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The Foundation Principles of Dental Cataphoresis.

By Weston A. Price, D.D.S.
Cleveland, O.

Read before the Second District Dental Society,
January, 1898.

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The detailed, progressive, modifications of application of cataphoresis to the dental organs are determined by great underlying principles, which principles are determined by conditions. It is these conditions, many of which are widely variable, and their relation to the process which we shall consider in this paper.

The process consists essentially, and exclusively in the following discussion, in the medication of a tooth by means of an electric current, where an interposing medicament is used under the electrode, which is in contact with the tooth.

The perfection of the application requires the placing in the tissue to be anesthetized, of a sufficient quantity of the medicament for that purpose. The successful placing of that quantity depends upon the current flowing (amperes), and the conditions of the tissue receiving it. The quantity of current flowing is determined by the pain limit (taking it for granted that we have sufficient voltage for any case). Now on what does this pain limit depend, and to what extent do its limits vary?

Constant and Pulsating Currents.

Before attempting to answer this question it is imperative that we distinguish between the actual pain limit of a tooth for a constant current and the pain limit for a current coming in pulsations. The former implies that the controller is capable of furnishing a current of such perfectly gradual increase of potential, that there will be no pulsations, not even the sudden increase of the five-hundred thousandth part of an ampere, as will be shown later, as required for a perfect instrument, for any case.

The latter, the pulsating current, implies that the controller while apparently furnishing a perfectly gradually increasing current, is actually furnishing one in a series of steps. Probably steps too small to be detected with ordinary commercial instruments, but very easily detected by the pain organs of the tooth. The practical application of this point

) instruments will be made later, but at present we will refer to the ıethod in which this pulsating current establishes a pain limit. All erve tissues are stimulated to carry impulses of their normal functions, y a variation in the current passing through them. The acuteness of the erve to receive these stimuli depends largely upon its normal function, 'hich in this particular case, is pain, and is infinitely more acute than ıat of most other nerves. It is the variations which produce these :imulations, and all who have used cataphoresis on these organs, have bserved very closely resembling phenomena in the make and break :imulations, with those of motor nerves.

For a more thorough consideration of the anelectrotonic and catlectrotonic stimulations of the nerves, reference can be made to any ood work on physiology, or to a previous article by the author.

It is true, as has been abundantly established, that every healthy ooth has a definite pain limit for a perfectly constant current. I have een able to establish this frequently, to within the one hundred-thouandth of an ampere, for a variety of total differences of potential, comensating with additional resistance.

To answer this question as to what determines this pain limit, as lso other questions we must consider, it becomes necessary for us to ıake many inquiries which must be answered from clinical data. For xample, what are the approximate differences in different teeth? and n the same tooth under different conditions?

The following data, compiled from one hundred and fifty sucessive cases, has been of the highest importance to me, both for the uccessful application to the individual cases, and for making general leductions. You will note by the different columns that the amperage nd voltage and resistance at both start and finish are given.

The tooth number corresponds with Allport's system of beginning o number from the superior, right, third, molar. Of course the age of he patient, as given, is only a guess, and the time, as shown by remarks, s very often extended to permit of completing another operation. The 'esistances have been worked out, but have not been corrected for the :ounter polarization current. Resistances of liquid conductors cannot e measured absolutely, directly, as can metals, by the method we use; out the results, for our purposes, are quite as accurate as we require. In he following, the anode was a small platinum wire, twisted with cotton; nd the cathode, two pads on the temples, of large size.

Record of Cataphoric Operations.—(CHART I.)

Serial Number.	Tooth Number.	Start.			Finish.			Time.	Size of Cavity.	Medicament.	Approximate Age.	Remarks.
		M. A.	Volts.	Resistance.	M. A.	Volts.	Resistance.					
3	2	0.12	5.	41,600	0.4	21.	52,500	15 m.	Large. ⅔ distance to nerve.	Sat. Cocaine in water.	20	Insulation easily effected. Normal condition of teeth was very sensitive. After application no sensation.
4	11	0.093	42.	450,000	.093	42.	450.000	1 hr.	Abrasion nearly to pulp. Secondary deposit of dentin.	Sat. Sol. Cocaine in water.	55	This was a remarkable case of abrasion, both chemical and mechanical. A glossy surface and extremely sensitive. Conditions extreme and demanded the destruction of the pulp. Application was made while inserting another large gold filling. Resistance so high that very slight effect was produced and that very superficial though general. Another sitting made.
5	"	0.13	72.	550,000	0.13	72.	550,000	10	Same as above.	Same as above.	"	The entire surface of cavity was covered with cement and a small hole bored through about bur No. 5. This concentrated the entire energy on a small surface right over pulp. In ten minutes drilled almost to the pulp and lowered the resistance to 275,000 ohms. Reapplied and in fifteen minutes removed pulp entire without sensation.
6	30	.4	3.2	8,000	0.6	5.6	9,330	12	Exposed and suppurating.	Sat. Sol. Cocaine in water.	21	Imperfect insulation. A hole in the rubber. Results middling. Drilled out part of pulp without sensation. Dentalization completed with White's fibre. No pain.
8	1	0.115	5.	43,470	0.5	16.	32,000	40	Abrasion extensive, caries and exposure.	Sat. Sol. Cocaine in water.	13	An exceptionally sensitive patient; teeth hypersensitive. Could not be dried out with cotton. Removed pulp entire without sensation.
9	26	0.105	3.2	256,000	0.125	32.5	260,000	30	Medium.	Sat. Sol. Cocaine in water.	25	A case of exceptionally dense dentine. The anesthesia perfect after running while putting in two gold fillings.

Record of Cataphoric Operations—Continued.

Serial Number.	Tooth Number.	Start. M. A.	Start. Volts.	Start. Resistance.	Finish. M. A.	Finish. Volts.	Finish. Resistance.	Time.	Size of Cavity.	Medicament.	Approximate Age.	Remarks.
10	30	0.21	4.	19,000	0.41	8.6	20,970	10	Large exposure	Sat. Coc. H_2O.	8	Drilled out the pulp without sensation. Devitalized remnants in roots.
11	29	0.4	7.	17,500	0.7	11.	15,710	10	Large Proximal	Sat. Coc. H_2O.	25	In ten minutes sensitiveness all gone. Drilled laterally across tubuli in all sides of cavity without sensation.
12	19	0.2	6.6	33,000	0.6	18.	30,000	15	Very large	Sat. Coc.	12	No sensation, though before it was simply unbearable.
13	11	0.075	5.4	72,000	0.195	42	215,300	20	Large, not exposed	Sat. Coc.	25	While putting in another gold filling was perfectly anesthetized, so that posterior cavity also was not sensitive.
14	18	(a) 0.28	5.3	18,900	(a) 0.35	8.	22,850	1 m m	Large, not exposed	Sat. Coc.	24	Two applications. First time mostly anesthetized, but some places not enough. Reapplied for two minutes and results perfect.
		(b) 0.4	6.6	16,500	(b) 0.6	8.	13,300					
15	18	0.055	5.3	96,360	0.225	42	186,660	15	Small	Sat. Coc.	21	Perfectly anesthetized while putting in another gold filling.
16	3 & 4	0.185 0.51	5.3 10.6	28,640 20,780	0.405	9.3	23,250	20	Medium	Sat. Coc.	24	Two applications, in two teeth together, and both times the results were much better in one tooth than the other.
17	16	0.13	5.3	28,150	0.41	6.6	16,040	10	Large crown, not exposed	Sat. Coc.	45	Perfect. A simple crown cavity. Easy.
18	30	0.24	5.3	28,083	0.39	6.6	16,920	20 and 10	Large, not exposed	Sat. Coc and Guiacol	12	The cavity was lined with residual decay which was very sensitive. After first application part was removed without sensation, being in the path of least resistance. Second application removed the rest, but one point high on dentine wall was still sensitive, through which the resistance was very high.
19	19	0.37	8.0	21,620	0.45	9.3	20,660	12	Small	50% Cocaine	40	Small distal cavity, but extremely sensitive. Had been treated with $AgNO_3$. Perfect anesthesia.

