vast irrigation and drainage systems constructed in tropical countries are often offset by a concomitant public health problem which is assuming serious proportions in many countries (*1*). Schistosomiasis, a debilitating parasitic disease, is transmitted by certain strains of fresh-water snails. In arid and semi-arid regions, where the disease is often endemic, the snail populations are usually held in check by periodic drought. Construction of canals and provision of a continual supply of water can lead to an explosive rise in snail population and a marked increase in the distribution and intensity of schistosomiasis. The design of canals without regard to this factor can lead to conditions like those shown in Fig. 1. If such canals are poorly maintained the snail populations thrive.

Previous studies with *Australorbis glabratus*, the intermediate host of

Fig. 1. Snail-infested irrigation canal in tropics.

schistosomiasis in the western hemisphere, show that this snail is usually absent from those sections of snail-inhabited streams where the average velocity locally goes above 30 or 40 cm/sec. (*2*). Unfortunately, in studies such as these, and in attempts to relate average stream gradient to snail absence (*3*), the fundamental hydrodynamic phenomena have usually been neglected.

To dislodge a snail, a drag force must be produced on the shell which will pull the snail from its position on the solid boundary. Nonuniform velocity distributions near solid boundaries make it necessary to investigate that velocity acting at shell height which will dislodge the snail.

The study (*4*) reported herein was therefore divided into three parts: (i) measurement of drag forces on the dry shells for the pertinent range of flow conditions and snail sizes; (ii) definition of the resistive ability of live specimens on various surfaces; and (iii) the study of live snails in a controlled flow to verify the behavior predicted from (i) and (ii). *Australorbis glabratus* was studied because of its importance in the western hemisphere.

To measure the very small drag forces, six snail shells of the type shown in Fig. 2 were mounted on a thin cross bar and then immersed in a laboratory

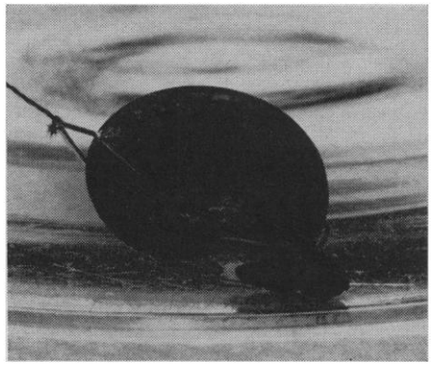

Fig. 2. *Australorbis glabratus* in harness.

stream. The stream had a local velocity distribution simulating the flow near the smooth lining of an irrigation canal. The net forces exerted on the snail shells ranged below 1 g per shell and were determined by a mechanical balance with a sensitivity of 50 mg. For comparison with conventional reference material such tests were also conducted with small spheres of corresponding dimensions, for which drag coefficients have been established in the past in uniform velocity fields. The dimensionless drag-coefficient C_D is computed on the basis of the relation of the total force F to the projected area A of the body in the direction of flow and to the square of the maximum velocity V_d observed at the top of the body. This relation is conventionally:

$$C_D = \frac{2F}{A\rho V_d^2}$$

wherein ρ is the density or specific mass of the fluid. The experimental results are given in Fig. 3 for a Reynolds number range of $R = 10^3$ to 10^4, which is defined as sphere diameter, or height of shell, d times the velocity V_d divided by the kinematic viscosity ν. It is seen that the drag coefficient for snail shells is essentially the same as that for spheres in the nonuniform flow field near the boundary considered here. These C_D values, however, are generally higher than the drag coefficient which is obtained for spheres in a uniform velocity field over the range of corresponding Reynolds numbers.

For the study of resisting ability in still water, a Puerto Rican strain of laboratory reared snails was available. These snails were furnished with small harnesses (Fig. 2) and trained to pull very light loads. A shallow aquarium containing a submerged platform served as the arena for this "snail taming." Platforms of various materials were used. A length of nylon thread attached to the snail harness was passed horizontally over a pulley outside of the aquarium. Increasing loads were then applied to the snail in increments of 100 mg every 2 to 5 minutes until the snail lost its hold. The snail was then again placed on the surface two or three more times, to see if it might be able to resist a larger force. If it could, weights were again added until dislodgment. Only the highest dislodging force was recorded for each snail to eliminate cases where the snail let go prematurely.