Serial Number.	Tooth Number.	Start.			Finish.			Time.	Size of Cavity.	Medicament.	Approximate Age.	Remarks.
		M. A.	Volts.	Resistance.	M. A.	Volts.	Resistance.					
20	31	0.14	5.3	20,240	0.27	5.3	19,620	15	Large exposure	H_2O alone	27	A good test case for the current alone. A large exposure and a hardy, tough man. After using water alone for 15 m. no appreciable difference in sensitiveness, which was extreme. Repeated with saturated sol. of C. and removed pulp without sensation.
		0.31	5.3	15,258	0.88	10.6		15		Sat. Coc.		
21	19	0.36 0.285 0.279	6.6 6.6 6.6	16,800 23,120	0.29 0.279	6.6 6.6 6.6	22,750 23,400 13,200	12 9 8	Large, nearly exposed	Sat. Coc.	26	Three applications. Tooth had been aching hard. A gradual lowering of pain limit. Slight anesthesia. Second trial. Slight results, enough to expose pulp and let pus escape. Third trial perfect.
22	30	0.62	5.3	8,540	1.64	10.6	4,379	12	Large, exposed	Cocaine Sat. Cocaine	10	Removed a very large polypus from the nerve painlessly, but hemorrhage was so profuse that everything was covered. Used strong H_2SO_4 as styptic painlessly and applied devitalizing fibre.
23	3	0.121	5.3	42,690	0.19	7.6	40,000	12	Medium	Cocaine Sat.	11	No sensation at first. Was stopped while excavating and when I returned to work found cavity sensitive.
24	12	0.24	5.3	22,080	0.65	10.6	16,300	20	Large suppurating exposure	Cocaine Sat.	16	Entirely removed pulp without sensation.
25	9&10	0.11	7.6	69,090	0.185	16.	84,486	12	Medium, not exposed	Cocaine Sat.	16	Two cavities at once about same size. Prepared both without sensation.
26	7 & 8	0.18	7.6	42,440	0.5	10.6	21,200	12	Two medium	Sat. Coc. in Guiacol	16	Two cavities at once. No. 8 splendid, but No. 7 still sensitive.
27	3	0.0026	1.2	461,616	....	....	....	60	Large	Current only	28	Horton method. Patient said absolutely no difference though every possible combination was made. Tooth extremely sensitive through all. See next case.

Serial Number.	Tooth Number.	Start.			Finish.			Time.	Size of Cavity.	Medicament.	Approximate Age.	Remarks.
		M. A.	Volts.	Resistance.	M. A.	Volts.	Resistance.					
28	3	0.34	5.3	15,580	0.37	14.6	39,450	10	Large	Sat. Cocaine in Guiacol	28	Same case as 27 with cataphoresis. No sensation on drilling. Perfect success.
29	12&13	0.04	5.3	13,250	0.95	9.3	9,780	20	Both large exposure	Sat. Coc. and Guiacol	30	In 20 m. drilled out both nerves as far as bur would reach.
30	5	0.2	5.3	18,700	0.2	5.3	20,700	10	Large exposure aching	50% Cocaine	27	A fierce toothache. In 10 m. pain had all stopped. Removed debris and re-applied, when all the pulp was removed.
		0.2	5.3		0.8	13.3		15				
31	29	0.065	5.3	53,770	0.14	8.	57,140	10	Large exposure	50% Cocaine	30	A similar case to the last, but had to be filled at the same sitting. First time removed part of pulp and second time remainder, and filled root and crown immediately.
		0.27	8.	29,620	0.55	25.3		20				
32	7	0.2	5.3	26,500	0.2	6.6	33,000	15	Medium	Sat. Coc. in Guiacol	16	Perfect results.
33	19	0.38	5.3	13,940	0.44	8.	18,180	20	Very large	Sat. Coc. and Guiacol in water	13	Drilled out all decay without sensation. Nerve not exposed.
36	dog	(Pulp of	cuspid nerve)	and	(Pulp	of cuspid muscle)	pid and					
		0.11	2.6	23,630	0.14	2.6	18,570	......	Relative resistance of nerve and muscle tissue	....	....	A dog was chloroformed and his right superior dental nerve dissected out and insulated to the mental foramen. The relative resistance through the path from pulp of cuspid to end of nerve and pulp to an equal distance on the muscle tissue noted as shown.
37	Sheep's Tooth.	1.8	21.	11,660	0.8	21	26,250	15	Exposed pulp	Methyl blue	....	A two-rooted fresh bicuspid of sheep was placed in circuit with current only through one root and methyl blue in cavity. No difference was noted in the extent of permeation.

Serial Number.	Tooth Number.	Start. M. A.	Start. Volts.	Start. Resistance.	Finish. M. A.	Finish. Volts.	Finish. Resistance.	Time.	Size of Cavity.	Medicament.	Approximate Age.	Remarks.
38	Sheep's Tooth.	1.2	21.	17,500	... ...	......	....	15	....	Strychnine Sulphate	....	Similar to above in arrangement. Found traces in root in which current was flowing.
39	Sheeps' Jaw	1.06 2.62	12. 12.	11,300 4,420	0.08 0.147	12. 12.	150,000 81,620	....	....	....		This was a similar test to No. 36 to determine the relative resistance of path through nerve and muscle. Figures in column called "Start" refer to nerve and muscle paths from pulp of central, and those in column "Finish" refer to same measurements from lateral, both showing a much greater conductivity in the muscle tissue.
40	4 & 5 5 alone 4 alone 5	0.32 0.2 0.1 0.4	5.3 4. 21. 10.6	16,590 20,000 210,000 26,500	0.8 0.9	14.6 16.	18,250 17,770	20 10	5 large exposure, 4 medium	Sat. Cocaine	16	Note difference between Nos. 5 and 4 above. After first application pulp was almost entirely removed from No. 5. Slight sensation in No. 4. Second application removed all from No. 5.
41	Frog	1.0	5.3	5,300	0.7	5.3	7,570	20	Chest to back	Strychnine Sulphate	..	This experiment was made to see if the current actually made any difference in the action of strychnine sulphate on a frog. In about 5 m. the characteristic spasms. The rigid spasms had almost ceased in 10 m. and in 20 m. it was perfectly lifeless. This had been applied for 30 m. the day before without the current and with no effect.
42	19	0.08	2.6	17,480	0.14	2.6	12,765	20	Verylarge, nerve slightly exposed	Sat. Guiacol and Coc. in water	11	Extremely sensitive tooth. Boy had been injured by a street car three weeks before, and his nerves were so sensitive that touching the enamel of any tooth made him cry. Tooth had ached badly. After using had but little trouble removing debris and part of pulp. No pain from devitalizing.

Record of Cataphoric Operations—Continued.

Serial Number.	Tooth Number.	Start.			Finish.			Time.	Size of Cavity.	Medicament.	Approximate Age.	Remarks.
		M. A.	Volts.	Resistance.	M. A.	Volts.	Resistance.					
43	5	0.3 0.5	5.3 6.6	13,896	0.76 0,78	6.6 8.	....	15 10	Medium large exposed	10% Guiacol and Sat. Cocaine	25	In 15 m. removed decay and part of pulp, and in 10 more the remainder.
44	3	0.6 0.6	5.3 5.3	8,833 8,833	0.7 0.7	6.6 42.	9,428 60,000	12 10	Medium	(1) KI and Guiacol (2) Cocaine Sat. in Water	27	First application no results. On removing anode found it jet black. Later found mistake in place of K. I. bottie. Had used Potassium Iodide in Guiacol. Second Application.
45	Frog.	...	....	No	current.			......	....	....		Placed pledget of cotton soaked with sulp. strychnine on frog's stomach for 30 m. with no apparent physiological effect. See case No. 41.
46	Frog.	1.	8.	8,000	...	....	...	30	Chest and back	Water		Used 1 No. A, as applied with sulphate of strychnine, but with no medicament except water for 30 m., with no apparent physiological effect except a dullness of motor reflexes in hind legs, owing to electrode being over motor centres. See case No. 41.
47	Frog.	2.	7.6	3,800	...	....	....	15 15	....	....		Placed pledget of cotton soaked with mercuric-bichlorid on frog's chest and he went into collapse in 10 m. In 20 m. dead.
48	12	0.2	2.6	13,000	0.8	13.3	16,625	14	Large exposure	Sat. Cocaine and 10% Guiacol		Completely drilled out nerve and filled root, whole operation not exceeding 35 to 40 m.
49	Frog. Nerve m'scle	0.03 0.12	1.3 1.3	43,330 10,830	....	....	....	....	....	Current		The relative resistance of the sciatic nerve and the muscle path to the same point. The foot was immersed in salt water and the other electrode applied, first to cut end of sciatic near lumbar attachment, and second to severed attachment. See resistances.
50	8 & 9	0.2	8.	40,000	0.25	9.3	36,800	20	Small	Sat. Cocaine	11	A very sensitive patient, but the anesthesia perfect.

Serial Number.	Tooth Number.	Start.			Finish.			Time.	Size of Cavity.	Medicament.	Approximate Age.	Remarks.
		M. A.	Volts.	Resistance.	M. A.	Volts.	Resistance.					
51	8	0.15	5.3	35,330	0.2	8.	40,000	12	Medium	Cocaine 10%	11	Perfect results.
52	7	0.2	5.3	26,500	0.38	12.	31,500	15	Medium	Cocaine 10%	30	Perfect results, though the tooth was so extremely sensitive before.
53	....	0.2	4.	20,000	0.6	6.6	11,000	10	Large	Cocaine 10%	11	Only medium results, owing to position of cavity could not perfectly insulate.
54	14	0.2 0.25	5.3 8.8	26,500 32,000	0.25 0.3	6.6 9.3	26,400 31,000	10 10	Large, exposed	Sat. Cocaine in Water.	26	First results not perfect because of leakage. Second application perfect. Removed pulp. Tooth had been aching very hard.
55	....	0.1	2.6	26,000	0.8	8.	10,000	12	Large, nerve exposed	Sat. Cocaine	24	After 10 m. the amperage suddenly increased, showing leakage. It was removed and results sufficient to remove part of pulp, rest devitalized.
56	31	0.2	5.3	26,500	0.58	9.3	16,030	12	Large exposure	Sat. Cocaine	30	Drilled out nerve without sensation. Partly sloughed away.
57	18	0.2	5.3	26,500	0.62	9.3	15,000	12	Very large exposure	Saturated Solution of Cocaine	16	Drilled out exposed pulp without pain. Had been aching hard for some time. Perfect results.
58	Gum	2.4	8.	3,330	....	....	....	5	Used on gum	Cocaine	20	Used for root extraction, gum well anesthetized.
59	4	0.22	6.6	30,000	0.3	10.6	3,530	10	Large	10% Cocaine	17	Perfectly anesthetized.
60	9	0.35	5.3	15,100	0.4	16.	40,000	10	Large	Sat. Cocaine	30	Perfectly anesthetized, pulp slightly exposed and capped.
61	3 & 4	0.15	4.	26,330	0.5	9.3	18,600	13	Large	Sat. Cocaine	26	Both perfectly anesthetized.
62	28 & 29	0.1	2.6	26,000	0.4	14.6	36,500	12	Both large	Sat. Cocaine	30	Both perfectly anesthetized.

Record of Cataphoric Operations—Continued.

Serial Number.	Tooth Number.	Start. M. A.	Start. Volts.	Start. Resistance.	Finish. M. A.	Finish. Volts.	Finish. Resistance.	Time.	Size of Cavity.	Medicament.	Approximate Age.	Remarks.
63	31	0.25	6.6	26,400	0.3	9.3	31,000	12	Large	Sat. Cocaine	16	No sensation except at one point in drilling across tubuli.
64	29	0.1	4.3	43,000	0.2	....	35,150	20	Large	Sat. Cocaine	18	Good, though a bad case to insulate from other fillings. Chlora percha used freely.
65	30	0.12	5.3	44,160	0.5	17.3	34,600	13	Medium	Sat. Cocaine	..	Compound cavity, but no sensation in preparation, except in a deep lateral undercut.
66	18	0.15	4.	26,660	0.32	8.	25,000	12	Medium	Sat. Cocaine	17	Drilled out without sensation, except when going across the tubuli in one direction in an undercut.
67	11	0.17	5.3	31,170	0.6	21.	35,000	10	Large exposure	Sat. Cocaine	22	Completely drilled out exposed nerve without a particle of sensation. Badly suppurated.
68	27	0.2 0.2	5.3 5.3	26,500 26,500	1. 0.8	9.3 12.	9,300 15,000	10 10	Very large exposure	Sat. Cocaine	38	The rubber slipped up enough to allow a break in the insulation as shown by the resistance. It was taken off and reapplied and a second application made, when every particle of the pulp was removed without sensation, evidently a very large apical foramen.
69	7	0.05	2.6	52,000	0.25	21.	84,000	10	Medium	Sat. Cocaine	15	Did excavating without a particle of sensation.
70	2	0.2	8.	40,000	0.6	12.	20,000	10	Small	Sat. Cocaine	26	Perfect results, although the current was leaking toward the last, as shown by the resistance.
71	28 & 29	0.3 x. 1.01	6.6 5.3 5.3	22,000 53,000 75,704	0.4 0.2 0.3	8. 10.6 21.	20,000 23,000 70,000	10 20 10	28 Large 29 Small	Sat. Cocaine first. Guiacol and Cocaine	28	A remarkable case. Two cavities were tried together for 10 m., when the small one showed no sensitiveness and the large one did, which was a large exposure. Reapplied on large exposure for 20 m. when partially removed. Reapplied for 10 m. and removed all of remainder of pulp. Root was filled at the time. The apical foramen was too small to find with the smallest broach.

Serial Number.	Tooth Number.	Start.			Finish.			Time.	Size of Cavity.	Medicament.	Approximate Age.	Remarks.
		M. A.	Volts.	Resistance.	M. A.	Volts.	Resistance.					
72	8	0.1	6.6	66,000	0.32	21.	65 620	12	Large	Sat. Cocaine	17	Perfect results. Nerve not exposed.
73	9	0.1	8.	80,000	0.35	21.	60,000	12	Small	Sat. Cocaine	23	Perfect results.
74	19	0.12 0.23 0.15	4. 5.3 9.3	33,330 23,040 62,000	0.25 0.32 0.7	8. 9.3 21.	32,000 26,844 30,000	10 20 8	Large exposure	Sat. Guiacol and Coc. Sat. Coc. in H_2O	25	In 10 m. drilled out part of pulp, but ant. root very sensitive. Reapplied for 20 m. and could not increase the current as ordinarily, and the ant. root still sensitive, though posterior, not even beyond the tip, through a large foramen. Removed pulp from posterior root and filled with an insulator and reapplied for 8 m. Found resistance much increased in ant. root alone. Removed all pulp without sensation.
75	30	0.12	6.6	55,000	0.4	21.	52,500	14	Large under gum	Sat. Cocaine H_2O	23	Perfect results. Insulation difficult.
76	10	0.05	13.3	266,000	0.15	42.	....	8	Very small	Guiacol and Sat. Cocaine	17	Splendid. Was extreme.
77	8	0.13	5.3	40,760	.3	21.	70,000	15	Large	H_2O Cocaine	12	One of the most sensitive patients in the country. Absolutely no sensation.
78	30	0.12	5.3	44,160	0.45	12.	....	16	Large exposure	Sat. Cocaine H_2O	26	Drilled out large suppurating pulp without sensation, except in extreme tips of roots.

Record of Cataphoric Operations—Concluded.