For snails tested on smooth surfaces, Fig. 4 shows that the snails able to resist the highest dislodging force were those of height $d = 1.3$ cm, requiring a force of almost 1.6 g for dislodgment. Larger snails were apparently weaker, perhaps due to aging.

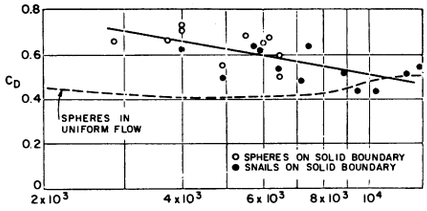

Fig. 3. Drag coefficients in shear flow. $R = Vd/\nu$, where d is the height of the shell or diameter of a sphere, V is the velocity at height d from boundary, and ν is the kinematic viscosity of the fluid.

If the C_D from Fig. 3 is used, it is possible to calculate the velocity required to produce this dislodging force on a snail of 1.3 cm diameter. As shown in Fig. 4, a velocity of 94 cm/sec at a distance 1.3 cm from the boundary would be necessary to dislodge the snails of this diameter. As the envelope curve shows, the force produced by this velocity distribution would also dislodge snails of all other diameters.

For loose granular surfaces, similar reasoning shows that a V_d of 36 cm/sec at $d = 1.3$ cm would dislodge all snails.

Usually, the responses of the snail followed a definite pattern with several interesting aspects. First, with application of a force the snail started to move "rapidly" in a direction opposite to the force. Its speed was slowed with increasing forces, as shown for a typical snail in Fig. 5. In this case the snail

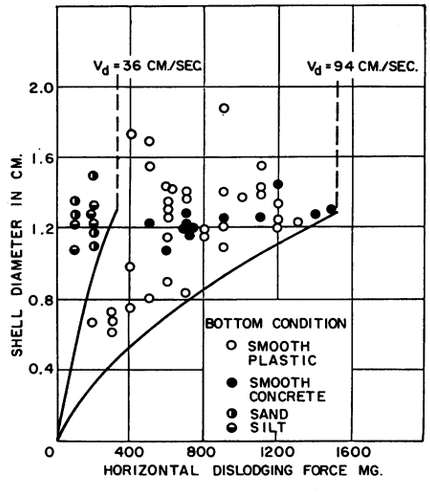

Fig. 4. Dislodging force on live snails plotted against shell diameter.

Table 1. Mean velocities in trapezoidal channels for control of *Australorbis glabratus*.

Discharge (m^3/sec)	Immobilizing mean velocity (cm/sec)
1	58
5	67
10	71
20	75
30	78
50	81

came to a halt at a load of 800 mg. With the addition of another 100 mg the snail lost its hold. The dislodging force obtained with this type of behavior was judged to be an accurate indication of the resistive ability of the snail.

It is amusing, if irrelevant, to calculate the "horsepower output" of these Puerto Rican snails by multiplying force and speed. The snail had a diameter of 1.88 cm and gross weight of 1.2 g. The temperature of the water was 23°C. For this snail, a maximum power of 5 erg or 0.40×10^{-6} horsepower is obtained. Thus, the output of 2.5 million snails would be equivalent to 1 horsepower, hardly an incentive for development of this power source.

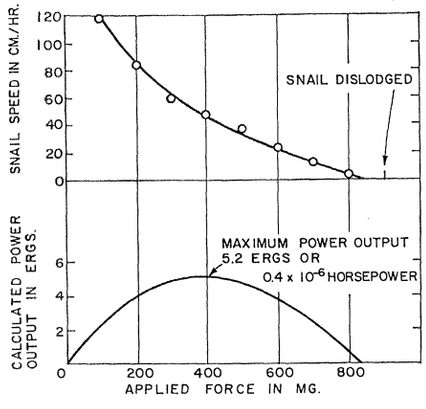

Fig. 5. Snail speed and power output for the largest snail tested.

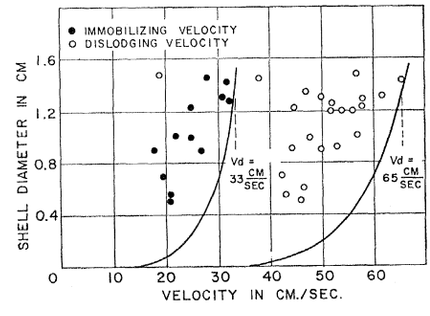

Fig. 6. Immobilizing and dislodging velocities plotted against shell diameter for live snails on smooth plastic bottom.