Serial Number.	Tooth Number.	Start. M. A.	Start. Volts.	Start. Resistance.	Finish. M. A.	Finish. Volts.	Finish. Resistance.	Time.	Size of Cavity.	Medicament.	Approximate Age.	Remarks.
79	20	0.3 0.2	2.6 5.3	86,600 26,500	0.15	5.3	35,350	25	Large	Sat. Cocaine H_2O	27	not slept for 48 hours. Tooth aching for a month. Too sensitive to dry with cotton pledget. M. A. constantly decreased for some time. Closer examination showed remnant of old cement filling over pulp which, when removed, allowed pus to escape. Reapplied, but could not remove all of pulp tissue. Devit. with fibre and when filling root found apical foramen very small, and resistance through root walls very low.
80	......	0.15	5.3	35,330	0.4	9.	22,500	12	Medium	H_2O Sat. Coc.	20	Completely anesthetized, but a recurrence after five minutes.
81	19	0.15	5.3	35,330	0.5	10.6	2.,200	20	Very large	Sat. Coc. H_2O	26	Completely removed pulp without sensation.
82	19	0.11	5.3	46,360	0.22	6.6	30,000	12	Large	Sat. Coc. H_2O	12	Perfect results.
83	29	0.1	4.	40,000	0.2	8.	40,000	15	Medium	Sat. Coc. H_2O	40	Perfectly anesthetized while putting in gold filling in No. 26.
84	29&30	0.21	5.3	25,230	0.46	8.	17,390	12	Both medium large	Sat. Coc. H_2O	20	Perfect results.
85	7	0.13	9.3	71,540	0.2	21.	105,000	12	Medium	Sat. Coc. H_2O	24	Perfect results, but a recurrence in five minutes.
86	8 & 9	0.1	4.	40,000	0.2	8.	40,000	18	Large both	Sat. H_2O Cocaine	28	Quite perfect results in 9, but not in 8. Reapplied and good in both.
....	....	0.37	10.2	....	0.41	18.2	...	10			..	
87	1	0.08	4.	50,000	0.45	9.3	20,630	17	Large	5% Cocaine H_2O	25	A hard patient, but perfect results.
88	13	0.08 0.12	5.3 9.3	66,250 77,500	0.2 0.23	10.6 32.0	53,000	... 25	Medium	Coc. Sat. H_2O	26 ..	A skeptical patient and teeth very sensitive. Touching the dentine unbearable. After using dentine did not hurt as much as the enamel when being drilled.

Serial Number.	Tooth Number.	Start.			Finish.			Time.	Size of Cavity.	Medicament.	Approximate Age.	Remarks.
		M. A.	Volts.	Resistance.	M. A.	Volts.	Resistance.					
89	G um	1.2	6.6	5,500	1.6	6.6	4,120	3	....	Brass Electrode in 50% H_2SO_4	50	Pyorrhœa, very deep pockets. Tooth elongating. Pockets washed with $H2SO_4$ 50%, and a brass electrode used in same solution. In three months no recurrence of pus. Three treatments were given.
90	14	0.1 0.28	4. 5.3	35,720	0.4 0.6	8. 10.6	20,000 17,660	20 10	Medium large	Sat. Cocaine H. 2°	30	Drilled out all of decay and found a large suppurating exposure. Reapplied for 10 m. and drilled out all except small buccal root which was devit. No sensation.
91	14	0.1	2.6	26,000	0.5	6.6	13,020	12	Medium large	Sat. Cocaine H. 2°	17	Perfect results, not exposed.
92	5	0.08	2.6	32,500	0.33	8.	....	15	Exposure large	Sat. Coc. H. 2°	26	Completely extirpated without pain.
93	4 & 5	0.13	4.	30,710	0.6	10.6	17,096	17	4 Exposed 5 Large	Sat. Coc. H. 2°	14	Perfect results. Hysterical patient. No. 5 large exposure. Removed pulp on broach and filled root without patient's knowledge.
94	28	0.25	9.3	37,200	0.32	16.	50,000	10	Small	Sat. Coc. H. 2°	35	Splendid.
95	8 & 9	0.08	4.	50,000	0.1	5.3	53,000	8	Both medium	Sat. Coc. H. 2°	28	Perfect.
96	......	0.07 0.4	2.6 6.6	37,140 15,860	0.4 0.85	6.6 10.6	16,500	17 7	Very large exposure	Sat. Coc. H. 2°	27	Tooth had been aching hard. Pain ceased quickly. Removed part of pulp and devit. No pain from devitalizing whatever.
97	30	0.07	2.6	37,140	0.5.	9.3	18,600	20	Very large not expos.	Sat. Coc. H. 2°	18	While cementing crown for another patient, completely anesthetized this tooth.
98	31	0.08	2.6	32,500	0.6	8.	13,330	8	Very large	Sat. Coc. H. 2°	26	Tooth excruciatingly sensitive. Perfect results.
99	4	0.15	5.3	35,330	0.4	10.6	26,250	16	Large	Sat. Coc. H. 2°	25	Perfect results.
100	11	0.1 0.35	5.3 8.	53,000	0.3 0.7	8. 12.	26,660 17,140	20	Very large	Sat. Coc. H. 2°	28	Perfect results.

Averages of Results.

verage pain limit (Mill. amps.), at start of first 50 cases	0.245
" voltage at start of first 50 cases	8.51
" resistance at start of first 50 cases	34,730 ohms.
" pain limit (Mill. amps.), at finish of first 50 cases	0.482
" voltage at finish of first 50 cases	12.25
" resistance at finish of first 50 cases	25,410 ohms.
" pain limit (Mill. amps.), at start of second 50 cases	0.155
" voltage at start of second 50 cases	5.2
" resistance at start of second 50 cases	33,540 ohms.
" pain limit (Mill. amps.), at finish of second 50 cases	0.406
" voltage at finish of second 50 cases	18.
" resistance at finish of second 50 cases	42,330 ohms.

Minimum pain limit at start 0.01 mill. amp. or $\frac{1}{100000}$ amperes. In 17 per cent. ie pain limit at start was less than 0.1 mill. amp. or $\frac{1}{10000}$ amperes. No commercial ill. amp. meter on the market at present would give a clear reading of these 17 cases.

From the foregoing clinical data we are able to make very valuable eductions, with which we can, in connection with the laws of electro-hysics and electro-chemistry, explain and determine most of the phe-omena of dental cataphoresis.

Some of these are as follows:

Deductions from Records.

1. The relation of the results to the amperage is in direct proportion in most cases; but not where the result desired is to anesthetize a part of the tooth 'hich is of relatively high resistance as compared with other parts of ie path, as for example, the margins of a cavity, where the center of is near the pulp, or where removing the pulp from a root, where the iteral resistance through the root walls is less than through the apex.

2. The results are not directly related to the resistance alone for the pain limit will permit, this is overcome by an increase of voltage. 'here are some conditions, however, where the pain limit will not permit, s for example, case 74.

3. The time is usually in inverse proportion to the amperage. The xceptions are the same as in the first.

4. There is not a definite relation between the time and the resis-ınce, though very often they are in direct proportion, the reason for hich will be shown later.

5. There is not necessarily a relation between the extent of surface : dentine exposed, and the time, though there is a very definite rela-on between the results, and the relative resistance through different ırts of that surface.

6. There is a constant relation between time and results.

7. The pain limit is very widely variable.

8. The resistance of teeth is markedly in direct proportion to the age of patient.

9. The pain limit is usually in indirect proportion to the age of patient.

From these observations it becomes clearly evident that the same relation of conditions does not exist when working in the roots as when working in the cavity, where the pulp is not exposed, for there seems to be an almost constant relation between the results and current in the latter, but not at all in the former. Now the amperage, or quantity of current, flowing, is the expression of the pain limit, hence the pain limit, or its source, does not bear the same relation to our work in preparing a cavity as it does in removing the pulp from roots.

These facts led me to investigate the relative resistance through the root walls of teeth, and through their apical foramena. The results were very startling to me, as no doubt they may be to some of you. Note the difference in the resistance of teeth in and out of the mouth, though all the latter had been soaking for weeks in water containing a few drops of camphophenique, simply to sterilize. (See Chart 2 and 3.)

Direction of Current Flow.

From these readings it is clearly evident that we have been mistaken in our assumption that the current was mostly all going through the tip of the root. On the contrary, it is an entire uncertainty which way the current is going, through the apical foramen or through the walls of a root. This at once explains why so often when we are trying to anesthetize the last remnant of pulp from a root it takes so much longer time than we should expect. Of course the ratio of the current flowing laterally through the walls is to that flowing through the apical foramen, as the resistance of the latter is to the former and the same relation exists between the different roots, if more than one, which accounts for the fact that often we can remove the pulp from one root long before we can from the other. In this case, if you will pardon a suggestion outside of the subject, before proceeding plug up the root from which you first remove the pulp tissue with an insulator. I have carefully prepared a table of resistance through the various sizes of apical foramena, taken from actual cases and have compared them with those observed in various sized openings in a tip of a glass tube drawn to as near as possible the shape of a pulp chamber in a single rooted tooth. You will observe that the resistances are in good relation, though higher in the tooth than in the glass tube, probably because in the former there are shreds of tissues which partially close the foramen.

Serial Number.	Tooth.	From cavity pulp not exposed.		From exposed pulp.		From pulp chamber through root walls, tips sealed.		From pulp chamber through tips, with walls sealed.		Lingual or single or anterior roots, tip sealed.		Buccal or posterior roots, tip sealed.	
		M. amp.	Resistance.	M. amp.	Resistance.	M. amp.	Resistance.	M. amp.	Resistance.	M. amp	Resistance.	M. amp.	Resistance.
1	Bicuspid....	0.2	99,700	1.0	17,300	Not exposed. 0.04 Exposed. 0.8	 473,000 22,300	Not exposed. 0.5 Exposed. 0.2	 437,300 99,700	Not exposed upper half. 0.01 Lower half. 0.01	 1,997,300 1,997,300	Pulp exposed, upper half. 0.2 Lower half. 0.6	 99,700 30,630
2	Lower molar......	0.2	99,700	0.6	30,630	Not exposed anterior root. 0.1 Posterior root. 0.13 Exposed pulp, anterior root. 0.2 Posterior root. 0.4	 197,300 130,630 99,700 47,300	Anterior root. 0.1 Posterior root. 0.1	 197,300 197,300	Upper half, not exposed. 0.02 Pulp exposed. 0.2 Lower half pulp exposed. 0.1	 997,000 997,000 197,300	Upper half, not exposed. 0.02 Pulp exposed. 0.2 Lower half, pulp exposed. 0.3	 997,000 99,700 63,630
3	Bicuspid....	..	....	1.3	12,680	0.8	22,300	0.23	84,256	Pulp exposed, upper half. 0.6	 30,630	Same root pulp exp., l. half. 0.2	 99,700
4	Upper molar........	1.0	17,300	1.3	12,680	Not exposed anterior root. 0.22 Posterior root. 0.01	 997,000 1,997,000	Not exposed anterior root. 0.02 Exposed. 0.2 Not exposed posterior root. 0.01 Exposed. 0.1	 997,000 99,700 1,997,000 197,300	Pulp exposed, upper half. 0.6 Lingual exposed. 0.02 Pulp exposed. 0.4	 30,630 997,000 47,300		
5	Lower molar........	..	....	1.75	7,720	Exposed anterior root. 1.1 Posterior root. 0.3	 15,480 63,960	Exposed anterior root. 0.3 Posterior root. 0.05	 63,960 437,300	Anterior and buccal roots, upper half not exposed. 0.6 Lower half. 0.8	 30,630 22,300		
6	Lower wisdom......	0.8	22,300	1.6	9,800	Not exposed. 0.6 Exposed. 1.3	 30,630 12,680	Not exposed. 0.2 Exposed. 0.3	 99,700 63,960				
7		..	....	0.67	27,150	0.57	33,387	0.1	197,300	Pulp exposed, upper half. 0.4 Lower half. 0.12	 47,300 163,966		
8	Lower wisdom......	..	....	0.62	29,558	0.5	37,300	0.12	163,966	Pulp exposed, upper half. 0.4 Lower half. 0.2	 47,300 99,700		
9	Bicuspid....	..	....	0.7	25,870	0.4	47,300	0.3	33,960	Pulp exposed, upper half. 0.17	 114,947	Same root, lower half. 0.2	 99,700
10	Upper wisdom......	0.6	30,630	0.8	22,300	Not exposed. 0.2 Exposed. 0.5	 99,700 37,300	Not exposed. 0.01 Exposed. 0.3	 1,997,300 63,960	Not exposed upper half. 0.2 Lower half. 0.02	 99,700 997,000	Same root pulp exp., u. half. 0.2 Lower half. 0.3	 99,700 63,960
11	Two-rooted bicuspid..	..	....	1.3	12,680	0.5	37,300	0.8	22,300	0.2	99,700	0.3	63,960

Resistances Through Moist Teeth to Mercury Bath, Voltage 20. External Resistance in Circuit, 2,700 Ohms.

(CHART III.)

Serial No.	Tooth old, soaked in water.	From pulp chamber through root walls, tips sealed.		From pulp chamber through tips, walls sealed.		From pulp chamber, through tips and walls.	
		M. amp.	Resistance.	M. amp.	Resistance.	M. amp.	Resistance.
12	Upper molar	0.6	30,630	2.4	5,633	3.0	3,966
13	Two-rooted bicuspid......	0.2	99,700	0.1	197,300	0.3	63,900
14	Upper molar...........	0.6	30,630	0.3	63,960	0.9	19,620
15	Upper molar	0.6	30,630	0.6	30,630	1.2	13,960
16	Lower molar	0.05	473,300	0.2	99,700	0.25	77,300
17	Lower molar	2.1	6,823	1.4	11,580	3.5	3,014
18	Upper molar	0.4	47,300	0.2	99,700	0.6	30,630
19	Lower molar	1.0	17,300	1.1	15,480	2.1	6,823
	Upper molar	0.7	25,870	0.5	37,300	1.2	13,960
				Lingual.			
				0.3	63,960		
				Buccal.			
				0.2	99,700		
21	Upper molar	0.2	99,700	0.85	20,829	1.05	16,347
22	Upper molar	0.1	197,300	0.2	99,700	0.3	63,960
				Lingual.			
				0.05	437,300		
				Buccal.			
				0.15	130,633		

Fresh Teeth Readings Taken Immediately After Extraction.

23	Upper molar	0.6	30,630	0.3	63,960	0.9	19,620
				Lingual.			
				0.1	197,300		
				Buccal.			
				0.2	99,700		
24	Child's tooth	..	....	1.1	15,980	1.8	8,110
25	Old man's 3d lower molar	0.6	30,630	0.4	47,300	1.0	17,300
26	Old man's 2d lower molar	0.3	63,960	0.2	99,700	0.5	37,300

In any case except a young patient it would seem that the resistance is just as likely as not to be greater through the foramen than through the walls of the root. (See Chart 4.)

These diameters were determined by placing in the opening to be measured, as through the apical foramen, a very fine, gradually tapering, steel broach, specially prepared, and measuring its diameter at point of contact. I have measured the resistances of many cases in the mouth by taking readings before drying for root filling, and then again filling the end of the root, and have, by associating these readings with the previous

esistance Through Apical Foramena of Increasing Size. Voltage 20. External Resistance in Series, 2,700 Ohms.

(CHART IV.)

Teeth Roots.			Drawn Glass Tube.		
iam., 1000th inch.	M. Amp.	Resistance.	Diameter, 1000th of an inch.	M. Amp.	Resistance.
9	0.4	47,300			
11	0.5	37,300	1	0.12	163,966
12	0.52	35,762	1.5	0.2	99,700
14	0.6	30,630	2	0.32	59,800
15	0.8	22,300	3	0.41	46,080
16	1.2	13,460	4	0.6	30,630
18	1.3	12,680	5	0.8	22,300
19	1.4	11,550	6	0.9	19,620
			7	1.1	15,480
6	0.3	63,960	8	1.8	8,410
7	0.4	47,300	9	2.4	5,633
9	0.5	37,300	10	2.8	4,442
10	0.52	35,762	11	3.1	3,751
11	0.6	30,630	12		
12	0.7	25,870	13	3.2	3,550
14	0.72	25,077	14	3.5	3,014
			15	4.2	2,061

ecords of pain limit, and results in removing pulp tissue, come very orcibly to the conclusion that almost invariably the pain limit is deternined in the apical foramen. The exceptions are easily distinguished, and easily explained. If this be so, it will account largely for the actual esults of experience.

Physical Effects of Electricity.

Just here, let us consider some of the physical effects of an electric current. One of these is the production of heat. From the law of the conservation of energy, we know that energy cannot be created or lost; hence the energy lost, as electric energy, by an electric current, in passing through a conductor, is not lost, but must change to an equivalent of some other kind of energy. In a metallic conductor the loss of electrical energy is practically all changed to heat. In fact, in any system of a homogeneous conductor, the heat generated by the passage of a current can be absolutely calculated by knowing two things, the fall of potential and the amperage, or the resistance and the amperage. In brief, it is expressed as follows: "The heat developed in a homogeneous portion of any circuit, is equal to the square of the current in the circuit multiplied by the resistance of that portion." This is known as Joule's law. It holds good for any homogeneous circuit, or for all parts that are homogeneous.