To test the results and conclusions of the previous studies, snail behavior was studied in flowing water. For this purpose a small lucite flume was used, equipped with recirculation and filtration devices. The width of the rectangular channel was 10 cm, the depth of flow 7 cm, and the length of the channel 80 cm. A maximum discharge of 1 liter per second could be established, resulting in surface velocities up to 65 cm/sec. As in the preceding study, the snails were placed on the bottom of the flume at still water conditions and allowed to get acclimated. Once they had resumed normal activities, the velocity of flow in the flume was slowly increased by small intervals. Water temperatures within the range of 23° to 26°C were stabilized for each flow condition by means of a heat exchanger in the system.

The reaction of *A. glabratus* to flowing water was remarkably similar in all the tests. At very low velocities they pointed in random directions, moving about freely. As the flow increased, the snails showed a definite tendency to move against the current. Eventually they faced directly into the flow and pulled their shells tightly over their bodies, with only the tentacles visible. At a V_d in the range of 20 to 30 cm/sec the snails were completely immobile, and this immobilizing velocity was recorded for each snail. The retracted position, facing upstream, offered the least resistance to the flow and was, therefore, the "safest." The few snails that persisted in moving at this point were driven rapidly downstream and soon lost their footing. With further increases in flow, the snails attempted to remain in a retracted position. Eventually, their shells were pulled back by the drag, either because they tired or because they moved inadvertently. In this position the drag on the shell became still larger, stretching the columellar muscle to the extreme. The snails frequently attempted to pull their shells back to a retracted position but were unable to do so.

Finally, the shell was stretched back in a horizontal position, oscillating rapidly. This action eventually pulled the snail's foot into a position perpendicular to the stream flow. A short time later the snail was pulled loose and was unable to regain its footing. The velocities at this stage were generally of the order of 60 cm/sec and were recorded as the "dislodging velocities."

The immobilizing velocities and the dislodging velocities for all snails are plotted in Fig. 6. Comparison of these results with those in Fig. 4 shows that, for a diameter of $d = 1.3$ cm, a V_d of 33 cm/sec will cause immobilization and 65 cm/sec will cause dislodgment. An envelope curve of velocity distribution is also shown through this value following the relation $V_d/V_o = (d/y_o)^{1/7}$, wherein V_o is the surface velocity and y_o the indicated total depth.

It is interesting to note that the dislodging velocity for flowing water is significantly lower than that predicted by still-water tests (Fig. 4). This difference is a measure of the reaction of the animal to the dynamic character of drag in flowing water.

Knowing the required velocity conditions at the boundary, it is possible to calculate the mean velocity for a given channel section which will produce the desired effect (*5*). Such mean velocities were evaluated for the wide range of channel geometries normally encountered in practice. They are summarized in Table 1 for various channel discharges. Velocities which would cause immobilization rather than dislodgment were chosen for the table of mean values. These are still significantly higher than values recommended from field observations (*2*) and should therefore prove quite conservative in design.

These results are of practical interest for well-maintained canals. Chemical and biological measures are also of great importance in the selection of suitable control schemes. For such planning the systematic approach of this study would seem to offer more reliable recommendations than were previously available on the basis of rather isolated field observations.

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References and Notes

1. J. H. Lanoix, *Bull. World Health Organ.* **18**, 1011 (1958).
2. G. W. Lattermoser, *J. Parasitol.* **30**, Suppl. 13 (1944); J. V. Scorza, J. Silva, L. Gonzalez, R. Machado, *Z. Tropenmed. Parasitol.* **12**, 191 (1960).
3. H. W. Harry and B. G. Cumbie, *Am. J. Trop. Med. Hyg.* **5**, 921 (1956).
4. W. R. Jobin, thesis, Massachusetts Institute of Technology (1961).
5. J. DeAraoz, *Bull. World Health Organ.* **27**, 99 (1963); S. Goldstein, *Modern Developments in Fluid Mechanics* (Oxford Univ. Press, London, 1938).

6. The Department of Tropical Public Health of the Harvard School of Public Health furnished the snails and some of the equipment. Dr. Edward H. Michelson of that department gave valuable assistance on the biological phases of this study.

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