There are modifications of conditions which may enter to make the circuit non-homogeneous, as for example, the difference of potential between a metal and a liquid, or two liquids, or the chemical changes taking place. If a gas is evolved, of course heat is absorbed. The increase, in the system, of chemical energy which would demonstrate itself as a counter, or polarization, current of the electrolysis, is also to be subtracted to make an absolute calculation. For our present purpose these may be neglected as they will practically be proportional in the different parts.

Let us suppose a practical case. A single rooted tooth, for simplicity say a central incisor, with large mesio-proximal cavity, extending half way to the pulp.

Heat Generated by Current.

Suppose the milliampere meter reads 0.4 and voltage is 25. Then the resistance of the circuit is 62,500 ohms; neglecting the polarization current.

Let us suppose the resistance through the dentine from the cavity to the pulp is 10,000 ohms, and from the pulp to the tissue, around the tooth, 45,000 ohms, and from this point to the negative electrode 7,500 ohms. Suppose, for simplicity, that the resistance from the pulp through the root walls is equal to that through the apical foramen. Then the path of our current will be, provided our cavity is perfectly insulated, as follows: All of it through the cavity and dentine to the pulp, and thence one-half through the root walls and one-half through the apical foramen, and thence to the negative electrode. As the current leaves the pulp, it has two paths, whose combined resistance is 45,000 ohms. Since the combined resistance of any shunt is equal to the product of the individual resistances of the paths divided by their sum, then the resistance of each of these two paths must be 90,000 ohms. Now, applying Joule's law to the various parts of this circuit, we have, the heat generated in the dentine between the cavity and pulp, represented as below; using the centi-gram-second system of units, which we shall use exclusively. This will require us to express our previous equation: $\text{Amperes}^2 \times \text{Ohms} \times .236 = \text{Calories}$. ($a^2 \times O \times 0.236 = C.$)

A calorie is the amount of heat required to raise one gramme of distilled water one degree centigrade.

Hence $0.0004^2 \times 10{,}000 \times 0.236 =$ calories of heat developed in 1 second in the dentine $= 0.0003776$. But one calorie is the amount of heat necessary to raise one cubic centimeter of distilled water, one degree centigrade, for 1 gramme = 1 cubic centimeter of distilled water at its maximum density (4° C.); therefore to express the actual rise of temperature in this part of the circuit, per second, we must determine the volume of matter heated, and express it in cubic centimeters, for the rise of temperature is in inverse ratio to the volume. We must also know the specific heat of the substance, for if the matter in question has a greater or less specific heat than water, it would experience a relatively less or greater change of temperature, from the same heat unit. As a matter of fact, the specific heat of blood is slightly less than that of water; 1 calorie would raise that amount of blood more than 1 degree C. Since the tissues we must consider are so variable and complicated, and since the error from this source will be comparatively small, we shall not complicate the consideration with this correction.

I have cut out a section of dentine corresponding as nearly as possible to that portion through which the current was passing in the case we are supposing, and found its volume to be 0.001727 C. Cm. This was determined by displacement in a small capillary tube. Applying this to our calculated heat developed, we get 0.0003776 × 580 = Rise of temperature in the dentine in 1 sec. in degrees centigrade = 0.219, and expressed in Fahrenheit, 0.394°.

If this elevation of temperature were quite evenly distributed through the dentine lying in the path of the current, it should not produce discomfort. As a matter of fact, however, it will not be evenly distributed for two reasons. The resistance through the different parts of the dentine will vary largely; and again the current is conveyed through the dentine by the contents of the dentinal tubes whose total cross sectional area, and also volume, is very much less than that of the lime salts. If these tubuli were all the same size and length, the heat would be relatively evenly distributed throughout the entire volume of dentine in the path, but the actual heat produced in any one of them would be much more than that we have calculated. If the volume of the conducting matter in the tubuli is relatively very much less than that of the dentine surrounding them, then the rise of temperature in them will be inversely greater, and in the ratio of their volumes.

The current is practically all conducted by the animal matter which constitutes 28 parts of normal dentine by weight. If the ratio of the specific volume of these two substances were the same as the ratio of their specific weights, we could substitute; but they are not. The specific weight of dentine, with animal matter extracted, is more than 20 per cent. greater than that of animal matter. This will make the specific volume of the animal matter about 33 per cent. in ordinary dentine. Now, if all the tubuli are helping alike to carry the current, that is, have the same size and length, then the rise of temperature in each one will be three times greater than we have calculated, or 0.657° C., or 1.182° F. This should not produce pain.

Let us proceed in the same way and determine the heat developed in the other parts of this circuit. In the body beyond the tooth the resistance is 7,500 ohms, and the amperage 0.0004. Then the total heat developed in this part of the circuit is $7{,}500 \times 0.0004^2 \times 0.236 =$ Calories $= 0.00028$. This quantity of heat is developed in very many times the unit of volume, 1 C. C. M., hence the rise of temperature will be relatively that much less.

As a matter of fact, by far the larger part of this resistance through the patient, is found in the external layers of the skin, which fact, associated with Joule's law, explains why we get a tickling sensation on the point of contact of a constant current, and not a tickling throughout the circuit. This has nothing to do with the sensation felt from a pulsation of current as a make or break. If most of the total current flowing is passing through the skin, through one or more minute areas, as through a hair follicle, or from a small point of any kind, we should get a sensation with a very low amperage. Hence use just as large an indifferent electrode as possible, both to reduce the total resistance of the circuit, and to diminish the possibility of sensation at that point.

Let us now determine the heat generated by the passage of the current through the root walls. Through this path we have 0.0002 amperes of current flowing, and the resistance is 90,000 ohms. The total heat generated is $0.0002^2 \times 90{,}000 \times 0.236$ Calories $= 0.0008496$.

If the volume in which this is developed is more or less than 1 C. Cm., the rise of temperature will be less or more than this number of degrees centigrade. The total volume of substance in the root walls is probably occasionally as great as one-half a C. Cm., though generally less. In a central of average size it is probably about one-fourth. It would be practically impossible to determine the relative volume of the conducting matter, and the non-conducting matter of the substance of the root walls, without an analysis, but we know that since the surface is so great, the concentration of heat will not be great enough in the individual tubuli to cause much rise of temperature, provided the tubuli are comparatively uniform in size and length, or in other words, of uniform conductivity.

Let us now determine the heat developed in the apical foramen in this case. It is $0.0002^2 \times 90{,}000 \times 0.236$ Calories $= 0.0008496$. If this were in a substance whose volume was 1 C. Cm., and whose specific heat was the same as that of water, the elevation of temperature in one second would be the above number of degrees C. But the volume is very much less.

We will assume without considerable error that the specific heat of the contents of the apical foramen is the same as that of water. The next thing for us to determine is the volume of the conducting matter in the apical foramen, through which the resistance is 90,000 ohms, and express it in terms of the unit 1 C. Cm. of water. This is one of the most difficult considerations we have, but I think it can be done very approximately. First we must determine how far up the pulp tissue we must consider. By measuring the resistance through the apical foramen of a root, and then gradually cutting it back from the tip, making readings frequently, it is easy to determine the relative resistance of the different areas. This can also be done by enlarging the same foramen and noting the resistance of certain measured sizes of openings. In this way I have determined that in all cases where the pulp chamber suddenly contracts at the apex, as most canals do, the resistance is almost all in the last one-eighth or often one-twentieth of an inch. For this reason, in these considerations I have neglected the resistance through pulp tissue, since relatively it is very small as compared with the other parts of the teeth. In the determination we are to make of this root, I have taken the tissue for about 3 millimeters. It is practically an impossibility to take the tissue from the root of one of these cases, and measure it; it must be done by other means. In order to use the same units which we have been using, the substance used instead of pulp tissue must have as nearly as possible the same specific weight as that tissue, and must be something we can handle. Since green hard wood and blood and water have so nearly the same specific weight, which means the same specific volume, we can substitute this substance for the pulp tissue, and still retain the same units, besides having something we can shape and handle.

From the table of observed resistances, I would say that to have 90,000 ohms resistance, the apical foramen would be about four-thousandths of an inch in diameter.

According to these requirements I have prepared from green applewood, as nearly as possible, fac-similes of the shape and volume of the tissue in various sized apical foramena. These being of the same specific weight as water, could by their weight express the volume of the tissue in question in C. Cm. For the absolute weight of these while green, I am entirely indebted to Dr. Miller, Professor of Physics of Case School of Applied Science. He was able to weigh them to within one-ten-thousandth part of a gram. These show that the weight of the tissue in question for the particular case which we are now considering, as nearly as I could prepare the specimen, was 0.21 milligrams, or since its specific volume is the same as that of water, approximately, its volume is 0.00021 C. Cm. Therefore the rise of temperature in this part of the path is $0.0008496 \times \frac{100000}{21} = 4.04$ degrees Centigrade, or 7.27° F. Of course the surrounding tissues would absorb heat more or less rapidly, but it is to be remembered that this quantity of heat is being liberated every second. It seems very convincing to me that it is at this point that the pain limit is determined in the case which we are considering, as indeed in most cases.

Relation of Heat to Pain Limit.

Now let us imagine some modifications of this case. Suppose the resistance through the dentine is 1,000 ohms instead of 10,000. What will be the changes of phenomena? The resistance of the circuit will be 53,000 ohms. Very clearly the pain limit will not change, so the milliampere meter will read the same. Really the only difference it will make will be that it will require less voltage, which will be 21.3 instead of 25.

Suppose the resistance through the dentine be 100,000 ohms. This will mean that for the same pain limit the voltage would be 61. In this case the heat generated in the dentine would be $100,000 \times 0.0004^2 \times 0.236$ calories, which, using the same conditions of cavity which we had before, would make a rise of temperature in the conducting medium of the dentine of 9.2° C., or 16.7° F. This would probably be almost the same concentration of heat which we had in the apex, and if the conducting tissue of the dentine were more sensitive than that at the apex, we would probably have the pain limit determined at this point. Now, suppose it is, and suppose you were able to increase the amperage to only 0.0003, what will be the effect of cutting out part of this dentine?

Of course it will lower the resistance of the circuit, but besides, if the pain limit is determined at this point, we will find by a new application, that the pain limit has raised. It is in this way that we are able frequently to determine just where the pain limit is being determined, as in case No. 5.

Suppose now the resistance through the walls of the root of this tooth were 200,000 ohms; then the combined resistance of this path and shunt would be $(200,000 \times 90,000) \div (200,000 + 90,000) = 62,060$ ohms, and the resistance of the circuit would be 79.560. The pain limit would clearly be found at the same place, though to produce the same concentration of heat at that point, the total amperage would not be so great. The pain limit of that apex is 0.0002 amperes, and the current flowing through these two paths is in inverse proportion to their resistance, hence the current flowing through the walls will be 0.00009 amperes, and the total .00029. This will require a potential of 23. volts. Here we have lowered the voltage by increasing the resistance; an apparent absurdity, nevertheless it is true.

Again, let us suppose the same case, but with the resistance through the root walls only 10,000 ohms. In this case the resistance of this part of the path, the two way part, will be: 90,000 × 10,000 ÷ (90,000 + 10,000) = 9,000, and the total resistance of the circuit is 26,500.

The pain limit of the apex is constant at 0.0002 amperes, and therefore the current flowing through the walls is to 0.0002 as 90,000 is to 10,000, or is .0018. Then the total current flowing is 0.0018 + 0.0002 = 0.002 amperes, or 2 milliamperes, with a voltage of 53. This would undoubtedly produce pain in the dentine, and the pain limit would in this case be determined in the dentine. On cutting out a part of the dentine, and taking a new reading of the pain limit, we would find it proportionately changed. This condition would be hard to identify unless you undertook to remove the pulp from the root, when you would be very much chagrined and surprised at the incredible length of time required as compared with the amperage. I have measured cases in the mouth that had given just such trouble in removing the pulp from the apical end of the root, and found the resistance through the wet walls, after filling the apex, but slightly greater than the total resistance before drying the tip for filling. If time would permit, these same relations should be applied to two and three roots of teeth, and they would explain quite perfectly the clinical data.

While we have these relations fresh in our minds, let us review the observations made from the clinical data. (See page xxx.)

The last two observations are undoubtedly due to the diminished size of the apical foramen, and the increased proportion of organic matter in the tooth substance with age. This matter of the relation of the resistance in a circuit to the relation of two paths in some part of the same circuit, should be clearly understood by the operator before he can give his patient his best services. I would advise every student of cataphoresis to make a study of it, for it is a factor to be considered in almost every cataphoric operation made on the teeth. It can be found in any good work on electricity. A quite thorough discussion of it can be found in the report of the Ohio State Meeting of December, 1896, in the February number of the *Ohio Journal*, or in the February and April numbers of *Cosmos*, by the author. No such condition as obtains in the teeth is found in the medication of other tissues of the body by the same means. And for two reasons: A difference in the nature of the tissue, and a great difference in the nature of the circuit.

Let us now consider the forces at work in the process. Except at infinite dilution of the medicines the electric current will not entirely disturb the internal forces within and between the various mediums, consequently we must consider these as well as the new ones arising from he presence of the current. First, what are the physical conditions that xist under the circumstances which we are considering?

Physical Conditions in Cataphoresis.

Beginning with the anode we have a conductor of the first class (a metal) in contact with a conductor of the second class (an electrolyte). This electrolyte is a solution of a compound substance which is in contact with another solution which has the same solvent f the medicament is in an aqueous solution, though different substances n solution. This second solution is also an electrolyte and is the conents of the dentinal tubes. The first electrolyte is also in contact with n insoluble porous partition, if you choose to call it such, the matrix of he dentine, which is composed chiefly of insoluble inorganic salts. This orous partition, as also the second solution, is in contact with other soluions of the tissues surrounding the tooth. Besides these we have an rganic cell membrane within the interstices of the porous partition.

The forces at work between these various substances, without the resence of an electric current, are those existing between liquids conaining different substances in solution, in different concentrations, with r without the same solvent, and those forces arising from potential differences existing between a metal and a liquid and between two liquids.

Taking these up separately we have first the potential difference existing between the metal and the first electrolyte, due to the solution pressure of the ions of that metal and the counter osmotic pressure of the ions of the compounds of that metal, if they exist, in the solution. These factors depend entirely upon the metal forming the anode and the solution. With gold or platinum and the cocaine solution this force would be infinitely slight and would not produce any considerable potential difference.

Osmosis.

Between the electrolytes, viz., the cocaine solution in the cavity and the contents of the tubes we would have the forces existing between all solutions. Of these Osmosis is the chief, and the only one which we need to consider. It is that force exerted by any substance held in solution in its efforts to fill all possible space. Osmosis does not require to take place through a diaphragm or wall of some kind, it takes place in any solution of uneven concentration, and is that force which makes the concentration uniform throughout. If a partition is in the way it will try to go through it, but if that partition is impermeable to that substance, though not to the solvent, it will then pull the solvent through to it. This force is enormous. In fact it is identical with the force that would be exerted by that same substance, in the same space, in the gaseous condition, if the solvent were removed. Time forbids any suggestion as to its relations to the other forces. In the solutions which we are considering we have certainly different concentrations, and if there is no semipermeable membrane these substances held in solutión will, by their efforts to equalize the concentration, diffuse each into the other solution. If there exists a membrane impermeable to them, but not to the solvent, they will try to draw the solvent of the other solution to them. As a matter of fact the cell tissue of these dentinal tubes have in their limiting membranes a membrane semipermeable to many solutions. This would not prevent the cocaine from entering, but would probably prevent some of the substances held in solution forming the contents of the cells, though not all. If all, then the cell would expand to take in water.

Between the cocaine solution and the solid substance of the dentine there would probably be a very slight potential difference, not a thousandth part of a volt, however, arising from the solution pressure of the ions of the latter in the former, forming, as betwen the metal and the first electrolyte, an electrical double layer. This force would be very slight.

Influence of Electric Current.

Let us now consider the forces existing under the same conditions when an electric current is passing through them.

Since an electric current cannot pass through any conductor of the second class except by means of the movement of ponderable matter, we must consider this force.

In every solution the molecules of the dissolved substance are to a greater or less extent dissociated. These dissociation products contain electric changes, either positive or negative, but always the same quantity of each in the solution. During the passage of an electric current these ions are attracted toward their opposite sign, and, at the electrodes, give up their electric charges and combine with it if possible, if not, are liberated to react in the solution or are given off as gas. Exactly the same quantity of ions must be liberated at the two electrodes at the same time, otherwise there would result an accumulation of positive or negative electricity in the solution, which is an impossibility, the detailed reason for which time will not permit.

In all parts of the solution there will be a migration of ions toward their respective attraction, but the velocity of this migration will depend upon this ion itself, and the concentration of the solution, with increased concentration a decrease of velocity, though not of conductivity. If the concentration of the ion gets low around the electrode new ions are formed from the molecules in the solution. At infinite dilution the dissociation is complete. This varies for different substances, but for cocaine hydrochlorate in water is far greater than any solution we would use. Of course the difference of concentration of the particular ion ill produce an osmotic pressure of this particular ion. Owing to the ifferent migration velocities of ions, the amount going each way would ot be equivalent at a particular point in cross section *unless* they had he same velocities, for example, K and NH_4; K and Cl. or K and L. ave almost identical velocities. These velocities are quite easily deter-ined. Please note this, as I did not make it clear in a recent paper.

In brief, "The quantity of an electrolyte decomposed is directly in roportion to the quantity of electricity which passes through it; or, the ate at which a body is electrolyzed is proportional to the current trength."

If the same current pass through different electrolytes the quantity f each ion evolved is proportional to its chemical equivalent. "The chem-cal equivalent is the weight of the radical of the ion in terms of the atom f hydrogen, divided by its valency." Which is equivalent to saying hat, "The number of electro-chemical equivalents evolved in a given ime by the passage of any current through any electrolyte is equal to he number of units of electricity which pass through the electrolyte in he given time."

From this we can determine the exact quantity of cocaine carried nto the tooth by electrolysis. The formula for cocaine hydrochlorate is $C_{19}\ H_{27}\ NO_4\ H\ Cl$. The best authorities I have been able to get on this ubject say that the Cl. forms the negative ion going to the positive pole, nd the balance of the molecule forms the positive ion going to the egative pole. If there is no other substance in solution to help carry he current these must do it. We know the migration velocity of Cl; it s, at infinite dilution, 0.00069 cm. per sec. under a potential gradient of volt per cm. So far as I know the exact migration velocity of the other on of cocaine hydrochlorate has not been determined until done by Prof. Morley for this paper.* It can be approximately guessed from its size nd constitution, though not accurately.

He finds it to be about one-tenth that of Cl or Na.

We can easily determine the quantity of the alkaloid that has ctually started toward the negative pole, though we cannot absolutely letermine just how far any portion of it has advanced without knowing ts migration velocity. In order to decompose an exact equivalent of ny substance it is necessary to send 96,540 coulombs of electricity hrough the circuit. This is known as the electro-chemical unit of elec-ricity. To find the electro-chemical equivalent of hydrochlorate of ocaine we divide its molecular weight by its valency, giving us 369 grams lecomposed by 96,540 coulombs. Suppose the current to be running for o minutes at 0.5 M. A. Then $\frac{369}{96540} \times \frac{1800}{} \times \frac{5}{10000} \times \frac{1000}{} =$ milligrams of cocaine, hydrochlorate decomposed, equals 3.43. Of this 3.11 milligrams has started toward the negative pole. This is a sufficient quantity to anaesthetize a considerable tissue, and especially in this nascent condition.

What are the other forces existing in this system during the passage of the current? The osmosis of the undissociated molecules has practically not been disturbed. The differences of potential between the electrode and the electrolyte has been changed or increased, as also between the electrolytes, and between the first electrolyte and the matrix of the dentine. This is probably the point of greatest interest of this paper. This we spoke of a few minutes ago as the electrical double sheet. It is produced by ions going off from a substance, the dentine in this case, into the solution by their own solution pressure. The substance they leave becomes negatively charged toward the substance they go to. Equilibrium is only established when the solution pressure of the ions is equaled by the electrostatic force thus set up. This is the electrical double sheet. Suppose a partition of clay, or better, unglazed earthen, with a solution on each side and an electrical current, is passed, what takes place? In most cases a movement toward the negative pole, though not always. Remember the solution is positive towards the substance from whence came these ions, and since the increase of positive charge to the liquid, the theory is that the substance of the porous partition, on account of the unbalanced electric charges, attracts the nearest film of the substance, and in this way drags it through the interstices in the form of a simple current. The measure of the result is determined by the quantity of current and the nature of the solution and partition. This is true electrical endosmose.

Question: To what extent does it occur in the process of cataphoresis as applied to the dental organs? We should say in passing that it is this electrical double sheet and its effect on the surface tension that produces the phenomena which we observe when we place a globule of mercury between the electrodes in a sulphuric acid solution. The extent of this electrical double sheet is determined largely by the specific resistance of the solution, and in fact is in direct proportion to it. The nature and especially the minute structure of the partition have a great deal to do with it.

Experimental Tests for Osmosis and Electrolysis.

An experimental test is the simplest way to make the determination required for the answering of the question just asked. If we select a substance of about the same resistance as the cocaine solutions used, and of very delicate test, we should with great thoroughness be able to come to some conclusions. For this purpose I have made a great many quantitative tests using as nearly as possible the same conditions as exist in the actual operation. To give an infinitely greater surface of dentine for the porous partition, I placed the solution within the pulp chamber and root canals after hermetically sealing the apical foramen. The teeth themselves were placed through cards of gutta percha, and the cavity perfectly separated from any possible connection with the outside solution, which was distilled water. The first solution used was sodium iodide and tests made frequently by the flame test for the sodium which appeared at the cathode in about ten minutes. Various concentrations and lengths of time were given and the solutions very carefully tested for iodine, and even after two hours none could be found. But the question arose, did any of the sodium go through, or did it come out of the tooth? To obviate this question a substance was selected that did not exist in the tooth, namely, lithium, and which has a very delicate test. Lithium iodide was used in many cases, in every one of which the lithium was more or less pronounced in accordance with the time. In 30 minutes it was very marked, and in 2 hours profuse. In no case could a trace of iodine be found. I had Prof. Morley, ex-president of the American Association for the Advancement of Science, repeat the tests, and he said he knew there was not the one ten-thousandth part of a gram of iodine came through, for he could not find a trace. He made a quantitative test. He detected the lithium by means of the spectroscope, and was unqualified in his assertion that the lithium got there by electrolysis. In fact, it arrived there at the time calculated from its migration velocity by electrolysis.

The question now arises, why should we not be assisted by this force of electric endosmose? For several reasons. The dentine contains tubes to be sure, but they are not open so a current can flow through them. If the solution passed through them it would have to penetrate the limiting membranes of the cell, which is a slow process. It might be suggested that it could go between the cells and tube walls, but the total cross sectional area of the intercellular spaces exposed in a cavity would be extremely small. Another great factor is the specific resistance of the solution which does not favor it.

As a matter of fact the phenomena of electrical endosmose are very often chiefly the result of the forces of osmosis acting naturally upon the products of electrolysis, or of cycical chemical processes in connection with electrolysis, as for example, the particles of carbon or many other substances in a solution. The carbon particles are insoluble, of course, but they are conductors of the first class, and when the current is passing it goes through them because they have less resistance than the solution

But where a current is passing from the surface of a conductor of the first class to a conductor of the second class, there must be either of two things, a liberation of the ion as gas, or it must unite with the electrode, or in a compound reaction with the substances of the solution. In this way the carbon particles enter into a compound molecule which later is broken up by dissociation, the carbon becoming a part of a positive ion, and is hurried along toward the negative pole. On its way it meets a positive ion for which it has a greater affinity than the electric charge carrying it, and it again forms a new compound, which if insoluble is left suspended in the solution. In this ionic form it could penetrate cell tissue or anything else that contained an electrolyte and be deposited.

Gentlemen, I regret the length of this paper, for I had hoped to have time to make some practical conclusions. This is really just the preface to the subject. In behalf of the needs and absolute requirements for the most successful application of this process, I appeal to the manufacturers for better apparatus. There is not delicacy or accuracy enough in our milliampere meters. We must have them reading to 1 milliampere in hundredths. Mine reads to hundredths of millionths of amperes; hundredths of thousandths of amperes will do for practical work. The controllers are yet far from what the sensitiveness of some teeth, to pulsations of current, demand.